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ΣΧΟΛΗ ΗΛΕΚΤΡΟΛΟΓΩΝ ΜΗΧΑΝΙΚΩΝ
ΚΑΙ ΜΗΧΑΝΙΚΩΝ ΥΠΟΛΟΓΙΣΤΩΝ
ΤΟΜΕΑΣ ΕΠΙΚΟΙΝΩΝΙΩΝ, ΗΛΕΚΤΡΟΝΙΚΗΣ ΚΑΙ ΣΥΣΤΗΜΑΤΩΝ ΠΛΗΡΟΦΟΡΙΚΗΣ

Υποστήριξη Συνδεδεμένης και Αυτοματοποιημένης Κινητικότητας μέσω 5G σε Διασυνοριακές Συνθήκες:

Προκλήσεις, Αξιολόγηση Απόδοσης και Μελλοντικές Προοπτικές

ΔΙΔΑΚΤΟΡΙΚΗ ΔΙΑΤΡΙΒΗ

Κωνσταντίνος Β. Τριχιάς

Αθήνα, Ιούνιος 2025

Εθνικο Μετσοβιο Πολυτεχνειο
Σχολη Ηλεκτρολογων Μηχανικων
και Μηχανικων Υπολογιστων
Τομεας Επικοινωνιων, Ηλεκτρονικης και Συστηματων
Πληροφορικης

5G Enabled Connected and Automated Mobility (CAM) in Cross-Border Conditions: Challenges, Performance Assessment and Way Forward

PhD DISSERTATION

Konstantinos V. Trichias

Athens, June 2025

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5G Enabled Connected and Automated Mobility (CAM) in Cross-Border Conditions:

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PhD DISSERTATION

Konstantinos V. Trichias

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Περίληψη

Η έρευνα που παρουσιάζεται διερευνά τις προκλήσεις ανάπτυξης και λειτουργίας της Συνδεδεμένης και Αυτοματοποιημένης Κινητικότητας (Connected and Automated Mobility - CAM) μέσω δικτύων 5G σε διασυνοριακές συνθήκες. Μέσω μιας σειράς εκτεταμένων μετρήσεων και αναλύσεων, αυτή η μελέτη αξιολογεί την απόδοση των υπηρεσιών CAM σε διασυνοριακές συνθήκες υπό διαφορετικές διαμορφώσεις δικτύου 5G και ρυθμίσεων της εφαρμογής CAM για 5G Non-Standalone (NSA) δίκτυα, ώστε να κατανοήσει τον αντίκτυπό τους στη διασυνοριακή απόδοση που βιώνει ένα αυτόνομο όχημα.

Η μελέτη ξεκινά με την περιγραφή της τρέχουσας κατάστασης των τεχνολογιών CAM, τονίζοντας τα οφέλη του 5G για το CAM και πραγματοποιεί μια εκτενή ανάλυση των εμποδίων στην υιοθέτηση και ανάπτυξη υπηρεσιών CAM πέρα από τα εθνικά σύνορα, συμπεριλαμβανομένων ζητημάτων που σχετίζονται με τη διαλειτουργικότητα του δικτύου, την τοποθέτηση edge nodes , τη διαμόρφωση των CAM εφαρμογών, το απόρρητο των δεδομένων και τον κατακερματισμό των ρυθμιστικών πλαισίων στα κράτη μέλη της ΕΕ.

Παρουσιάζεται μια ολοκληρωμένη ανάλυση των απαιτήσεων της Ευρωπαϊκής βιομηχανίας, αποκαλύπτοντας ότι οι βασικοί παράγοντες για την επιτυχή ανάπτυξη CAM περιλαμβάνουν την απρόσκοπτη κάλυψη δικτύου, τα ισχυρά μέτρα κυβερνο-ασφάλειας και την εναρμόνιση των τεχνικών προτύπων. Επιπλέον, η μελέτη τονίζει τη σημασία της διασυνοριακής συνεργασίας μεταξύ των εθνικών κυβερνήσεων, των παρόχων τηλεπικοινωνιών και των κατασκευαστών αυτόνομων οχημάτων. Στα πλαίσια της μελέτης δημιουργήθηκε ένας υπερσύγχρονος διασυνοριακός διάδρομος 5G μεταξύ των συνόρων Ελλάδας και Τουρκίας όπου πραγματοποιήθηκαν εκτενείς μετρήσεις για τον εντοπισμό των βέλτιστων λύσεων για τον μετριασμό των διασυνοριακών προκλήσεων και τη βελτιστοποίηση της διασυνοριακής απόδοσης των εφαρμογών CAM.

Η έρευνα παρουσιάζει μια λεπτομερή ανάλυση των βασικών παραμέτρων δικτύου, συμπεριλαμβανομένης της καθυστέρησης από άκρο σε άκρο (E2E), των χρόνων διακοπής υπηρεσίας και των επιπτώσεων διαφορετικών στρατηγικών περιαγωγής και διασύνδεσης, στην παρατηρούμενη απόδοση. Τα ευρήματα υποδεικνύουν ότι το Home Routing (HR) με άμεση διασύνδεση των γειτονικών δικτύων προσφέρει την πιο αξιόπιστη απόδοση για υπηρεσίες CAM, με την καθυστέρηση E2E να ικανοποιεί σταθερά τις αυστηρές απαιτήσεις κάτω των 100 ms. Αντίθετα, η στρατηγική Local Breakout (LBO), αν και είναι ωφέλιμη για τη μείωση της καθυστέρησης δικτύου υπό ιδανικές συνθήκες, παρουσιάζει σημαντικά μειονεκτήματα ως προς την παροχή αδιάκοπης σύνδεσης. Η μελέτη υπογραμμίζει επίσης τον κρίσιμο ρόλο του edge computing στην σημαντική βελτίωση των χρόνων απόκρισης, καθιστώντας το μια προτιμώμενη λύση για εφαρμογές CAM.

Συμπερασματικά, η συγκεκριμένη διατριβή προσφέρει μερικά από τα πρώτα παγκοσμίως διαθέσιμα συμπεράσματα σχετικά με τη διασυνοριακή απόδοση εφαρμογών CAM μέσω δικτύων 5G-Non-Standalone (5G-NSA), βασισμένα σε πραγματικές μετρήσεις δικτύου και εφαρμογών, εξερευνώντας τα όρια απόδοσης των εφαρμογών CAM μέσω δικτύων 5G-NSA σε διασυνοριακές συνθήκες, ενώ προσδιορίζει και τις κατάλληλες ρυθμίσεις δικτύων και διαμορφώσεις εφαρμογών για βελτιστοποίηση της απόδοσης. Η μελέτη παρέχει επίσης έναν οδικό χάρτη για τη μελλοντική ανάπτυξη του CAM στην Ευρώπη, τονίζοντας την ανάγκη για συνεχείς επενδύσεις σε υποδομές 5G (εξέλιξη προς δίκτυα 5G-SA), μεγαλύτερη διασυνοριακή ρυθμιστική ευθυγράμμιση και προληπτική προετοιμασία για την ενοποίηση των μελλοντικών δικτύων B5G και 6G. Αντιμετωπίζοντας αυτούς τους τομείς, η ΕΕ μπορεί να επιταχύνει την ανάπτυξη του CAM, συμβάλλοντας έτσι σε ασφαλέστερα, αποτελεσματικότερα και φιλικά προς το περιβάλλον συστήματα μεταφορών.

Λέξεις Κλειδιά:

- Συνδεδεμένη και Αυτοματοποιημένη Κινητικότητα (CAM)
- 5G- Non-Stand Alone (5G-NSA)
- Προκλήσεις Διαχείρισης Κινητικότητας Δικτύων
- Μεταπομπή (Handover) μεταξύ PLMN για δίκτυα 5G
- Διασυνοριακός Διάδρομος 5G
- Περιαγωγή εφαρμογών Συνδεδεμένης και Αυτοματοποιημένη Κινητικότητας
- Αξιολόγηση απόδοσης εφαρμογών CAM μέσω δικτύων 5G
- Βελτιστοποίηση διασυνοριακής απόδοσης για εφαρμογές CAM

Abstract

The work presented in this study investigates the deployment and operational challenges of 5G-enabled Connected and Automated Mobility (CAM) in cross-border conditions. Through a series of comprehensive measurements and analyses, this study evaluates the performance of various 5G network configurations and CAM application settings specifically in the context of 5G Non-Standalone (NSA) architecture, to understand their impact on the CAM user experienced performance across borders.

The study begins by outlining the current state of CAM technologies, highlighting the benefits of 5G for CAM, and performs an extensive analysis of the barriers to the adoption and deployment of CAM services across national borders, including issues related to network interoperability, edge node placement, On Board Unit (OBU) and CAM application configuration, data privacy, and the fragmentation of regulatory frameworks across EU member states.

A comprehensive analysis of stakeholders' perspectives is presented, revealing that key factors for successful CAM deployment include seamless network coverage, robust cybersecurity measures, and the harmonization of technical standards. Furthermore, the study emphasizes the importance of cross-border cooperation among national governments, telecommunications providers, and automotive manufacturers to ensure the continuity of CAM services as vehicles move between different jurisdictions. A state-of-the art cross-border 5G corridor is set-up between the borders of Greece and Turkey, and extensive measurement campaigns are performed to identify the optimum solutions to mitigate the cross-border challenges and to optimize CAM performance across borders, Level 4 using autonomous tracks and 5G NSA networks.

The research presents a detailed examination of key network parameters, including end-to-end (E2E) latency, handover interruption times, and the effects of different roaming and interconnection strategies on service continuity, as well as thorough investigation of the effect of different OBU and application configurations on the observed performance. The findings indicate that the Home Routing (HR) with Direct interconnection configuration offers the most reliable performance for CAM services, with E2E latency consistently meeting the stringent requirements of less than 100 ms. In contrast, the Local Breakout (LBO) strategy, while beneficial in reducing latency under ideal conditions, exhibits significant drawbacks during inter-Public Land Mobile Network (PLMN) handovers, leading to unacceptable service interruptions.

Furthermore, the study highlights the critical role of edge computing in reducing latency, where placing applications closer to the network edge substantially improves response times, making it a preferred solution for latency-sensitive CAM applications. The dissertation also identifies the challenges posed by inter-PLMN handovers, particularly in maintaining the Quality of Service (QoS) for high-priority CAM applications during cross-border transitions.

In conclusion, the work presented in this study offers some of the first globally available insights regarding cross-border CAM performance with 5G-NSA networks, based on real-life network and application measurements, showcasing the performance limits of 5G-NSA networks for cross-border CAM and pointing towards the proper networks settings and application configurations to optimize performance. The study also provides a roadmap for the future development of CAM in Europe, emphasizing the need for continued investment in 5G infrastructure (evolution towards 5G-SA networks), greater cross-border regulatory alignment, and proactive preparation for the integration of B5G and 6G technologies. By addressing these areas, the EU can accelerate the deployment of CAM, thereby contributing to safer, more efficient, and environmentally friendly transportation systems.

Keywords:

- Connected and Automated Mobility (CAM)
- 5G- Non-Stand Alone (5G-NSA)
- Inter-PLMN Handover
- 5G Cross-Border Corridor
- CAM Mobility Management challenges
- Roaming for CAM
- Inter-PLMN interconnection
- Edge server placement for CAM
- 5G NSA performance evaluation
- 5G NSA optimization for CAM services
- V2X communications
- CAM stakeholders' requirements
- Autonomous vehicle & OBU optimization

Ευχαριστίες

Η αναζήτηση της γνώσης δεν τελειώνει ποτέ και εύχομαι να μπορέσω να συνεχίσω το ταξίδι της ανακάλυψης για πολλά χρόνια ακόμα. Ωστόσο, με την ολοκλήρωση της διδακτορικής μου έρευνας, ένα μεγάλο κεφάλαιο στις ακαδημαϊκές και επιστημονικές μου προσπάθειες φτάνει στο τέλος του. Η εμπειρία της διεξαγωγής της διδακτορικής μου έρευνας παράλληλα με τις επαγγελματικές και προσωπικές μου υποχρεώσεις δεν ήταν εύκολη, καθώς απαιτούσε σωματική και ψυχική επιμονή σε καλές και κακές στιγμές, και ως εκ τούτου, δεν ήταν ένα ταξίδι που θα μπορούσα να ολοκληρώσω μόνος μου. Έτσι, αισθάνομαι ότι οφείλω την ευγνωμοσύνη μου σε αρκετούς ανθρώπους που με ενέπνευσαν να κυνηγήσω αυτή την ακαδημαϊκή περιπέτεια και με βοήθησαν να την ολοκληρώσω.

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Table of Contents

List of Figures

List of Tables

Abbreviations Table

Abbreviation	Explanation
3GPP	3rd Generation Partnership Project
4G	Fourth Generation (mobile telecommunications)
5G	Fifth Generation (mobile telecommunications)
5G NSA	5G Non-Standalone
5G PPP	5G Public-Private Partnership
5GC	5G Core Network
802.11bd	IEEE 802.11bd (WAVE Next Generation)
802.11p	IEEE 802.11p (WAVE)
AAS	Advanced Antenna System
ACCA	Anticipated Cooperative Collision Avoidance
AD	Autonomous Driving
ADAS	Advanced Driving Assistance System
AI	Artificial Intelligence
AMF	Access and Mobility Management Function
AS	Application Server
BBM	Broadband Machine-Type
BLER	Block Error Rate
bps	Bits per second
CA	Carrier Aggregation
CAM	Connected and Automated Mobility
CAM (messages)	Cooperative Awareness Messages
CAV	Connected and Automated Vehicle
CBC	Cross-Border Corridor
CCAM	Cooperative Connected and Automated Mobility
CEF	Connecting Europe Facility
CI	Confidence Interval
CoMP-JT	Cooperative Multi Point - Joint Transmission
COTS	Commercial Off-The-Shelf
CP	Control Plane
CP/DP	Control Plane/Data Plane
CPM	Collective Perception Message
C-RAN	Cloud Radio Access Network
C-RNTI	Cell Radio Network Temporary Identifier
CS	Considered Solutions
CUPS	Control and User Plane Separation
C-V2X	Cellular Vehicle-to-Everything
D2D	Device-to-Device
dB	Decibels
DC	Dual Connectivity
DENM	Decentralized Environmental Notification Message
DL	Downlink
DSB	Downlink Symbol Blanking
DSRC	Dedicated Short-Range Communication
DTX/DRX	Discontinuous Transmission/Reception
E2E	End-to-End
EC	European Commission
ECC	Electronic Communications Committee
ECU	Electronic Control Unit
eDRx	Extended Discontinuous Reception

eMBB	Enhanced Mobile Broadband
eNB	Evolved Node B
EPC	Evolved Packet Core
ES-PT	Spain-Portugal
EU	European Union
FCC	Federal Communications Commission
GDPR	General Data Protection Regulation
gNB	Next Generation Node B (5G Base Station)
GNSS	Global Navigation Satellite System
GPRS	General Packet Radio Service
GPS	Global Positioning System
GR-TR	Greece-Turkey
GRX	GPRS Roaming Exchange
GRX/IPX	GPRS Roaming Exchange/IP Exchange
GSM	Global System for Mobile Communications
GSMA	GSM Association
GTP-U	GPRS Tunnelling Protocol – User plane
GUI	Graphical User Interface
HARQ	Hybrid Automatic Repeat reQuest
HD	High Definition
HET	Handover Execution Time
HIT	Handover Interruption Time
HO	Handover
HOF	Handover Failure
H-PGW	Home Packet Gateway
H-PLMN	Home Public Land Mobile Network
HR	Home Routed
HSS	Home Subscriber Server
HTTP	Hypertext Transfer Protocol
HTTPS	Hypertext Transfer Protocol Secure
ICI	Inter-Carrier Interference
IEEE	Institute of Electrical and Electronics Engineers
IMEI	International Mobile Equipment Identity
IoT	Internet of Things
IP	Internet Protocol
IPsec	Internet Protocol Security
IPX	Internet Protocol Exchange
ISD	Inter-Site Distance
ITS	Intelligent Transportation System
KPI	Key Performance Indicator
LBO	Local Break-Out
LDM	Local Dynamic Map
LDPC	Low-Density Parity-Check
Lidar	Light Detection and Ranging
LoS	Line of Sight
LTE	Long-Term Evolution
LTE-V2X	Long-Term Evolution Vehicle-to-Everything
MAC	Medium Access Control
MBB	Make Before Break
MBMS	Multimedia Broadcast Multicast Service
Mbps	Megabits per second
MCC	Mobile Country Code

MCM	Manoeuvre Coordination Messages
MCS	Modulation and Coding Scheme
MEC	Mobile Edge Computing
MEC	Multi-Access Edge Computing
MIMO	Multiple Input Multiple Output
ML	Machine Learning
MM	Mobility Management
MME	Mobility Management Entity
mMTC	Massive Machine-Type Communications
MNO	Mobile Network Operator
MSE	Mobility State Estimation
N2V	Network-to-Vehicle
NACK	Negative Acknowledgement
NB-IoT	Narrowband Internet of Things
NFC	Near Field Communication
NGC	Next Generation Core
NHTSA	National Highway Traffic Safety Administration
NLoS	Non-Line of Sight
NOMA	Non-Orthogonal Multiple Access
NR	New Radio
NR-V2X	New Radio Vehicle-to-Everything
NSA	Non-Standalone
OBD	On-Board Diagnostics
OBU	On-Board Unit
OEM	Original Equipment Manufacturer
OFDM	Orthogonal Frequency-Division Multiplexing
OMA	Orthogonal Multiple Access
OSPF	Open Shortest Path First
OSS	Operations Support Systems
PCF	Policy and Control Function
PDCCH	Physical Downlink Control Channel
PDCP	Packet Data Convergence Protocol
PDN	Packet Data Network
PDU	Protocol Data Unit
PDU	Packet Data Unit
PER	Packet Error Rate
PGW	PDN Gateway
PGW / P-GW	Packet Gateway
PHY	Physical Layer
PLC	Programmable Logic Controller
PLMN	Public Land Mobile Network
PoC	Proof of Concept
PRR	Packet Reception Rate
PSCCH	Physical Shared Control Channel
PSFCH	Physical Sidelink Feedback Channel
PSSCH	Physical Sidelink Shared Channel
QOE	Quality of Experience
QoS	Quality of Service
R&I	Research and Innovation
RA	Random Access
RACH	Random Access Channel
RAN	Radio Access Network

RAT	Radio Access Technology
RB	Resource Block
RLF	Radio Link Failure
RPM	Revolutions Per Minute
RSI	Roadside Infrastructure
RSRP	Reference Signal Received Power
RSU	Roadside Unit
RTD	Round-Trip Delay
RTT	Round-Trip Time
SA	Standalone
SAE	Society of Automotive Engineers
SBA	Service Based Architecture
SCI	Sidelink Control Information
SC-PTM	Single Cell – Point to Multi-point
SCS	Sub-Carrier Spacing
SDN	Software Defined Networking
SEPP	Security Edge Protection Proxy
SGi	Serving Gateway - Interface
SgNB	Serving gNB
SGW	Serving Gateway
SIM	Subscriber Identity Module
SINR	Signal-to-Interference-plus-Noise Ratio
SMF	Session Management Function
SNR	Signal-to-Noise Ratio
SotA	State of the Art
SPS	Semi-Persistent Scheduling
SRB	Signaling Radio Bearer
SSC	Session and Service Continuity
TCP	Transmission Control Protocol
TDD	Time Division Duplexing
TEN-T	Trans-European Transport Network
TF	Traffic Flows
TgNB	Target gNB
ToD	Tele-operated Driving
TRX	Transmit/Receive
TTT	Time To Trigger
UAV	Unmanned Aerial Vehicle
UC	Use Case
UDC	User Data Consolidation
UDP	User Datagram Protocol
UE	User Equipment
UL	Uplink
UML	Unified Modeling Language
UPF	User Plane Function
URLLC	Ultra-Reliable Low-Latency Communications
US	Use Story
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VANET	Vehicular Ad-hoc Network

vEPC	Virtual Evolved Packet Core
V-PGW	Visiting Packet Gateway
V-PLMN	Visited Public Land Mobile Network
VPN	Virtual Private Network
VRU	Vulnerable Road Users
XBI	Cross-Border Issues
ZSM	Zero Touch Service Management

Εκτεταμένη Περίληψη στα Ελληνικά

Κεφάλαιο 1

Αυτή η διδακτορική διατριβή παρουσιάζει μια ολοκληρωμένη μελέτη των τεχνικών, λειτουργικών και στρατηγικών διαστάσεων που εμπλέκονται στην ενεργοποίηση της Συνδεδεμένης και Αυτοματοποιημένης Κινητικότητας (CAM) μέσω δικτύων 5G, με ιδιαίτερη έμφαση στις προκλήσεις που αντιμετωπίζονται σε διασυνοριακά σενάρια. Ο κεντρικός στόχος της διατριβής είναι να διερευνήσει πώς η υποδομή κινητών επικοινωνιών 5G μπορεί να βελτιστοποιηθεί για να υποστηρίξει ισχυρές, αδιάλειπτες εφαρμογές CAM καθώς τα οχήματα κινούνται πέρα από τα εθνικά σύνορα και μεταξύ διαφορετικών φορέων εκμετάλλευσης δικτύων κινητής τηλεφωνίας (MNOs). Μέσω μιας εις βάθους ανάλυσης των τρεχόντων προτύπων, αρχιτεκτονικών και αναπτύξεων, καθώς και μέσω πειραματισμού σε πραγματικές εγκαταστάσεις 5G στα σύνορα Ελλάδας-Τουρκίας, η εργασία εντοπίζει βασικά εμπόδια και προτείνει συγκεκριμένες λύσεις για τη διευκόλυνση της ασφαλούς και αποτελεσματικής συνδεσιμότητας CAM σε τέτοια σύνθετα περιβάλλοντα.

Το κεφάλαιο 1 εισάγει την έννοια και τους βασικούς όρους της διατριβής. Επίσης, παρουσιάζει το τρέχον τοπίο ξεκινώντας με μια επισκόπηση του πώς η αυτοκινητοβιομηχανία μεταβαίνει προς οχήματα που έχουν ολοένα και μεγαλύτερη επίγνωση του περιβάλλοντός τους, αξιοποιώντας έναν συνδυασμό ενσωματωμένων αισθητήρων και εξωτερικών ασύρματων διεπαφών επικοινωνίας. Η έννοια του Vehicle-to-Everything (V2X), η οποία περιλαμβάνει την επικοινωνία μεταξύ οχημάτων (V2V), επικοινωνία με υποδομές (V2I), επικοινωνία με δίκτυα (V2N) και επικοινωνία με πεζούς (V2P), χρησιμεύει ως η τεχνολογική βάση για τις υπηρεσίες CAM. Εξετάζεται η εξέλιξη των προτύπων επικοινωνίας V2X, συγκρίνοντας τις παραδοσιακές επικοινωνίες Dedicated Short-Range Communications (DSRC) που βασίζονται στο IEEE 802.11p με νεότερες εναλλακτικές λύσεις που βασίζονται σε κινητά δίκτυα, όπως το LTE-V2X και το 5G New Radio V2X (NR-V2X), που τυποποιήθηκαν στις εκδόσεις 14 και 16 του 3GPP αντίστοιχα. Ενώ το DSRC προσφέρει χαμηλή καθυστέρηση κατάλληλη για βασικές εφαρμογές ασφάλειας, οι νεότερες τεχνολογίες κινητής τηλεφωνίας προσφέρουν πλεονεκτήματα όσον αφορά την επεκτασιμότητα, την αξιοπιστία και την υποστήριξη για πιο σύνθετες απαιτήσεις ποιότητας υπηρεσίας (QoS), ειδικά σε σενάρια υψηλής πυκνότητας ή μη οπτικής επαφής.

Η ενότητα συνεχίζει με την ανάλυση των θεμελιωδών αρχών των εφαρμογών CAM, εστιάζοντας στον τρόπο με τον οποίο τα οχήματα ανταλλάσσουν περιοδικά Μηνύματα Συνεργατικής Ευαισθητοποίησης (Cooperative Awareness Messages - CAM), τα οποία παρέχουν ενημερώσεις σε πραγματικό χρόνο σχετικά με τη θέση, την ταχύτητα και την κατεύθυνση. Αυτά τα μηνύματα είναι κρίσιμα για την οικοδόμηση μιας κοινής αντίληψης του περιβάλλοντος του οχήματος, επιτρέποντας την ενημερωμένη και ασφαλή αυτόνομη λήψη αποφάσεων. Επιπλέον, το σύστημα βασίζεται σε Αποκεντρωμένα Μηνύματα Περιβαλλοντικής Ειδοποίησης (Decentralized Environmental Notification Messages - DENM), τα οποία βασίζονται σε συμβάντα και χρησιμοποιούνται για τη διάδοση επειγόντων προειδοποιήσεων κινδύνου. Ωστόσο, τα τρέχοντα πρωτόκολλα επικοινωνίας, συμπεριλαμβανομένων τόσο του IEEE 802.11p όσο και του LTE-V2X, παρουσιάζουν περιορισμούς στην έγκαιρη μετάδοση αυτών των DENM λόγω ενσωματωμένων καθυστερήσεων στους μηχανισμούς πρόσβασης στα κανάλια. Αυτό εισάγει κινδύνους για την ασφάλεια, ιδίως σε ταχέως μεταβαλλόμενα περιβάλλοντα κυκλοφορίας.

Αναλύεται επίσης η στρατηγική της Ευρωπαϊκής Ένωσης για την ανάπτυξη υποδομών και υπηρεσιών CAM. Το όραμα της ΕΕ, που διατυπώνεται μέσω πρωτοβουλιών όπως το Connecting Europe Facility (CEF) και το Διευρωπαϊκό Δίκτυο Μεταφορών (TEN-T), στοχεύει στη διασφάλιση αδιάλειπτης κάλυψης 5G κατά μήκος των κύριων αστικών διαδρόμων και των οδών μεταφορών έως το 2025. Η ενεργοποίηση μιας τέτοιας κάλυψης είναι απαραίτητη για την υποστήριξη των υπηρεσιών CAM σε διαφορετικές χώρες. Μια σημαντική πρόκληση που εντοπίστηκε είναι η διασφάλιση της συνέχειας των υπηρεσιών καθώς τα οχήματα κινούνται μεταξύ διαφορετικών δικτύων κινητής τηλεφωνίας, ιδίως πέρα από διεθνή σύνορα. Λαμβάνονται επίσης υπόψη οι τεχνικές επιπτώσεις της αλλαγής παρόχου δικτύου (inter-PLMN Handover), όπου η ενσωματωμένη μονάδα επικοινωνίας του οχήματος πρέπει να αλλάξει από έναν εθνικό πάροχο κινητής τηλεφωνίας σε έναν άλλο. Η διακοπή συνδεσιμότητας, που προκαλείται λόγω των απαιτούμενων ρυθμίσεων και συγχρονισμού συχνότητας, μπορεί να θέσει σε κίνδυνο την αξιοπιστία και την ασφάλεια των εφαρμογών CAM.

Το κεφάλαιο 1 προχωρά με την υποβολή μιας σειράς ερευνητικών ερωτημάτων σε διάφορους θεματικούς άξονες. Επιδιώκει να εντοπίσει τα πιο κρίσιμα εμπόδια στην διασυνοριακή ανάπτυξη υπηρεσιών CAM και αξιολογεί πιθανές λύσεις, τόσο από την άποψη της βελτιστοποίησης δικτύου όσο και από την άποψη του εξοπλισμού οχημάτων. Η μελέτη διερευνά περαιτέρω τις βέλτιστες διαμορφώσεις για δίκτυα 5G - όπως η δομή πλαισίου, η επιλογή ζώνης συχνοτήτων εκπομπής και οι ρυθμίσεις time division duplexing (TDD) - προκειμένου να υποστηριχθεί η κινητικότητα σε σενάρια στον πραγματικό κόσμο. Εξετάζονται επίσης ζητήματα σε επίπεδο εφαρμογής, συμπεριλαμβανομένου του τρόπου σχεδιασμού εφαρμογών CAM που μπορούν να παραμείνουν ανθεκτικές στις διακοπές συνδεσιμότητας που προκαλούνται από τις αλλαγές παρόχου δικτύου και του τρόπου με τον οποίο η χρήση edge αντί για cloud computing επηρεάζει την καθυστέρηση και την απόκριση των εφαρμογών. Η Ενότητα 1 ολοκληρώνεται με την παρουσίαση της δομής της υπόλοιπης διδακτορικής διατριβής.

Κεφάλαιο 2

Το δεύτερο κεφάλαιο της διατριβής προσφέρει μια εκτενή ανάλυση της τρέχουσας βιβλιογραφίας σχετικά με τις προκλήσεις των τηλεπικοινωνιακών δικτύων και της αλλαγής παρόχου επικοινωνιών (Handover -HO) που εμπλέκονται στην υποστήριξη υπηρεσιών Συνδεδεμένης και Αυτοματοποιημένης Κινητικότητας (CAM) μέσω δικτύων 5G, με ιδιαίτερη sτη διασυνοριακή κινητικότητα και την αλλαγή εθνικού παρόχου (inter-PLMN HO). Αυτό το μέρος της διατριβής δημιουργεί μια τεχνική βάση για την κατανόηση των περιορισμών των τρεχόντων προτύπων, εντοπίζει κρίσιμα κενά στις υπάρχουσες προσεγγίσεις και εξετάζει τόσο τις ακαδημαϊκές όσο και τις βιομηχανικές καινοτομίες που μπορούν να επιτρέψουν εξαιρετικά αξιόπιστη, χαμηλής καθυστέρησης και αδιάκοπες επικοινωνίες για χρήστες με υψηλή κινητικότητα - ειδικά αυτόνομα οχήματα - που λειτουργούν πέρα από τα εθνικά σύνορα.

Η ανάλυση ξεκινά με την οριοθέτηση της θεμελιώδους πρόκλησης κινητικότητας στα κυψελοειδή δίκτυα. Παραδοσιακά, τα κινητά συστήματα βελτιστοποιούνταν για ενδο-δικτυακές αλλαγές σημείου πρόσβασης (intra-PLMN HO), αντιμετωπίζοντας τις αλλαγές σημείου πρόσβασης μεταξύ διαφορετικών δικτύων (inter-PLMN) ως σπάνιες εξαιρέσεις με ανεκτικότητα σε σύντομες διακοπές υπηρεσιών. Ωστόσο, με την εμφάνιση της αυτόνομης οδήγησης και άλλων υπηρεσιών CAM ευαίσθητων στην καθυστέρηση, αυτές οι υποθέσεις δεν είναι πλέον βάσιμες. Η διατριβή επισημαίνει ότι ενώ τα intra-PLMN HO εξακολουθούν να χρησιμοποιούν μηχανισμούς που κληρονομούνται από το LTE, η κινητικότητα μεταξύ PLMN (inter-PLMN) έχει ελάχιστα αναφερθεί στη βιβλιογραφία ή στα πρότυπα ανάπτυξης του 5G, παρά την κρίσιμη σημασία της για την απρόσκοπτη διασυνοριακή επικοινωνία οχημάτων.

Ακολουθεί μια εις βάθος ανάλυση των προτύπων επικοινωνίας που σχετίζονται με το CAM, ξεκινώντας με τις λειτουργίες sidelink communication του LTE-V2X και NR-V2X της 3GPP. Αυτά τα πρότυπα αξιολογούνται τόσο από άποψη αρχιτεκτονικού σχεδιασμού όσο και από άποψη της ικανότητάς τους να ανταποκρίνονται στις απαιτήσεις καθυστέρησης, αξιοπιστίας και κάλυψης των προηγμένων εφαρμογών CAM. Το LTE-V2X (Έκδοση 14) βασίζεται σε δύο λειτουργίες κατανομής πόρων πλευρικής ζεύξης (sidelink): Τη λειτουργία 3 (mode 3), όπου το δίκτυο (eNB) βοηθά στον προγραμματισμό της μετάδοσης, και τη λειτουργία 4 (mode 4), όπου τα οχήματα κατανέμουν πόρους δικτύου αυτόνομα - μια απαραίτητη εναλλακτική λύση όταν η κάλυψη δικτύου δεν είναι διαθέσιμη. Η αναφορά εμβαθύνει σε τεχνικές λεπτομέρειες που περιγράφουν format προγραμματισμού πόρων δικτύου όπως το Semi-Persistent Scheduling (SPS), το Sidelink Control Information (SCI) και ο τρόπος με τον οποίο τα οχήματα μεταδίδουν Μηνύματα Συνεργατικής Ενημέρωσης (CAM) χρησιμοποιώντας αυτές τις τεχνικές.

Προχωρώντας στο NR-V2X, που παρουσιάστηκε στις εκδόσεις 15 και 16 του 3GPP, η αναφορά εξηγεί πώς οι τεχνολογίες 5G βελτιώνουν τις δυνατότητες επικοινωνίας οχημάτων. Το NR-V2X ενσωματώνει προηγμένα σχήματα κωδικοποίησης καναλιών (κωδικούς LDPC και Polar), ευέλικτες δομές πλαισίων με κλιμακούμενες αποστάσεις sub-carriers και προγραμματισμό mini-slot που επιτρέπει τη μετάδοση περιοδικής και μη περιοδικής κίνησης με εξαιρετικά χαμηλή καθυστέρηση. Σε αντίθεση με το LTE-V2X, το NR-V2X επεκτείνει τις λειτουργίες επικοινωνίας πέρα από την μαζική εκπομπή (broadcast) ώστε να περιλαμβάνει unicast και groupcast, υποστηριζόμενες από μηχανισμούς αναμετάδοσης με δυνατότητα ανάδρασης. Αυτές οι τεχνικές βελτιώσεις στοχεύουν στην ικανοποίηση πιο αυστηρών δεικτών απόδοσης (Key Performance Indicators – KPI), όπως η καθυστέρηση υπο-χιλιοστού (ms) του δευτερολέπτου και η αξιοπιστία 99,999% - παραμέτρους απαραίτητες για κρίσιμα σενάρια αυτόνομης οδήγησης.

Παράλληλα με τις τεχνολογίες που βασίζονται στο 3GPP, η διατριβή παρουσιάζει μια διεξοδική ανάλυση του προτύπου IEEE 802.11p (DSRC) και της εξέλιξής του στο 802.11bd. Ενώ το 802.11p ήταν ένα πρώιμο πρότυπο για δίκτυα ad hoc οχημάτων, οι περιορισμοί του σε σενάρια υψηλής πυκνότητας και υψηλής ταχύτητας ώθησαν την ανάπτυξη του 802.11bd, το οποίο εισάγει καινοτομίες όπως εναλλακτικές αριθμολογίες OFDM, αναμεταδόσεις με επίγνωση της συμφόρησης, midambles για καλύτερη εκτίμηση καναλιού και διαμόρφωση διπλού φορέα. Αυτά τα χαρακτηριστικά στοχεύουν στον διπλασιασμό τόσο της εμβέλειας όσο και της απόδοσης, διατηρώντας παράλληλα την συμβατότητα με προηγούμενες τεχνολογίες.

Η διατριβή στη συνέχεια εστιάζει στις διαδικασίες αλλαγής σημείου πρόσβασης σε δίκτυα 5G, ξεκινώντας με σενάρια intra-PLMN. Η τυπική διαδικασία κατά την 3GPP περιλαμβάνει διάφορα στοιχεία που συμβάλλουν στο Handover Interruption Time (HIT), το οποίο είναι κατά μέσο όρο περίπου 49,5 ms. Αυτή η καθυστέρηση μπορεί να είναι αποδεκτή για μη κρίσιμες εφαρμογές, αλλά είναι ανεπαρκής για υπηρεσίες CAM που απαιτούν συνεχή συνδεσιμότητα. Εισάγονται προηγμένες λύσεις όπως η "Λειτουργία Συνέχειας Συνεδρίας και Υπηρεσίας (Sessions & Service Continuity -SSC) 3", οι οποίες εφαρμόζουν έναν μηχανισμό Make Before Break (MBB) κατά τον οποίο το όχημα πρώτα συνδέεται με το καινούριο δίκτυο πριν αποδεσμεύσει τη σύνδεσή του με το παλιό δίκτυο, για τη μείωση ή την εξάλειψη του HIT. Ωστόσο, αυτή η τεχνική απαιτεί εξαρτήματα χρήστη (User Equipment -UEs) με δυνατότητες διπλής συνδεσιμότητας και δεν έχει ακόμη αναπτυχθεί εμπορικά.

Η πολυπλοκότητα αυξάνεται σημαντικά όταν εξετάζονται τα inter-PLMN HO, δηλαδή οι αλλαγές σημείου πρόσβασης μεταξύ διαφορετικών παρόχων δικτύου, ειδικά πέρα από τα εθνικά σύνορα. Σε αντίθεση με τα σενάρια intra-PLMN, τα interPLMN HO δεν διαθέτουν κοινές “άγκυρες δικτύου”, βασίζονται σε ενδιάμεσους δίαυλους GRX/IPX και συχνά υποφέρουν από απρόβλεπτες καθυστερήσεις και πιθανές διακοπές. Η αναφορά εξετάζει εναλλακτικές προτάσεις, συμπεριλαμβανομένων των άμεσων διασυνδέσεων μεταξύ παρόχων δικτύων (παράκαμψη των δίαυλων GRX/IPX) και της τεχνικής του Local Break-Out (LBO), αλλά τονίζει την περιορισμένη επεκτασιμότητά τους και το υψηλό τους κόστος. Ακόμη και η λειτουργία SSC mode3 δεν μπορεί να υλοποιηθεί σε περιπτώσεις Inter-PLMN HO, λόγω της υπόθεσης ότι η αλλαγή σημείου πρόσβασης συμβαίνει μέσα στο ίδιο δίκτυο - μια υπόθεση που ακυρώνεται σε διασυνοριακά σενάρια.

Η διατριβή εξετάζει επίσης την τεχνική βιβλιογραφία σχετικά με τα σχήματα περιαγωγής στις εκδόσεις 15 και 16 της 3GPP. Τα δίκτυα 5G Non-Stand Alone (NSA), τα οποία εξαρτώνται από την υπάρχουσα υποδομή LTE, αντιπαραβάλλονται με τα μεταγενέστερα δίκτυα 5G Stand Alone (5G SA) τα οποία λειτουργούν αυτόνομα (χωρίς εξάρτηση στο LTE), τα οποία προσφέρουν καλύτερη υποστήριξη για εφαρμογές χαμηλής καθυστέρησης. Ωστόσο, αναγνωρίζεται ότι η πλήρης ανάπτυξη δικτύων 5G-SA βρίσκεται ακόμη σε εξέλιξη και οι αρχιτεκτονικές NSA εισάγουν αρκετές ανεπάρκειες που παρεμποδίζουν τις υπηρεσίες CAM.

Εξετάζονται αρκετές πρόσφατες ερευνητικές συνεισφορές, καθεμία από τις οποίες προτείνει βελτιώσεις για τη μείωση της καθυστέρησης και τη βελτίωση της συνέχειας της υπηρεσίας. Αυτές περιλαμβάνουν τα λεγόμενα soft handovers που βασίζονται σε διπλή συνδεσιμότητα, στρατηγικές παράδοσης υπό όρους όπου η αλλαγή παρόχου εξαρτάται από τον εξοπλισμό του χρήστη (συσκευή) και όχι από το δίκτυο, σχήματα αναμετάδοσης που βασίζονται σε επικοινωνία Device to Device (D2D) και λύσεις δικτύωσης που ορίζονται από λογισμικό (Software Defined Networking - SDN) για προγνωστικές και βασισμένες στο περιβάλλον αποφάσεις παράδοσης. Κάθε προτεινόμενη μέθοδος αξιολογείται ως προς τη σκοπιμότητα, την πολυπλοκότητα και την ευθυγράμμιση με τις απαιτήσεις που αφορούν συγκεκριμένα τις εφαρμογές CAM. Αξίζει να σημειωθεί ότι, ενώ ορισμένες λύσεις προσφέρουν θεωρητικές μειώσεις καθυστέρησης έως και μονοψήφια χιλιοστά του δευτερολέπτου, οι περισσότερες βασίζονται σε ιδανικές υποθέσεις ή εστιάζουν στην κινητικότητα εντός του ίδιου παρόχου, καθιστώντας τες μη πρακτικές για διασυνοριακές εφαρμογές στον πραγματικό κόσμο.

Η διατριβή εντοπίζει υποσχόμενες ερευνητικές κατευθύνσεις και τεχνικές όπως η δυναμική ομαδοποίηση με Συντονισμένη Πολλαπλή Μετάδοση (Coordinated Multipoint - CoMP) για περιβάλλοντα μέτριας κινητικότητας και οι κατανεμημένες αναπτύξεις MEC (Mobile Edge Computing) για τη μείωση της καθυστέρησης που σχετίζεται με τη μετεγκατάσταση υπηρεσιών κατά τη διάρκεια των handovers. Ωστόσο, επικρίνει τις υπεραπλουστεύσεις που συχνά γίνονται στην αξιολόγηση τέτοιων λύσεων, συμπεριλαμβανομένων των μη ρεαλιστικών υποθέσεων καθυστέρησης, της υποεκτίμησης των επιβαρύνσεων σηματοδότησης δικτύου (signalling overhead) και της έλλειψης επεκτασιμότητας σε διασυνοριακά περιβάλλοντα.

Καταλήγοντας, αυτό το κεφάλαιο της διατριβής παρουσιάζει μια λεπτομερή, τεχνικά αυστηρή αξιολόγηση της τρέχουσας κατάστασης της διαχείρισης της κινητικότητας 5G στο πλαίσιο του CAM. Υπογραμμίζει ότι ενώ έχει σημειωθεί σημαντική πρόοδος στην κινητικότητα σε συνθήκες intra-PLMN και στα πρωτόκολλα επικοινωνίας V2X, η κινητικότητα σε συνθήκες inter-PLMN παραμένει ένα σημαντικό πρόβλημα. Η αναφορά καταλήγει πως απαιτείται μια ολιστική προσέγγιση που υπερβαίνει τη βελτιστοποίηση των μεμονωμένων βημάτων handover, υποστηρίζοντας αντ' αυτού συντονισμένες εξελίξεις στην αρχιτεκτονική δικτύου, τα πρωτόκολλα ραδιοεπικοινωνίας, την ενορχήστρωση MEC και τον σχεδιασμό των εφαρμογών CAM. Αυτή η ανάλυση όχι μόνο παρέχει την τεχνική βάση για το υπόλοιπο της διατριβής, αλλά θέτει επίσης το σκηνικό για τις πρακτικές δοκιμές και τις πειραματικές αξιολογήσεις που θα διεξαχθούν σε επόμενα κεφάλαια.

Κεφάλαιο 3

Το τρίτο κεφάλαιο της διατριβής παρέχει μια λεπτομερή ανάλυση των πολύπλευρων προκλήσεων και των πιθανών λύσεων που εμπλέκονται στην υποστήριξη CAM εφαρμογών μέσω 5G σε διασυνοριακά σενάρια. Βασίζεται στη θεωρητική βάση που δημιουργήθηκε στα προηγούμενα κεφάλαια, μεταβαίνοντας από μια γενική επισκόπηση των τεχνολογιών κινητικότητας και V2X τελευταίας τεχνολογίας σε μια εστιασμένη εξέταση των λειτουργικών, επιχειρησιακών και κανονιστικών προκλήσεων όπως αυτές αναδύονται σε πραγματικά διακρατικά πλαίσια. Το κεφάλαιο όχι μόνο χαρτογραφεί συστηματικά αυτές τις προκλήσεις, αλλά προτείνει και αξιολογεί επίσης στοχευμένες τεχνολογικές και στρατηγικές λύσεις, βασιζόμενο σε μεγάλο βαθμό στη συμβολή των ενδιαφερόμενων μερών, στις γνώσεις από ερευνητικά έργα της ΕΕ και στις εμπειρίες ανάπτυξης σε ευρωπαϊκούς διασυνοριακούς διαδρόμους.

Το κεφάλαιο ξεκινά με τον καθορισμό των λειτουργικών και μη λειτουργικών απαιτήσεων που απαιτούνται για την υποστήριξη των CAM εφαρμογών μέσω δικτύων 5G σε διασυνοριακές συνθήκες. Με βάση μια έρευνα βασικών ευρωπαϊκών φορέων εκμετάλλευσης δικτύων κινητής τηλεφωνίας, προμηθευτών εξοπλισμού και άλλων εμπειρογνωμόνων του τομέα (ιδίως από το έργο 5G-MOBIX), οι απαιτήσεις ιεραρχούνται χρησιμοποιώντας τη μέθοδο MoSCoW. Οι κρίσιμες λειτουργικές απαιτήσεις περιλαμβάνουν την υποστήριξη για βελτιωμένο Mobile Broadband (eMBB) και virtualization, οι οποίες θεωρούνται απαραίτητες και συνδέονται στενά με τη διαθεσιμότητα αυτόνομων δικτύου 5G (SA). Οι μη λειτουργικές προτεραιότητες, όπως η επεκτασιμότητα, η δυνατότητα αναβάθμισης, η αξιοπιστία και η ασφάλεια, προσδιορίζονται επίσης ως θεμελιώδεις παράγοντες για την παροχή ολοκληρωμένων υπηρεσιών CAM.

Στη συνέχεια, το έγγραφο κατηγοριοποιεί τις προκλήσεις της διασυνοριακής ανάπτυξης CAM σε τέσσερις κύριες διαστάσεις: **τηλεπικοινωνίες, εφαρμογές CAM, ασφάλεια / ιδιωτικότητα και κανονιστικές ρυθμίσεις**. Κάθε διάσταση διερευνάται σε βάθος, υποστηρίζεται από συγκεκριμένα παραδείγματα και τεχνική ανάλυση.

Στον τομέα των **τηλεπικοινωνιών**, οι διαδικασίες περιαγωγής και Handover αναλύονται περαιτέρω μιας και αποτελούν τις κύριες πηγές καθυστέρησης και διακοπής υπηρεσίας. Η μελέτη διακρίνει μεταξύ διαφορετικών σεναρίων περιαγωγής: μεταξύ πυρήνων NSA (μη αυτόνομων), μεταξύ πυρήνων SA και υβριδικών δικτύων NSA-SA. Τα σχήματα περιαγωγής με δρομολόγηση μέσω του αρχικού δικτύου (Home Routing - HR) εισάγουν σημαντική καθυστέρηση, καθιστώντας τα ακατάλληλα για εξαιρετικά αξιόπιστες εφαρμογές επικοινωνίας χαμηλής καθυστέρησης (URLLC) όπως το CAM. Οι λύσεις που εξερευνώνται περιλαμβάνουν προληπτική κατανομή πόρων URLLC στο δευτερεύον δίκτυο (Visiting PLMN), άμεση διασύνδεση μεταξύ παρόχων για την παράκαμψη διαδρομών GRX/IPX υψηλής καθυστέρησης και μηχανισμούς διαχείρισης υπηρεσιών μηδενικής επαφής (Zero touch Service Management - ZSM) με επίγνωση εφαρμογών.

Για το handover, αναλύονται τρία κύρια σενάρια: επικαλυπτόμενη κάλυψη (overlapping coverage), κενά κάλυψης και υβριδικό HO μεταξύ δικτύων 4G και 5G. Η επικαλυπτόμενη κάλυψη μπορεί να οδηγήσει σε παρεμβολές και φαινόμενα πινγκ-πονγκ μεταξύ των δικτύων παρόχων, τα κενά κάλυψης προκαλούν απώλεια σύνδεσης ενώ το υβριδικό HO εισάγει ασυνέπειες στην απόδοση, ιδίως στην καθυστέρηση. Οι λύσεις κυμαίνονται από βελτιστοποίηση παραμέτρων HO που καθοδηγείται από Τεχνητή Νοημοσύνη (AI) και πλεονασμό πολλαπλών SIM έως εφεδρική δορυφορική υποστήριξη για κάλυψη κενών και απρόσκοπτες μεταβάσεις που βασίζονται σε ενορχήστρωση μεταξύ των διαφορετικών RAT (Radio Access Technologies). Η πολυπλοκότητα του συντονισμού της συμπεριφοράς των HO μεταξύ γειτονικών παρόχων δικτύου αναδεικνύεται ως ένα σημαντικό άλυτο ζήτημα.

Η διάσταση των **εφαρμογών CAM** επικεντρώνεται στη συνέχεια των υπηρεσιών, τη διαλειτουργικότητα δεδομένων και πρωτοκόλλων, καθώς και σε μοναδικές προκλήσεις που σχετίζονται με τα σύνορα, όπως ο συγχρονισμός ρολογιού και η γεωγραφική ανακάλυψη (geo-driven discovery). Οι εφαρμογές CAM είναι ιδιαίτερα ευαίσθητες σε διακοπές που προκαλούνται από τα HO, ειδικά σε σενάρια όπως ο τηλεχειρισμός οχημάτων. Οι προτεινόμενες λύσεις περιλαμβάνουν προληπτική ανταλλαγή πληροφοριών σχετικά με τις ζώνες HO ή πλήρως αυτόνομη εφεδρική χρήση κατά τη διάρκεια διακοπών. Οι προκλήσεις δια-λειτουργικότητας προσεγγίζονται μέσω της τυποποίησης των μορφών δεδομένων και των Application Programming Interfaces (API), της δημιουργίας ενός "πρωτεύοντος" κέντρου δεδομένων Intelligent Transportation System (ITS) ανά περιοχή ή του συγχρονισμού σε πραγματικό χρόνο και της οικοδόμησης συναίνεσης μεταξύ γειτονικών συστημάτων διαχείρισης κυκλοφορίας.

Η διάσταση της **ασφάλειας και της ιδιωτικότητας**, αφορά τους αντικρουόμενους κανονισμούς προστασίας δεδομένων μεταξύ χωρών της ΕΕ και χωρών εκτός ΕΕ, τα νομικά πλαίσια για τη νόμιμη επεξεργασία δεδομένων και την εγκαθίδρυση εμπιστοσύνης στην επικοινωνία μεταξύ δικτύων. Ενώ το GDPR της ΕΕ προσφέρει μια εναρμονισμένη βάση, η πρακτική εφαρμογή πέρα από τα σύνορα αντιμετωπίζει σημαντικά εμπόδια. Η διατριβή προτείνει πρωτόκολλα διαπραγμάτευσης που υποστηρίζονται από την Τεχνητή Νοημοσύνη για την επίτευξη αποδεκτών διαμορφώσεων απορρήτου μεταξύ των παρόχων δικτύου και προωθεί τυποποιημένα τεχνικά μέτρα όπως η κρυπτογράφηση TLS, η ψευδο-ανονυμοποίηση και οι στρατηγικές απορρήτου βάσει σχεδιασμού. Δίνεται επίσης έμφαση στις διαδικασίες παραβίασης δεδομένων, στις κοινές χαρτογραφήσεις για την επεξεργασία και στις απαιτήσεις εκπαίδευσης του προσωπικού.

Το **κανονιστικό** (regulatory) τμήμα αποκαλύπτει ίσως τα πιο δυσεπίλυτα προβλήματα, που κυμαίνονται από ασυνεπείς νόμους κυκλοφορίας και διαδικασίες έγκρισης αυτόνομων οχημάτων έως πρωτόκολλα αλληλεπίδρασης επιβολής του νόμου. Η απουσία ενιαίων κανονισμών κινδυνεύει να υπονομεύσει τη λειτουργικότητα των αυτόνομων οχημάτων, ιδίως όταν οι νομικές διαδικασίες και οι διαμορφώσεις λογισμικού των εφαρμογών, διαφέρουν από χώρα σε χώρα. Οι προτεινόμενες λύσεις περιλαμβάνουν τη χρήση γεωφράξεων (geo-fencing) για την επιβολή νόμιμων ζωνών λειτουργίας, τη δυναμική αναδιαμόρφωση της συμπεριφοράς των αυτόνομων οχημάτων με βάση ενσωματωμένους χάρτες HD και τυποποιημένα πρωτόκολλα μηνυμάτων έκτακτης ανάγκης για αλληλεπιδράσεις με την αστυνομία και τις υπηρεσίες δημόσιας ασφάλειας.

Βασιζόμενη σε αυτήν την ολοκληρωμένη χαρτογράφηση των προκλήσεων, η διατριβή εισάγει τεχνολογικούς παράγοντες για την επίλυσή τους. Κεντρικό στοιχείο αυτών των παραγόντων είναι η λειτουργία Συνέχειας Συνεδρίας και Υπηρεσίας (SSC) που ορίζεται από τη 3GPP. Η Λειτουργία SSC 1 διασφαλίζει τη συνέχεια IP μέσω του Home Routing αλλά υποφέρει από αυξημένη καθυστέρηση. Η Λειτουργία 2 βελτιστοποιεί την καθυστέρηση μέσω τοπικής διακλάδωσης, αλλά διακόπτει την υπηρεσία λόγω αλλαγών IP. Η Λειτουργία 3 (Make-Before-Break) παρέχει τόσο χαμηλή καθυστέρηση όσο και συνέχεια υπηρεσίας, αλλά απαιτεί δίκτυα 5G SA και εξελιγμένες δυνατότητες εξοπλισμού χρήστη (UE). Ομοίως, οι τρόποι δρομολόγησης - Home Routing (HR) έναντι Local Break-Out (LBO) - αναλύονται όσον αφορά τους συμβιβασμούς τους μεταξύ καθυστέρησης, διατήρησης συνεδρίας και επεκτασιμότητας, ιδιαίτερα σε πολλαπλές εθνικές δικαιοδοσίες.

Ένα άλλο σημαντικό σημείο εστίασης είναι το Mobile Edge Computing (MEC), το οποίο παίζει ζωτικό ρόλο στη φιλοξενία υπηρεσιών CAM με ελάχιστη καθυστέρηση. Συζητούνται διάφορα μοντέλα ανάπτυξης, όπως το "Bump in the Wire", το κατανεμημένο EPC και το SGW-LBO, το καθένα με πλεονεκτήματα και περιορισμούς όσον αφορά τη συνέχεια της υπηρεσίας, την επεκτασιμότητα και την πολυπλοκότητα υλοποίησης. Οι μεταδόσεις MEC-σε-MEC μεταξύ διαφορετικών παρόχων παραμένουν ένα αδύναμο σημείο, με τις περισσότερες λύσεις να βασίζονται στη διαχείριση συνεδριών σε επίπεδο εφαρμογής ή στην άμεση διασύνδεση δικτύου, οι οποίες δεν είναι καθολικά κλιμακούμενες ή εφικτές.

Για να συνοψιστεί η συζήτηση, το κεφάλαιο παρουσιάζει έναν συνθετικό πίνακα που κατηγοριοποιεί τις βασικές διασυνοριακές προκλήσεις ανά τομέα παράλληλα με τις πιο πολλά υποσχόμενες τεχνικές και διαδικαστικές λύσεις. Η ενότητα ολοκληρώνεται με μια προβολή των αναμενόμενων οφελών από την ευρεία ανάπτυξη 5G SA, δίνοντας έμφαση στον κρίσιμο ρόλο διεπαφών όπως οι N32 και N9, που ορίζονται από το 3GPP, στην υποστήριξη ασφαλούς και αποτελεσματικής επικοινωνίας μεταξύ PLMN. Το έγγραφο υπογραμμίζει την αναγκαιότητα ανάπτυξης ενδιάμεσων λύσεων συμβατών με 5G NSA ή μικτές αναπτύξεις, καθώς η πλήρης διείσδυση SA σε όλη την Ευρώπη παραμένει μακροπρόθεσμος στόχος.

Συνολικά, αυτή η ενότητα όχι μόνο προσδιορίζει το ολοκληρωμένο σύνολο προκλήσεων που αντιμετωπίζει η εφαρμογή υπηρεσιών CAM, αλλά αξιολογεί επίσης τη σκοπιμότητα και την ωριμότητα των τεχνολογικών, αρχιτεκτονικών και κανονιστικών λύσεων. Λειτουργεί τόσο ως οδικός χάρτης όσο και ως κρίσιμο διαγνωστικό εργαλείο για τους ενδιαφερόμενους φορείς που σχεδιάζουν την ανάπτυξη αυτοματοποιημένων υπηρεσιών κινητικότητας με δυνατότητα 5G σε πραγματικές συνθήκες πέρα από τα εθνικά σύνορα.

Με βάση την ανάλυση που παρουσιάζεται σε αυτή την ενότητα, προκρίνονται και τα σενάρια και οι λύσεις που θα αξιολογηθούν στο πειραματικό κομμάτι της διατριβής. Αυτά είναι:

- Βελτιστοποίηση ρυθμίσεων δικτύων 5G-NSA για διασυνοριακά handover
- Ακριβείς μετρήσεις απόδοσης, καθυστέρησης και διακοπής υπηρεσίας σε διασυνοριακές συνθήκες
- Διασύνδεση μεταξύ παρόχων: GRX/IPX vs Άμεσης διασύνδεσης με οπτική ίνα (Direct interconnection)
- Αρχιτεκτονική δρομολόγησης δεδομένων μεταξύ παρόχων: Home Routing vs Local Break-Out
- Χρήση περιβαλλόντων cloud & τοποθέτηση τους: Cloud vs Edge Computing
- Δημιουργία και χρήση συγκεκριμένων αλγορίθμων βελτιστοποίηση του inter-PLMN Handover (επίπεδο εφαρμογής)

Κεφάλαιο 4

Κατόπιν του εντοπισμού των πιο κρίσιμων προκλήσεων και των πιο ελπιδοφόρων λύσεων για την υποστήριξη της διασυνοριακής λειτουργικότητας CAM, η διατριβή προχωρά στην περιγραφή της πειραματικής εγκατάστασης που χρησιμοποιήθηκε για την εκτέλεση δοκιμών CAM σε πραγματικές συνθήκες, προκειμένου να μετρηθεί η πραγματική εμπειρία των χρηστών CAM σε διασυνοριακές συνθήκες και να αξιολογηθούν και να επικυρωθούν οι επιλεγμένες λύσεις. Η Ενότητα 4 παρουσιάζει τον σχεδιασμό, την αρχιτεκτονική, την ανάπτυξη και την εμπειρική επικύρωση εφαρμογών CAM που βασίζονται σε 5G στον πραγματικό διασυνοριακό διάδρομο των συνόρων Κήπων-Υψάλων μεταξύ Ελλάδας και Τουρκίας, στην περιοχή του Έβρου. Ως μία από τις πρώτες προσπάθειες παγκοσμίως που αφορούν την ανάπτυξη και αξιολόγηση εφαρμογών CAM μέσω δικτύων 5G σε διασυνοριακό πλαίσιο, η εργασία παρέχει μια ολοκληρωμένη τεχνολογική, αρχιτεκτονική και εμπειρική αξιολόγηση των υπηρεσιών CAM σε πραγματικές συνθήκες.

Στο επίκεντρο της μελέτης βρίσκεται η ανάπτυξη ενός Διασυνοριακού Διαδρόμου (CBC) 5G, που ενσωματώνει υποδομές από την COSMOTE και την Turkcell, χρησιμοποιώντας ένα οδικό τμήμα 10 χλμ. εξοπλισμένο με τέσσερις σταθμούς βάσης 5G (gNodeBs) από την Ericsson. Αυτή η υποδομή παρείχε ετερογενή κάλυψη λόγω τοπογραφικών και περιβαλλοντικών προκλήσεων, ιδίως ενός μεγάλου μεταλλικού φράχτη κατά μήκος του Ελληνικού συνοριακού σταθμού και της μεταβλητής κυκλοφορίας βαρέων οχημάτων που δημιουργούσαν προβλήματα στην μετάδοση του σήματος (ανακλάσεις, μπλοκάρισμα, κλπ.). Η βελτιστοποίηση των παραμέτρων του Δικτύου 5G, συμπεριλαμβανομένων των ρυθμίσεων HO μεταξύ διαφορετικών δικτύων, ήταν απαραίτητη για την επίτευξη της επιθυμητής ποιότητας υπηρεσιών, ιδίως για την αποφυγή του φαινομένου πινγκ-πονγκ (συχνή εναλλαγή δικτύου πρόσβασης) και των διακοπών σύνδεσης.

Η αρχιτεκτονική που χρησιμοποιήθηκε για τις δοκιμές περιελάμβανε εικονικές αναπτύξεις Evolved Packet Core (vEPC) σε περιβάλλοντα edge cloud, τοποθετημένα στην Αλεξανδρούπολη (GR) και στο Κάρταλ (TR), με δίκτυα κινητής τηλεφωνίας διασυνδεδεμένα μέσω δημόσιων γραμμών διαδικτύου (GRX/IPX) και με άμεση σύνδεση οπτικών ινών. Τα θετικά και τα αρνητικά σημεία αυτών των διαμορφώσεων δικτύου αξιολογήθηκαν αυστηρά ως προς την καθυστέρηση και απόδοση τους. Η διαμόρφωση NSA (3GPP Έκδοση 15, Επιλογή 3x) και η ρύθμιση Home Routing (HR) εξασφάλισαν συνεπή διαχείριση της συνδεσιμότητας μέσω του αρχικού δικτύου (Home PLMN), αν και με αυξημένη καθυστέρηση κατά την περιαγωγή.

Μια βασική καινοτομία που παρουσιάζεται σε αυτή την εργασία είναι ο σχεδιασμός και η εφαρμογή ενός αλγορίθμου βελτιστοποίησης του Handover σε επίπεδο εφαρμογής, για να διασφαλιστεί η απρόσκοπτη απόδοση και συνδεσιμότητα της εφαρμογής κατά τη διάρκεια των μεταβάσεων μεταξύ PLMN σε λειτουργία LBO. Αυτός ο αλγόριθμος προβλέπει τις αλλαγές δικτύου χρησιμοποιώντας GPS και προσαρμοσμένη λογική, ειδοποιεί όλα τα σχετικά στοιχεία του συστήματος, αποθηκεύει δεδομένα αισθητήρων σε buffer κατά τη διάρκεια κενών συνδεσιμότητας και διατηρεί βασικές λειτουργίες ασφαλείας (όπως αυτόνομο φρενάρισμα με βάση το ενσωματωμένο LiDAR) μέχρι την επανασύνδεση του αυτόνομου οχήματος με το δίκτυο (σε περίπτωση απώλειας σύνδεσης). Η δημιουργία και αξιολόγηση αυτού του αλγορίθμου σε πραγματικές συνθήκες είναι και μία από τις βασικές συνεισφορές της διδακτορικής διατριβής.

Το hardware που χρησιμοποιήθηκε περιελάβανε ειδικά κατασκευασμένες ενσωματωμένες μονάδες (OBU) ενσωματωμένες με μόντεμ 5G Quectel, LiDAR, αναγνώστες NFC, μονάδες GNSS και διάφορους αισθητήρες περιβάλλοντος και εγγύτητας. Αυτές οι OBU αποτέλεσαν τη ραχοκοκαλιά των δυνατοτήτων αυτόνομων οχημάτων της δοκιμής, εγκατεστημένες σε ένα φορτηγό Ford επιπέδου αυτόνομης οδήγησης 4. Επιπρόσθετα, υπήρχαν μονάδες Roadside units (RSU) με αναγνώριση εικόνας, έλεγχο μπάρας συνόρων και ενσωμάτωση φωτεινού σηματοδότη, όλα συντονισμένα μέσω της πλατφόρμας της WINGS.

Οι εφαρμογές CAM που δοκιμάστηκαν παρουσίασαν προηγμένη λειτουργικότητα, όπως η αυτόνομη διέλευση οχήματος από το συνοριακό σταθμό χωρίς επαφή, η ετοιμότητα προγνωστικού ελέγχου και η προστασία ευάλωτων χρηστών του οδικού δικτύου (VRU). Τα δεδομένα από οχήματα και υποδομές υποβλήθηκαν σε επεξεργασία σε πραγματικό χρόνο μέσω πλατφορμών edge που φιλοξενούνται τόσο στην Ελλάδα όσο και στην Τουρκία, επιτρέποντας τη δυναμική αξιολόγηση κινδύνου και τη λήψη αποφάσεων σε πραγματικό χρόνο. Η σύντηξη αισθητήρων από κινητές και σταθερές πηγές (φορτηγά, κάμερες δρόμου, φορητές συσκευές) επέτρεψε αυξημένη επίγνωση της κατάστασης και ενισχυμένη ασφάλεια, με το σύστημα να είναι ικανό για προληπτικές αποφάσεις, όπως η ειδοποίηση των αξιωματικών ή η ενεργοποίηση επιθεωρήσεων με βάση τον κίνδυνο που προκύπτει από την τεχνητή νοημοσύνη.

Δοκιμάστηκαν αρκετές παράμετροι απόδοσης που αφορούν συγκεκριμένα το 5G. Εξετάστηκε η επίδραση διαφορετικών διαμορφώσεων Time Division Duplexing (TDD) (π.χ., 4+2+4 έναντι 4+1+3+2), οι μετρήσεις απόδοσης UL/DL, η επίδραση της συσσωμάτωσης φορέων (Carrier Aggregation - CA) και ο ρόλος των ζωνών προστασίας φάσματος στον μετριασμό των παρεμβολών. Τα ευρήματα επιβεβαίωσαν ότι η απόδοση του UL επηρεάζεται σε μεγάλο βαθμό από την διαμόρφωση του TDD frame, την απόσταση από τους σταθμούς βάσης και την ενεργοποίηση του CA, ενώ η απόδοση του DL έδειξε σχετική σταθερότητα σε διαφορετικές ρυθμίσεις TDD. Μια ζώνη προστασίας φάσματος 50 MHz μεταξύ των δύο φορέων εκμετάλλευσης ελαχιστοποίησε με επιτυχία τις παρεμβολές.

Αυτή η εργασία αναφέρεται επίσης και ευθυγραμμίζεται με τις συστάσεις ευρωπαϊκών και παγκόσμιων φορέων τυποποίησης, όπως η ECC και η GSMA, ιδιαίτερα σχετικά με τον συγχρονισμό, τις ζώνες προστασίας φάσματος και τις στρατηγικές συνύπαρξης για μη συγχρονισμένες λειτουργίες TDD. Αξίζει να σημειωθεί ότι τα ευρήματα ενισχύουν τη σύσταση της GSMA ότι οι μεγάλες ζώνες ασφαλείας φάσματος (guard bands) και η βελτιστοποίηση δικτύου είναι πιο αποτελεσματικά από τον συγχρονισμό όταν αντιμετωπίζονται περιορισμοί διασυνοριακής ανάπτυξης.

Με βάση την παραπάνω μελέτη και ανάλυση, επιλέχτηκαν οι βέλτιστες ρυθμίσεις παραμέτρων δικτύου, αυτόνομου οχήματος και εφαρμογής CAM, για το πειραματικό στάδιο και σχεδιάστηκαν τα βήματα και τα σενάρια της πειραματικής μελέτης σε πραγματικές συνθήκες που ακολούθησε και παρουσιάζεται στο επόμενο κεφάλαιο.

Κεφάλαιο 5

Αυτό το κεφάλαιο της διατριβής προσφέρει μια πλούσια και μεθοδική αξιολόγηση των υπηρεσιών Συνδεδεμένης και Αυτοματοποιημένης Κινητικότητας (CAM) με δυνατότητα 5G σε πραγματικές διασυνοριακές συνθήκες. Η βάση της ανάλυσης που παρουσιάζεται είναι το εκτεταμένο σύνολο δοκιμών που διεξήχθησαν κατά μήκος των ελληνοτουρκικών συνόρων (GR-TR) στο πλαίσιο του έργου 5G-MOBIX. Αυτό το σύνολο πειραματικών διεργασιών σχεδιάστηκαν για να αξιολογήσουν κριτικά την απόδοση διαφόρων διαμορφώσεων δικτύου και στρατηγικών διαχείρισης κινητικότητας, εστιάζοντας ιδιαίτερα στην ικανότητά τους να υποστηρίζουν απρόσκοπτα εφαρμογές CAM υπό τις προκλήσεις που θέτουν οι διασυνοριακές μεταδόσεις μεταξύ διαφορετικών δικτύων / παρόχων (όπως παρουσιάστηκαν σε προηγούμενες ενότητες).

Η αξιολόγηση βασίστηκε σε ένα προσεκτικά δομημένο πειραματικό πλαίσιο, το οποίο παρουσιάζεται λεπτομερώς. Πραγματικά οχήματα, συμπεριλαμβανομένου ενός αυτόνομου φορτηγού Επιπέδου 4, εξοπλισμένα με Ενσωματωμένες Μονάδες (OBU) και αισθητήρες Lidar, που αλληλεπιδρούσαν με διακομιστές εφαρμογών τοποθετημένους σε περιβάλλοντα cloud και edge. Αυτά τα οχήματα πραγματοποίησαν πολυάριθμες δοκιμαστικές διαδρομές και στις δύο κατευθύνσεις πέρα από τα σύνορα, ενώ πειραματικά δεδομένα συλλέχθηκαν τόσο από τις συσκευές χρηστών (οχήματα) όσο και από την υποδομή δικτύου 5G. Οι δοκιμές κάλυπταν πολλαπλές διασυνοριακές μεταδόσεις, καταγράφοντας δεδομένα από την μετάδοση δεδομένων στο uplink έως την καθυστέρηση σε επίπεδο εφαρμογής και τη συνέχεια της υπηρεσίας, προσφέροντας έτσι μια πλήρη ανάλυση.

Οι δοκιμές διερεύνησαν πέντε ξεχωριστά πειραματικά σενάρια που συνδυάζουν διαφορετικές ρυθμίσεις συνδεσιμότητας μεταξύ δικτύων (PLMN), αλγορίθμους δρομολόγησης δεδομένων (Home Routing vs LBO) και τοποθετήσεις διακομιστών (cloud ή edge). Για κάθε διαμόρφωση, η απόδοση αξιολογήθηκε με βάση τρεις κρίσιμους δείκτες απόδοσης (KPI): Uplink Throughput, καθυστέρηση από άκρο σε άκρο (E2E) και χρόνο διακοπής Υπηρεσίας λόγω κινητικότητας (interruption time). Σε όλα τα σενάρια, το uplink throughput πληρούσε σταθερά τις απαιτήσεις των εφαρμογών CAM, κυρίως λόγω των μικρών μεγεθών ωφέλιμου φορτίου (payload) που σχετίζονται με τα Μηνύματα Συνεργατικής Ευαισθητοποίησης (CAM) και τα Αποκεντρωμένα Μηνύματα Ειδοποίησης Περιβάλλοντος (DENM). Ωστόσο, σημειώθηκε ότι η τοποθέτηση εξωτερικής κεραίας στα οχήματα βελτίωσε σημαντικά τη ποιότητα σήματος, αποκαλύπτοντας μια σημαντική παράμετρο σχεδιασμού για τους κατασκευαστές πρωτότυπου εξοπλισμού (OEM) των οχημάτων.

Η καθυστέρηση E2E, που αντιπροσωπεύει τον χρόνο μετ' επιστροφής για τα μηνύματα εφαρμογής μεταξύ του OBU και του διακομιστή, παρουσίασε πολύ μεγαλύτερη διακύμανση και αποδείχθηκε ιδιαίτερα ευαίσθητη στην επιλεγμένη διαμόρφωση δικτύου. Κατά τη χρήση διακομιστών cloud με δημόσια διασύνδεση στο διαδίκτυο και δρομολόγηση Home Routing, οι τιμές καθυστέρησης ήταν πολύ υψηλές, με μέσο όρο περίπου 212 χιλιοστά του δευτερολέπτου, πολύ πάνω από το όριο των 100 χιλιοστών του δευτερολέπτου που θεωρείται το όριο για τις εφαρμογές CAM. Η αντικατάσταση της δημόσιας διασύνδεσης με άμεση διασύνδεση μεταξύ των δύο δικτύων απέδωσε αισθητή βελτίωση, μειώνοντας την καθυστέρηση σε περίπου 118 χιλιοστά του δευτερολέπτου. Περαιτέρω μείωση επιτεύχθηκε μέσω της χρήσης διακομιστών edge. Σε αυτήν την περίπτωση, οι τιμές καθυστέρησης ήταν κατά μέσο όρο περίπου 82 χιλιοστά του δευτερολέπτου και μειώθηκαν ακόμη και σε 12 χιλιοστά του δευτερολέπτου σε ευνοϊκές συνθήκες, υπερβαίνοντας έτσι τους στόχους απόδοσης που έχουν οριστεί για τις περιπτώσεις χρήσης CAM.

Ωστόσο, αυτές οι βελτιώσεις στην καθυστέρηση ήρθαν με αντίτιμο όσον αφορά τη συνέχεια της υπηρεσίας. Ο χρόνος διακοπής υπηρεσίας λόγω κινητικότητας - που ορίζεται ως ο χρόνος μεταξύ της λήψης του τελευταίου μηνύματος εφαρμογής πριν από ένα HO και της λήψης του πρώτου μηνύματος μετά το HO - ήταν σταθερά πάνω από τα επιθυμητά όρια. Σε όλα τα σενάρια δρομολόγησης me Home Routing, οι μέσοι χρόνοι διακοπής κυμαίνονταν από 710 έως 870 χιλιοστά του δευτερολέπτου. Αυτές οι τιμές είναι προβληματικές για υπηρεσίες CAM κρίσιμες για την ασφάλεια, όπως το αυτόνομο σταμάτημα ενός οχήματος όταν ανιχνεύει τη παρουσία ευάλωτων χρηστών του δρόμου (π.χ. πεζών). Ακόμα και με την χρήση διακομιστών edge και την άμεση διασύνδεση μεταξύ δικτύων, η μείωση της διακοπής της υπηρεσίας ήταν οριακή, υποδεικνύοντας ότι ο χρόνος διακοπής συνδέεται σε μεγάλο βαθμό με τους εγγενείς περιορισμούς της αρχιτεκτονικής 5G Non-Standalone (NSA) και τον τρόπο με τον οποίο διαχειρίζεται τις μεταβάσεις μεταξύ των συνεδριών PLMN.

Ένα ιδιαίτερα αξιοσημείωτο εύρημα προέκυψε από την αξιολόγηση της δρομολόγησης Local Break-Out (LBO). Το LBO αποδείχθηκε ότι μειώνει σημαντικά την καθυστέρηση E2E, ειδικά όταν το όχημα λειτουργούσε εντός του Visited-PLMN και μπορούσε να συνδεθεί με έναν τοπικό διακομιστή edge. Σε αυτήν τη ρύθμιση, η καθυστέρηση μειώθηκε έως και 55% σε σύγκριση με την δρομολόγηση Home Routing. Ωστόσο, αποκάλυψε επίσης ένα κρίσιμο μειονέκτημα: ο χρόνος διακοπής της υπηρεσίας στην περίπτωση του LBO αυξήθηκε σε πάνω από 4,5 δευτερόλεπτα. Αυτός ο ακραίος χρόνος διακοπής αποδόθηκε στην ανάγκη η OBU να ενεργοποιήσει μια αλλαγή Packet Gateway (P-GW) κατά τη διάρκεια του HO, η οποία δεν υποστηρίζεται ακόμη αποτελεσματικά σε αναπτύξεις NSA και δεν μπορεί να ενεργοποιηθεί από την πλευρά του δικτύου. Η προκύπτουσα καθυστέρηση καθιστά τη χρήση του LBO σε διασυνοριακά σενάρια ανέφικτη για υπηρεσίες CAM ευαίσθητες στην καθηστέρηση με τις τρέχουσες δυνατότητες δικτύου.

Μια λεπτομερής σύγκριση των πέντε πειραματικών σεναρίων έδειξε ότι ο συνδυασμός edge computing, άμεσης διασύνδεσης και home routing προσέφερε την πιο ισορροπημένη λύση. Ενώ η καθυστέρηση δεν ήταν τόσο χαμηλή όσο με το LBO, ήταν γενικά εντός ενός αποδεκτού εύρους για μη κρίσιμες εφαρμογές και ο χρόνος διακοπής της υπηρεσίας παρέμεινε κάτω από ένα δευτερόλεπτο. Αυτή η διαμόρφωση αναδείχθηκε έτσι ως η πιο πρακτική και ρεαλιστική επιλογή για την αρχική ανάπτυξη υπηρεσιών CAM με δυνατότητα 5G σε διασυνοριακά περιβάλλοντα (με ανάπτυξη 5G-NSA).

Η ενότητα ολοκληρώνεται με μια σειρά από συγκεντρωτικές αναλύσεις απόδοσης που υπογραμμίζουν τις σχέσεις μεταξύ των αποφάσεων σχεδιασμού δικτύου και της απόδοσης των εφαρμογών. Δείχνει ότι η άμεση διασύνδεση μεταξύ δικτύων 5G βελτιώνει σταθερά την καθυστέρηση σε όλες τις διαμορφώσεις, ανεξάρτητα από το αν ο διακομιστής εφαρμογών βρίσκεται στο cloud ή στο edge. Επιπλέον, η τοποθέτηση της εφαρμογής στο edge αποδίδει πάντα χαμηλότερη καθυστέρηση από την ανάπτυξη στο cloud. Ωστόσο, όταν η δρομολόγηση δεδομένων περιελάμβανε τη διέλευση στο Visited-PLMN και επιστροφή μέσω του Home-PLMN, η καθυστέρηση αυξήθηκε απότομα, ειδικά στο μοντέλο δημόσιας διασύνδεσης.

Οι χρόνοι διακοπής της υπηρεσίας, αντίθετα, έδειξαν μικρή ευαισθησία στην επιλογή μεταξύ ανάπτυξης cloud και edge ή δημόσιας έναντι άμεσης διασύνδεσης, εκτός από την περίπτωση της δρομολόγησης LBO. Αντ' αυτού, οι χρόνοι διακοπής φάνηκαν να περιορίζονται ουσιαστικά από τους τρέχοντες περιορισμούς των δικτύων NSA και τις διαδικασίες HO, συμπεριλαμβανομένης της έλλειψης υποστήριξης για μετεγκατάσταση συνεδρίας που ξεκινά από το δίκτυο.

Συνολικά, αυτή η ενότητα συνεισφέρει σημαντικές εμπειρικές γνώσεις σχετικά με την απόδοση σε πραγματικό κόσμο των εφαρμογών CAM με δυνατότητα 5G σε διασυνοριακά περιβάλλοντα. Επιβεβαιώνει ότι με τις σωστές αρχιτεκτονικές επιλογές — συγκεκριμένα, την χρήση διακομιστών edge και την άμεση διασύνδεση δικτύων — τα δίκτυα 5G-NSA μπορούν να υποστηρίξουν ένα μεγάλο υποσύνολο υπηρεσιών CAM. Ωστόσο, υπογραμμίζει επίσης ότι οι πιο αυστηρές απαιτήσεις, όπως αυτές που αφορούν την ταχεία απόκριση του οχήματος και τη συνεχή εξαιρετικά αξιόπιστη επικοινωνία, θα παραμείνουν εκτός εμβέλειας έως ότου τα προηγμένα δίκτυα 5G Standalone (SA) αναπτυχθούν ευρύτερα. Αυτά τα ευρήματα έχουν πρακτικές επιπτώσεις για τους φορείς εκμετάλλευσης, τους προμηθευτές, τους κατασκευαστές οχημάτων και τους υπεύθυνους χάραξης πολιτικής, προσφέροντας έναν τεκμηριωμένο χάρτη (roadmap) για τον τρόπο μετάβασης από τις τρέχουσες δοκιμαστικές διαμορφώσεις σε ισχυρές, κλιμακωτές αναπτύξεις CAM μεταξύ των Ευρωπαϊκών συνόρων.

Κεφάλαιο 6

Αυτό είναι το τελευταίο μέρος της διατριβής και παρέχει μια ολοκληρωμένη σύνθεση των ερευνητικών ευρημάτων, ενοποιώντας τις πειραματικές γνώσεις, τις αναλύσεις των ενδιαφερόμενων μερών και τις βιβλιογραφικές αναλύσεις σε ένα ενιαίο συμπέρασμα. Η ενότητα εξετάζει τις προκλήσεις, τις προτεινόμενες λύσεις και τις εμπειρικές παρατηρήσεις σχετικά με την ανάπτυξη υπηρεσιών Συνδεδεμένης και Αυτοματοποιημένης Κινητικότητας (CAM) μέσω 5G, ειδικά σε διασυνοριακά περιβάλλοντα. Επανεξετάζει τα ερευνητικά ερωτήματα που τέθηκαν στην αρχή της διατριβής και παρέχει σαφείς, βασισμένες σε τεκμήρια απαντήσεις που προέκυψαν από τις διεξαγόμενες δοκιμές και την ευρύτερη τεχνική αξιολόγηση.

Η ενότητα περιγράφει πώς η διατριβή εξέτασε συστηματικά το τρέχον ερευνητικό τοπίο, συνεργάστηκε με τα ενδιαφερόμενα μέρη για να προσδιορίσει τις προσδοκίες και τις απαιτήσεις και συμμετείχε στον σχεδιασμό και την εκτέλεση μιας πειραματικής εκστρατείας πλήρους κλίμακας σε πραγματικές συνθήκες στα ελληνοτουρκικά σύνορα. Τα αποτελέσματα που ελήφθησαν από αυτόν τον διασυνοριακό διάδρομο - τον πρώτο του είδους του στην Ευρώπη - παρείχαν ουσιαστικές γνώσεις σχετικά με τις δυνατότητες απόδοσης και τους περιορισμούς των δικτύων 5G όταν χρησιμοποιούνται για την υποστήριξη εφαρμογών CAM υπό πραγματικές συνθήκες. Ένα κεντρικό συμπέρασμα που εξάγεται σε αυτήν την ενότητα είναι η αναγνώριση ότι τα τρέχοντα δίκτυα 5G NSA δεν είναι ακόμη ικανά να υποστηρίξουν πλήρως τις πιο απαιτητικές περιπτώσεις χρήσης CAM κατά τη διάρκεια των μεταβιβάσεων μεταξύ γειτονικών δικτύων 5G. Η διατριβή εντοπίζει ένα ευρύ φάσμα προκλήσεων - τόσο τεχνικών όσο και μη τεχνικών- που πρέπει να αντιμετωπιστούν πριν από την αξιόπιστη, απρόσκοπτη ανάπτυξη υπηρεσιών CAM σε κλίμακα πέρα από τα εθνικά σύνορα. Οι τεχνικές προκλήσεις περιλαμβάνουν ζητήματα όπως η συνέχεια των υπηρεσιών και των συνεδριών, η πολυπλοκότητα της δρομολόγησης δεδομένων, η ενσωμάτωση MEC (Multi-access Edge Computing), ο συγχρονισμός δικτύου και οι ρυθμίσεις περιαγωγής. Ταυτόχρονα, η μελέτη τονίζει ότι οι μη τεχνικές πτυχές -όπως η κανονιστική ευθυγράμμιση, το απόρρητο δεδομένων (π.χ. συμμόρφωση με τον GDPR), η διασυνοριακή εναρμόνιση του φάσματος και τα νομικά πλαίσια- είναι εξίσου κρίσιμες για την επιτυχία.

Η διατριβή υπερβαίνει τον απλό εντοπισμό προκλήσεων. Αξιολογεί και δοκιμάζει επίσης μια σειρά από πιθανές λύσεις, προσφέροντας τόσο θεωρητικές αναλύσεις όσο και πρακτικά δεδομένα απόδοσης. Μερικοί από τους βασικούς μηχανισμούς που διερευνήθηκαν περιλαμβάνουν προγνωστική ανάλυση για προληπτική κατανομή πόρων δικτύου, στρατηγικές μετριασμού σε επίπεδο εφαρμογής, όπως λειτουργίες δημιουργίας αντιγράφων ασφαλείας και προληπτική διαμόρφωση IP, και αρχιτεκτονικά μοντέλα όπως η άμεση διασύνδεση και η συνεργασία edge-cloud. Μέσω δοκιμών στο πεδίο, η μελέτη επιβεβαίωσε ότι λύσεις όπως η τοποθέτηση edge server και η άμεση διασύνδεση μεταξύδικτύων μπορούν να μειώσουν σημαντικά την καθυστέρηση από άκρο σε άκρο —συχνά φέρνοντάς την εντός αποδεκτών ορίων για CAM— αλλά ότι η συνέχεια της υπηρεσίας κατά τη διάρκεια της αλλαγής δικτύου παραμένει ένα σημαντικό σημείο συμφόρησης.

Επιπλέον, η ενότητα παρέχει απαντήσεις σε όλα τα βασικά ερευνητικά ερωτήματα:

- Σχετικά με τη **φύση των διασυνοριακών προκλήσεων**, η μελέτη προσδιορίζει τέσσερις κύριους τομείς - τηλεπικοινωνιακά συστήματα, λογική εφαρμογών CAM, ασφάλεια/ιδιωτικότητα και ρυθμιστικά ζητήματα - ο καθένας με το δικό του σύνολο τεχνικών και λειτουργικών εμποδίων. Προτείνονται και αξιολογούνται λύσεις για κάθε ένα από αυτά, τόσο θεωρητικά όσο και μέσω δοκιμών στο πεδίο.

- Όσον αφορά τις **προτεραιότητες των ενδιαφερόμενων μερών (stakeholders)**, η έρευνα διαπίστωσε ότι η υποστήριξη για βασικές λειτουργίες ενισχυμένης κινητής ευρυζωνικής σύνδεσης (eMBB) και εικονικοποίηση (virtualization) θεωρείται απαραίτητη. Τα ενδιαφερόμενα μέρη αναμένουν επίσης υποστήριξη για εξαιρετικά αξιόπιστη επικοινωνία χαμηλής καθυστέρησης (URLLC), επεκτασιμότητα, δυνατότητα αναβάθμισης και υψηλή αξιοπιστία, τα οποία αποτελούν προϋποθέσεις για αξιόπιστες υπηρεσίες CAM.
- Όσον αφορά τη **βέλτιστη διαμόρφωση δικτύου**, η μελέτη δείχνει ότι ο συνδυασμός άμεσης διασύνδεσης και Home Routing (HR) χρησιμοποιώντας edge servers προσφέρει την καλύτερη αντιστάθμιση μεταξύ καθυστέρησης και συνέχειας υπηρεσίας στις τρέχουσες αναπτύξεις 5G NSA. Ενώ το μοντέλο Local Break-Out (LBO) παρέχει ακόμη χαμηλότερη καθυστέρηση, έχει ως αποτέλεσμα υψηλό χρόνο διακοπής υπηρεσίας λόγω της επανεπιλογής Packet-GW, καθιστώντας το ακατάλληλο υπό τους τρέχοντες αρχιτεκτονικούς περιορισμούς.
- Τονίζεται η σημασία ενός **καλά συντονισμένου σχήματος συγχρονισμού και συχνότητας Time Division Duplexing (TDD)** και μιας κοινής δομής πλαισίου, ζωνών προστασίας φάσματος και ενός κοινού σχεδιασμού δικτύου μεταξύ γειτονικών δικτύων για τις διασυνοριακές λειτουργίες CAM.
- Αξιολογείται επίσης ο **αντίκτυπος των περιβαλλοντικών συνθηκών**. Τα αποτελέσματα των δοκιμών δείχνουν ότι παράγοντες όπως η υγρασία, οι βροχοπτώσεις, η απόσταση από τους σταθμούς βάσης και τα φυσικά εμπόδια (π.χ. μεταλλικές κατασκευές) μπορούν να υποβαθμίσουν σημαντικά την ποιότητα του σήματος και την απόκριση του δικτύου. Αυτά τα ευρήματα υποδεικνύουν την ανάγκη για πλεονάζουσες και πυκνές αναπτύξεις δικτύου σε διασυνοριακές περιοχές.
- Εξετάζεται επίσης η **διαμόρφωση της Ενσωματωμένης Μονάδας (OBU)**. Οι OBU θα πρέπει να υποστηρίζουν πολλαπλή συνδεσιμότητα, εξωτερικές κεραίες, αναφορά αισθητήρων ανα υπο-χιλιοστό του δευτερολέπτου και προηγμένες δυνατότητες V2X για να διασφαλίζεται η αξιοπιστία κατά τη διάρκεια διασυνοριακών περασμάτων.
- Η ενότητα εξετάζει επίσης τον αντίκτυπο στην **απόδοση κατά τη διάρκεια περιαγωγής** μεταξύ δικτύων 5G. Καταλήγει στο συμπέρασμα ότι ενώ η καθυστέρηση είναι διαχειρίσιμη υπό βέλτιστες διαμορφώσεις, η διακοπή της υπηρεσίας παραμένει σημαντική - με τον χαμηλότερο παρατηρούμενο χρόνο διακοπής να είναι περίπου 700 ms, ο οποίος είναι ανεπαρκής για κρίσιμες εφαρμογές ασφαλείας. Αυτό υποδηλώνει ότι ενώ το 5G NSA μπορεί να υποστηρίξει πολλές μη κρίσιμες λειτουργίες CAM, οι πιο απαιτητικές εφαρμογές απαιτούν δίκτυα 5G SA (Standalone).
- Τέλος, η ενότητα προτείνει τις πιο **υποσχόμενες ερευνητικές οδούς** για το μέλλον. Αναγνωρίζει ότι ενώ ορισμένες βελτιώσεις στην απόδοση είναι εφικτές μέσω προσεκτικής βελτιστοποίησης, μόνο η μετάβαση στο 5G SA - και τελικά στο 6G - θα αντιμετωπίσει τα εναπομείναντα κενά. Το όραμα του 6G, με τις υποσχέσεις του για καθυστέρηση υπο-χιλιοστού του δευτερολέπτου, έξυπνη κατανομή πόρων και απρόσκοπτη διαλειτουργικότητα δικτύου, υπόσχεται ένα μέλλον όπου η πλήρως αυτόνομη, διασυνοριακή λειτουργία εφαρμογών CAM θα μπορούσε να γίνει πραγματικότητα.

Αυτή η ενότητα συνοψίζει επίσης τις βασικές συνεισφορές της διατριβής. Ορισμένες από τις επισημασμένες συνεισφορές που αναμένεται να έχουν αντίκτυπο στον σχετικό τομέα σπουδών και μπορούν να χρησιμοποιηθούν για περαιτέρω έρευνα στον τομέα της διασυνοριακής λειτουργικότητας CAM είναι: i) η εκτεταμένη και ολοκληρωμένη βιβλιογραφική έρευνα, ii) η ανάλυση απαιτήσεων που παρουσιάζεται με γνώμονα τις ανάγκες των ενδιαφερόμενων μερών (stakeholders), iii) η συγκριτική αξιολόγηση τεχνολογίας και η αξιολόγηση απόδοσης για τη διασυνοριακή λειτουργία CAM με δίκτυα 5G-NSA 3GPP Rel.15 (για να λειτουργήσουν ως βάση για μελλοντικές εκστρατείες μέτρησης), iv) η ταξινόμηση των προκλήσεων και λύσεων διαχείρισης κινητικότητας μεταξύ PLMN, v) ο σχεδιασμός, η ανάπτυξη και η βελτιστοποίηση στοχευμένων μηχανισμών συνέχειας υπηρεσιών σε επίπεδο εφαρμογής και vi) οι στοχευμένες συστάσεις και προτάσεις που αφορούν συγκεκριμένα ενδιαφερόμενα μέρη.

Συμπερασματικά, η Ενότητα 6 συνοψίζει το βασικό μήνυμα της διατριβής: αν και τα δίκτυα 5G NSA αντιπροσωπεύουν ένα ζωτικό πρώτο βήμα για την ενεργοποίηση των διασυνοριακών υπηρεσιών CAM, οι περιορισμοί τους -ιδίως όσον αφορά τη συνέχεια των υπηρεσιών κατά τη διάρκεια της περιαγωγής μεταξύ δικτύων- τα εμποδίζουν να πληρούν τα υψηλότερα πρότυπα απόδοσης που απαιτούνται για κρίσιμες εφαρμογές. Η έρευνα καθιστά σαφές ότι τόσο η τεχνική εξέλιξη (μέσω 5G SA και 6G) όσο και η διατομεακή συνεργασία (μεταξύ παρόχων δικτύου, ρυθμιστικών αρχών και κατασκευαστών) θα είναι απαραίτητες για την πλήρη αξιοποίηση των δυνατοτήτων της διασυνοριακής αυτόνομης κινητικότητας στην Ευρώπη και πέραν αυτής.

1 Introduction

1.1 Overview of Connected and Automated Mobility

The automotive industry is in the midst of a transition toward producing vehicles that are more aware of their surroundings. For many years, there has been a goal that vehicles should be able to communicate with not only other vehicles (Vehicle-to-Vehicle, V2V) but also with nearby Infrastructure (V2I), Networks (V2N) and even Pedestrians (V2P). Collectively these use cases have become known as vehicle-to-everything (V2X) connectivity. Even if a clear date for a global commercial launch of SAE[1] Level 4 and above autonomous driving services has not been established yet [1], various tests are already ongoing in different parts of the world. In this context, the external wireless connectivity represents a powerful extension to the embedded sensors already used by cars. In fact, all Original Equipment Manufacturers (OEMs) agree to consider the connectivity as a must for autonomous driving levels 4 or 5. Interestingly enough, the role of connectivity as a further Advanced Driving Assistance System (ADAS) has been found to be valuable already from autonomous driving SAE level 1.

Now, with advances in electronics, sensing technologies and computing techniques such as Machine Learning (ML) and computer vision, such Connected and Automated Mobility (CAM) use cases are starting to become reality. New vehicles today can take a more active role by warning drivers of potential collisions with oncoming vehicles, assisting with emergency braking and monitoring intersections, to name just a few examples. In the automotive industry, this trend is viewed as the beginning of an evolution to automated and eventually fully autonomous vehicles. In an autonomous vehicle scenario, the vehicle's on-board computers will be fully capable of performing all driving operations on their own, with no human monitoring required.

In the U.S., the National Highway Traffic Safety Administration (NHTSA) has been progressing the use of IEEE 802.11p-based Dedicated Short-Range Communication (DSRC) technology for V2V communications. The technology was developed specifically for V2V applications that require critical latency of ~100ms, very high reliability and security authentication with privacy safeguards. The DSRC standard[2] was finalized in 2009 and has been subjected to extensive testing by automakers and select large-scale trials. Stakeholders have completed work on use of DSRC to protect vulnerable road users. The Federal Communications Commission (FCC) has allocated dedicated spectrum for transportation safety applications in 1999 in the 5.850-5.925 GHz band to ensure operation without interference that DSRC-based V2V systems plan to leverage.

The most prominent competitor of 802.11p are the 3GPP developed cellular network communications standards with specific extensions to support V2X communication. The support of V2X services already started from the 3GPP Rel.14 4G-LTE (LTE-V2X) era, often termed Cellular V2X (C-V2X), and further evolved with 3GPP Rel.16 5G based V2X communication, often termed NR-V2X. The general 5G System architecture for 3GPP Rel.16 is specified by the 3GPP SA2 Group in TS23.501 [2] and TS23.502 [3] while the 3GPP specification TS23.287 [4] targets the 5G system architecture enhancements required to support V2X services in 3GPP Rel.16. The latter specification will largely be based on the significant technical work which is reported in 3GPP technical report TR22.886 "Study on enhancement of 3GPP Support for 5G V2X Services" [5] and TR23.786 "Study on architecture enhancements for Evolved Packet System (EPS) and 5G System to support advanced V2X services" [6].

[1] Society of Automotive Engineers (SAE): Levels of Autonomous driving, https://www.sae.org/news/2019/01/sae-updates-j3016automated-driving-graphic
[2] https://www.itsstandards.eu/25-2/cen-dsrc/

In contrast to the US which has been an early promoter of the 802.11p technology, the European Union (EU) has shown a slight preference towards 5G (without excluding use of 802.11p) for V2X, while its interest in supporting Connected and Automated Mobility (CAM) services has been greatly highlighted. The European Commission's (EC) vision to be able to provide CAM services over major urban areas and main transport paths by 2025 [7] is starting to take shape. This EC action plan [7] has set forth a clear roadmap for public and private investment into 5G infrastructure along the main EU transport paths, to enable advanced seamless Cooperative CAM (CCAM) services across Europe, spanning multiple vertical fields (security, safety, efficiency, entertainment and more) and multiple modes of transportation (vehicular, railways, shipping, etc.). To this end, the Trans-European Transport Network (TEN-T) initiative [8] defines nine critical corridors for transportation across Europe where advanced CAM services are expected to be fully supported by 2025, creating novel business opportunities. To complete this long-term vision, the EU has put forth the idea of Connecting Europe Facility (CEF) [9], combining digital, transport and energy infrastructures across Europe, providing a true unified digital and technological end-to-end European ecosystem, in which 5G is going to play an integral part.

Despite the fact that early evaluation of the two communication standards indicate that C-V2X (Rel.14) outperforms 802.11p/DSRC in terms of reliability, resilience to interference and Non-Line of Sight (NLOS) communication, both communication technologies are capable of supporting safety applications that demand an end-to-end latency of around 100 msec, as long as the vehicle density is not very high. However, as the quality of service (QoS) requirements of V2X use-cases become more stringent, which is the case in many advanced V2X applications (see Section 2.3), the two current V2X Radio Access Technologies (RATs) fall short of providing the desired performance.

In order to diminish the performance gap between DSRC and C-V2X and to support additional modes of operations and increase the offered throughput, a new Study Group called the IEEE 802.11 Next Generation V2X was formed in March 2018. This resulted in the formation of IEEE Task Group 802.11bd[3] (TGbd) in January 2019. On the other hand, 3GPP has already delivered the New Radio (NR) V2X as part of its Rel. 16. NR V2X is expected to support advanced V2X applications that require much more stringent QoS guarantees compared to applications that can be supported by C-V2X (Rel.14 based version). The high-level evolution of the V2X communication standards along with the key objectives of each generation are depicted in Figure 1.

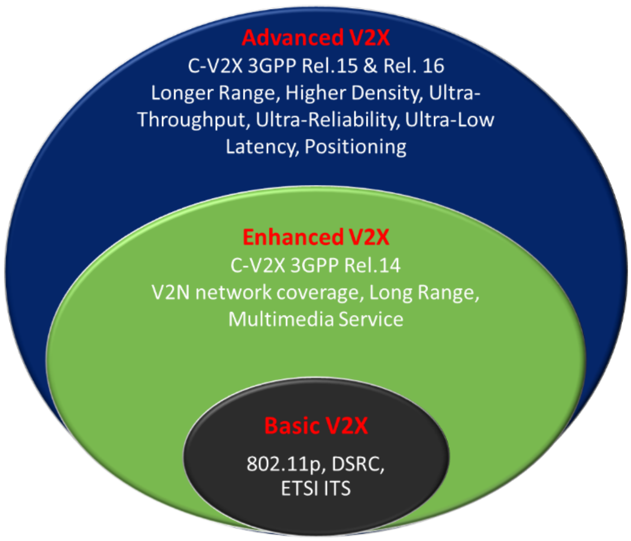


Figure 1: V2X Evolution

[3] https://standards.ieee.org/ieee/802.11bd/7451/

In terms of their design objectives, 802.11bd and NR V2X have certain similarities. For example, both evolutionary RATs are being designed to improve the reliability of offered services, lower the end-to-end latency and support applications that require high throughput. However, their design methodologies significantly differ. 802.11bd requires the new standard, i.e., 802.11bd to be backward compatible with 802.11p. This implies that 802.11bd and 802.11p devices must be able to communicate with each other while operating on the same channel. On the other hand, 3GPP does not impose a similar constraint on NR V2X. Vehicles equipped with NR V2X can still communicate with C-V2X devices. However, this will be achieved through a dual-radio system, i.e., one radio for C-V2X and another for NR V2X.

1.1.1 CAM basic principles

The (cooperative) connected and automated mobility ((C)CAM) solutions, ranging from autonomous or remote driving to extended sensor-based environmental perception and platooning, are expected to bring significant improvements on mobility, including commuting, travelling, as well as goods transportation and logistics. For instance, the more than 1,500 billion tons-km of freight traffic via road in EU-28[4] reflect the importance of advanced CAM services across Europe e.g., reducing fuel consumption with truck platooning. In this context, the EU has set the target for "all urban areas and major terrestrial transport paths to have uninterrupted 5G coverage by 2025" [7]. Before diving into the details of autonomous mobility, it is important to clarify some basic principles regarding Vehicular (ad-hoc) Networks or VANETS.

Vehicular networks can be considered as a derivation of mobile ad-hoc networks (MANETs). In a VANET each vehicle is defined as a node of the network and is equipped with a unit of on-board communication OBU (On-Board Unit). The function of the OBU is to exchange information with other vehicles or with stationary access points located on the roads, called RSU (roadside units) or directly via the mobile networks (i.e., via a eNB/gNB). Figure 2 depicts the main communications modes in a VANET including Vehicle to Network (V2N), Vehicle to Infrastructure (V2I) and Vehicle to Vehicle (V2V).

The elements that make up the VANET networks when operating with each other form domains, which refer to a set of logical and physical elements that work collectively to establish communications between nodes and RSU [10]. These domains are classified according to their operation in:

- Domain in the vehicle: bidirectional communication network inside the vehicle which can be connected wired or wirelessly.
- Ad hoc domain: this domain refers to the wireless communication used to link the nodes with each other or the nodes with the RSU. This communication can be established through the standard presented by the IEEE or through other wireless technologies (Wi-Fi®, WiMAX®, LTE, etc.).
- Infrastructure domain: formed by the access networks and the infrastructure that supports the Internet access (backend) requested by the nodes and / or the RSU. Communication can be done using wired and / or wireless technologies.

[4] Eurostat, Road freight transport statistics: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Road_freight_transport_statistics&oldid=575068

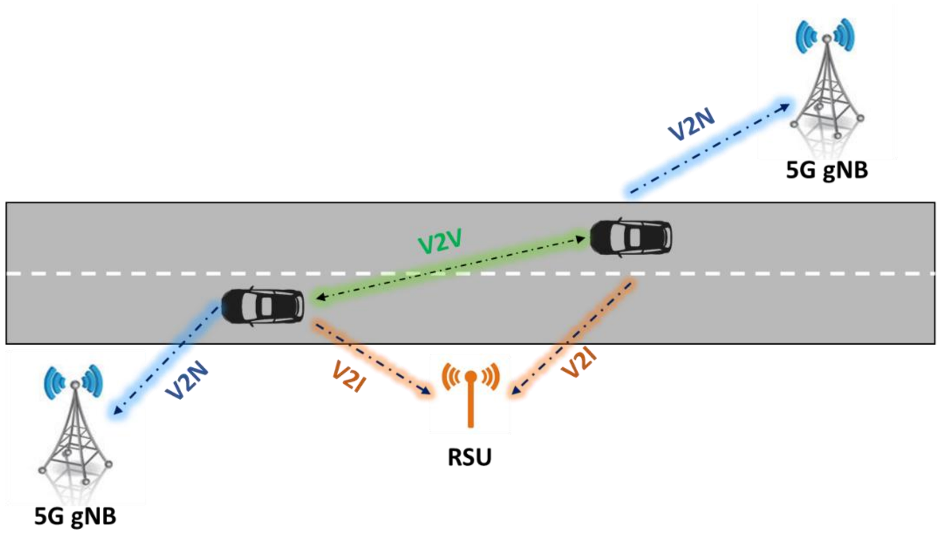


Figure 2: VANET communications concept

A big portion of the communication in all V2X modes is based on the periodic exchange of messages among the vehicles and/or between a vehicle and a remote Intelligent Transportation System (ITS) server over the network. This periodic communication is key for most CAM application as it provides the groundwork for the collection of information from multiple vehicles and based on its fusion and processing, it allows for the generation of the "big picture" of a certain vehicular environment which drives any autonomous driving decisions. The type of data usually exchanged with periodic communication are the location, trajectory and velocity of each vehicle which allows for the creation of such vehicular environment cooperative maps. Other types of data may also be exchanged such as engine temperature and revs, and other detected objects by vehicles (e.g., pedestrians, bicycles, etc.).

As it is critical for every vehicle to receive this information from all the surrounding vehicles, especially the ones that are located outside its Line of Sight (LoS), e.g., behind a corner, in order to be able to operate in autonomous mode without the risk of an accident, ETSI has standardized these types of messages which are called **Cooperative Awareness Messages (CAMs)** [11]. CAMs are now adopted by all vehicular and equipment manufacturers facilitating the interoperability of the various vehicular components and applications. The transmission frequency of CAMs is set to 10 Hz which is deemed enough even for the most challenging vehicular environments with high velocity. The continuous reception of these messages is critical for VANET / CAM applications, as the high velocity environments means that the position, speed and trajectory of every other vehicle on the road is very dynamic, hence information from older CAM messages can easily be outdated.

However, periodic traffic is not the only traffic that should be supported for the successful deployment of CAM services. Actually, the messages warning of an accident ahead, which are generated based on events on the roads, are potentially the most critical ones as they need to be quickly propagated to the rest of the vehicles on the road, to avoid further accidents. ETSI has also standardized this type of messages, in order to guarantee universal reception and understanding of these messages across vehicular manufacturers and application developers. These aperiodic messages are called **Decentralized Environmental Notification Messages (DENM)** and are defined in [12]. Both CAM and DENM messages are instrumental for the correct operation of every VANET application and through them, vehicles are fully aware of their surroundings and may construct a Local Dynamic Map (LDM) with all the vehicles on the road and potential hazardous locations/events.

Despite the importance of both messages, some of the features of LTE-V2X and IEEE 802.11p may not provide full support for the transmission of DENMs. This is mostly due to the fact that both "Listen before Talk" (802.11p) and "Semi-Persistent Scheduling" (LTE-V2X) have an inherent waiting period that each message needs to wait for, before being transmitted. As DENM messages are extremely important as they carry information on sudden or dangerous road events, they should not be delayed by such mechanisms, and they should be granted immediate priority by the scheduler (prioritized over CAMs). On top of that, the currently used channel sensing scheme for channel estimation (which results in the selection of the transmission scheme and coding) which averages the channel over observations of 1 second, is not considered accurate enough for highly dynamic vehicular environments where channel fading is very fast and could lead the dropping of important messages (such as a DENM message) which could result in accidents.

It becomes clear that aperiodic event-driven traffic is more troublesome for the vehicular communication protocols while the loss of a DENM message is much more severe than the loss of a CAM message, highlighting the importance of addressing those issues. Solutions in terms of short-term sensing with sensing windows down to 100 msec and the repetition of DENM messages without waiting for a negative acknowledgement (NACK), have been investigated in literature [13], and have produced promising results indicating a significant performance improvement (lower latencies and lower drop rates for DENM). However, the weaknesses of such decentralized communications protocols for CAM applications remain obvious, and that is why communication over cellular networks (4G/5G) is considered very promising.

1.2 EU's Vision for CAM

The European Commission's (EC) vision to launch initial 5G services by 2020 and to cover major urban areas and main transport paths by 2025 [7] is starting to take shape. This EC action plan [7] has set forth a clear roadmap for public and private investment into 5G infrastructure along the main EU transport paths, to enable advanced seamless Connected and Automated Mobility (CAM) services across Europe, spanning multiple vertical fields (security, safety, efficiency, entertainment and more) and multiple modes of transportation (vehicular, railways, shipping, etc.). To this end, the Trans-European Transport Network (TEN-T) initiative [8] defines nine critical corridors for transportation across Europe (see Figure 3) where advanced CAM services are expected to be fully supported by 2025, creating novel business opportunities. To complete this long-term vision, the EU has put forth the idea of Connecting Europe Facility (CEF)[9], combining digital, transport and energy infrastructures across Europe, providing a true unified digital and technological end-to-end European ecosystem, in which 5G is going to play an integral part.

However, in order to establish uninterrupted and smooth connectivity along the entire corridors (each spanning multiple European nations), capable of supporting the stringent requirements of the CAM applications, service and session continuity need to be guaranteed even when vehicles cross national borders and are hence changing their serving 5G network provider or Mobile Network Operator (MNO). ***Session continuity*** is defined as the capability of a node to maintain its ongoing IP sessions while changing its (IP) point of attachment (when changing network). The simultaneous switching of the application server and host as well, while maintaining full operational capacity for the application is termed ***service continuity***. Maintaining session and service continuity in these cross-border conditions (i.e. when changing 5G providers) is perhaps the biggest challenge of the CAM stakeholders at this time, proven by the commissioning of three Innovation projects from the EU tasked with researching CAM functionality at cross-border conditions, namely 5G-MOBIX[14], 5G-CARMEN [15] and 5G-CROCO [16].

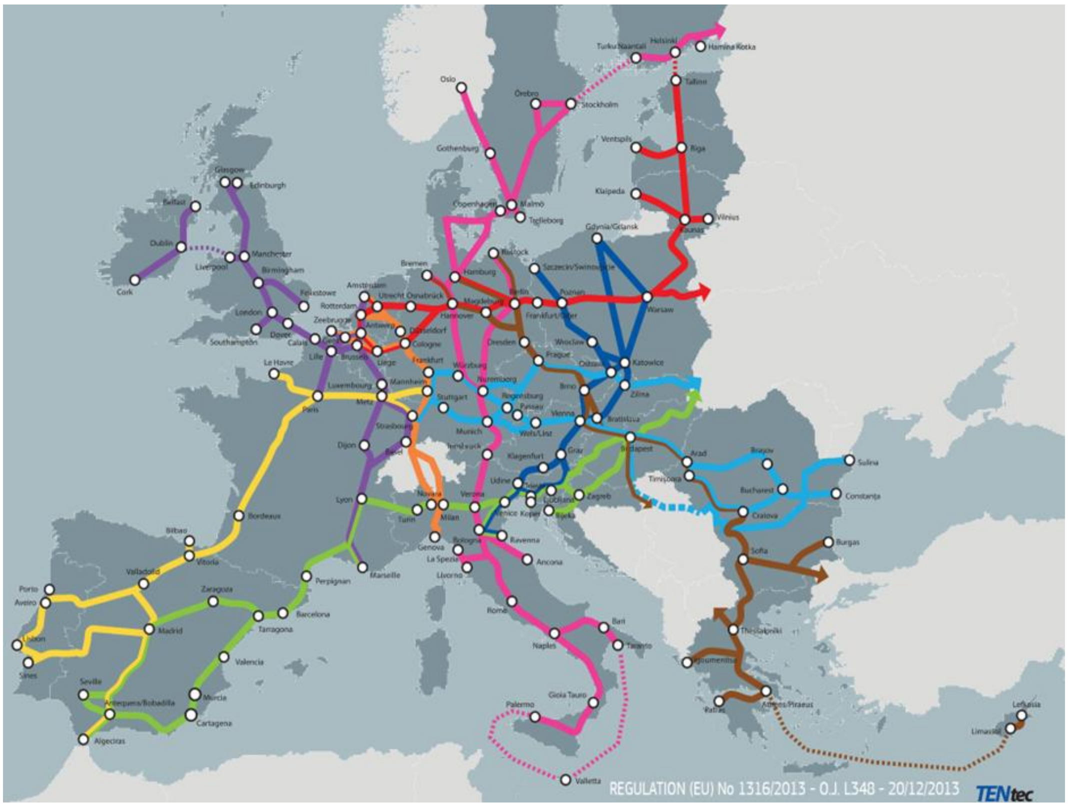


Figure 3: Trans-European Transport Network (TEN-T) [8]

While there are multiple factors affecting the successful session and service continuity when changing 5G network provider, the most important one is arguably the Handover (HO) procedure during which the actual "switching" of service of the User Equipment (UE) from its currently serving cell to a target cell. When the target cell also happens to belong to a different MNO (i.e. moving from the Home MNO (H-MNO) to the Visiting MNO (V-MNO)) as is the case in cross-border conditions, then we are talking about an *inter-MNO* or *Inter-PLMN* (Public Land Mobile Network) HO [3]. The HO procedure has remained largely the same from 4G to 5G networks (as described in [2] and [3]) and minor service interruptions are usually expected every time a HO occurs (intra or inter MNO), termed as ***HO Interruption Time (HIT)***. The HIT is mostly dominated by the time it takes for the UE to re-tune its transceivers to the target cell's frequencies and to be able to achieve synchronization with the cell. During this time, the UE has no connectivity with any cell in the network.

1.3 Problem definition & research questions

The work performed in the context of this dissertation has focused on analysing the current Connected and Automated Mobility landscape, identifying the key challenges that currently prevent the smooth provisioning of CAM application in cross-border areas, and nominating several potential solutions that have the potential of mitigating the effect of these challenges and improving the performance experienced by the CAM users in cross-border environments. Through the design of specialized algorithms (mechanisms) for CAM application cross-border operation and their validation through extensive measurement campaigns over a real-life 5G NSA networks between Greece and Turkey, this study provides some of the first ever insights onto the operation and performance of 5G networks for CAM application in cross-border conditions and under varying configurations and environmental and situation conditions, and quantifies the respective performance of the CAM applications and the proposed mitigating solutions.

The main research question addressed by this dissertation can be broken down to the following components to be addressed as individual research questions / scientific contributions:

- 5G enabled cross-border CAM challenges & stakeholder views
    - What are the main challenges (technical and non-technical) that need to be addressed in order to provision CAM services in cross-border conditions?
    - Which are the most promising solutions for each of these challenges?
    - What do the EU stakeholders consider as key factors & requirements to support CAM applications in cross-border conditions?

- 5G Network oriented research questions
    - What is the optimal 5G-NSA Network ***configuration & optimization*** to support CAM operation in cross border conditions?
    - What are the optimal ***frequency settings and TDD frame structure*** for neighbouring cross-border 5G networks?
    - What is the ***effect of environmental & situational conditions*** on 5G network performance in hard border conditions?

- Autonomous vehicle optimization for CAM operation
    - What is the optimum configuration for the ***OBU and other hardware*** placed on the autonomous vehicle?
    - What are the expected ***pain-points during cross-border operation*** for autonomous vehicles?

- CAM Application design for cross-border operation
    - What design consideration need to be taken into account for ***CAM application operation in cross-border conditions***?
    - What type of ***application -level HO mechanisms*** need to be designed to support cross-border operation?

- 5G enabled CAM Service Performance
    - What is the optimal CAM Application configuration & optimization to support CAM operation in cross border conditions?
    - What is the effect on the application performance of cloud or edge servers utilization?
    - What is the effect on end-user experienced performance based on the different types of inter-PLMN connectivity?
    - What is the effect on end-user experienced performance based on the different types of roaming schemes?
    - What is the impact of HO on the E2E performance of a CAM user?
    - Can the stringent CAM requirements be met during an inter-PLMN HO? Which CAM applications could be supported and which not?
    - Which of the investigated solutions provide the best performance? under what conditions?

- What are the remaining challenges, and can they be expected to be addressed by 5G SA networks?

The rest of this thesis report is structured as follows:

- **Section 2** provides a state of the art analysis to familiarize the reader with the main themes of this thesis and to provide detailed information regarding the functionality of CAM applications, their standardized patterns of communication and the key requirements of the most prominent V2X Use cases, 3GPP technologies and the protocols that are currently in place for Handover between eNB/gNBs and between networks and the relevant Research and Innovation activities that are currently taking place to address the identified issues.
- **Section 3** presents insights regarding the main functional and non-functional requirements of the key EU CAM and Telecom stakeholders for 5G-enabled mobility in cross-border environments, while it also presents a detailed analysis and categorization of all the current challenges and bottlenecks that need to be overcome for the smooth provisioning of CAM functionality in cross-border environments along with the respective most promising solutions according to recent literature, progressing a few key solutions to be tested in the field.
- **Section 4** provides an overview of the technical considerations that had to be tackled on network, vehicle, OBU and application level in order to define appropriate experiments that would lead to scientifically significant results. Moreover, this section provides an overview of the trial and experimentation structure that was followed for the real-life trials, including the network and application architecture, as well as the specifications of the equipment used.
- **Section 5** presents the trial set-up and the measurement framework and provides the detailed measurements obtained during the real-life trials at the Greece-Turkey corridor, including a comprehensive analysis of the presented results and a detailed explanation of the respective insights. This section concludes with discussing the aggregate results and overall insights on network and CAM application level.
- **Section 6** finally offers some concluding remarks, highlighting the key learnings from the work carried-out in the context of this thesis and answering the previously posed research questions, while it also discusses the way forward for (B)5G-enabled CAM cross-border functionality.

2 State of the Art Analysis

Mobility management and in general the service provisioning to highly mobile users has always been one of the main challenges of mobile networks. The focus so far has been mainly falling on serving mobile users within the same PLMN / MNO domain as inter-MNO HOs were considered a border-line case with limited applicability, while service interruption in such cases came to be expected even by the users. However, with the rise of autonomous mobility a whole new domain of applications came to existence demanding extremely low latencies and high reliability even in cross-border conditions. Despite this abrupt surge in demand for service and session continuity, inter-MNO HO has barely been investigated by researchers, while even for intra-MNO HO the same mechanism as for 4G is used. The SotA analysis presented in this section tries to categorize and understand the available work around mobility management enhancements and HO improvements. First, an overview of the relevant standards is provided (IEEE and 3GPP) explaining the currently available Mobility Management mechanisms in 5G and the CAM related standards that need to be adhered to. Secondly, an analysis of the generic HO improvement approaches is presented attempting to identify and extract the useful components, while the works specifically targeting inter-MNO improvements and multi-connectivity approaches are specifically highlighted. Subsequently, an overview of the work around the additional aspects of HO that need to be considered for a successful inter-MNO mobility management is presented. Finally, an overview of the V2X requirements and KPIs that need to be met for successful CAM services provisioning is presented while an analysis of the current Research and Innovation landscape around C-V2X is also outlined.

2.1 CAM Relevant Standards

2.1.1 3GPP C-V2X Standardisation (mode3, mode 4)

Initially, 3GPP Long Term Evolution (LTE) specified device-to-device (D2D) communications as part of (Proximity Services) ProSe services in Release 12 and Release 13. The PC5 interface, also referred to as the *Sidelink (SL)* provided physical layer support mainly for D2D communication. In Release 14 as part of introducing LTE-V2X communication service, sidelink design enhanced specifically addressing high speed and high-density scenarios as shown in Figure 4. These features set the starting point for the evolution of vehicular applications not previously supported by mobile communication technology and pave the way for future-proof connectivity in the automotive domain [17].

LTE V2X supports the delivery of basic safety messages (BSM) like ***CAMs*** and ***DENMs***. NR-V2X as part of Release 15/16 is supposed to support a range of challenging V2X services, including very precise positioning and ranging to enable cooperative and automated driving that requires ultra-reliability and low latency. NR-V2X will complement and co-exist with LTE-V2X. 3GPP has defined the requirements for support of enhanced V2X use cases in NR-V2X, which are summarized in *Table 1*. The advanced V2X services envisioned for NR-V2X require an enhanced design of the NR sidelink (NR-PC5) to meet the stringent reliability and latency requirements of the addressed use cases. Figure 4 provides the overview of the 3GPP V2X standards evolution and the key supported characteristics at each generation [17].

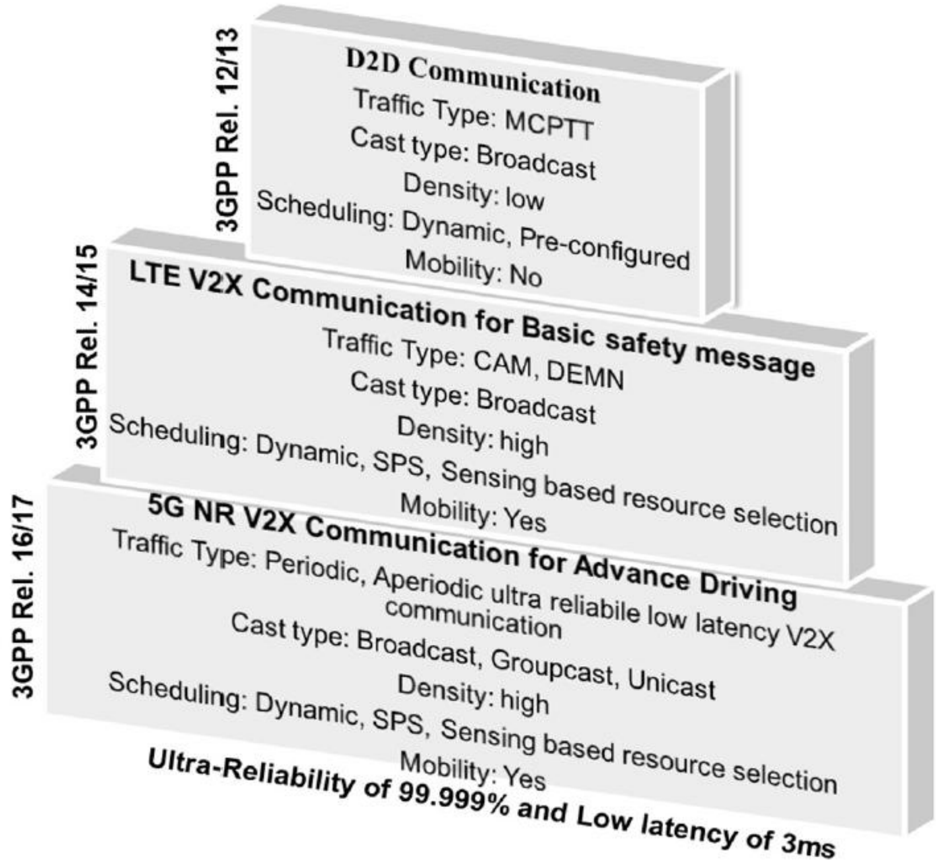


Figure 4: 3GPP V2X/Sidelink evolution with each release [17]

2.1.1.1 Rel.14 LTE-V2X

Figure 5 below depicts the functional LTE-V2X architecture with a 4G core. The C-V2X sidelink shares the same single carrier frequency division multiple access (SC-FDMA) technique as the LTE uplink, with the same time structure and the same numerology. In the time domain, the minimum resource is the Transmission Time Interval (TTI) 1 ms, which corresponds to 14 multi-carrier OFDM symbols. In the frequency domain, a group of 12 subcarriers spaced 15 kHz apart form a resource block (RB) of 180 kHz. Unlike the long-range LTE, in the time domain only 9 symbols (instead of 12) are used for data transmission, since those dedicated to the demodulation reference signals (DMRSs) have increased from 2 to 4, with the last symbol left empty to allow timing adjustment and transmission-to-reception switching. In the frequency domain, the concept of subchannel has been included that groups a given number of RBs. Every data packet may occupy one or more adjacent subchannels during one TTI [18].

For each packet, the control part, which is transmitted within the so-called Sidelink Control Information (SCI), is carried on dedicated resources in the same TTI. The main traffic pattern considered for the C-V2X sidelink are the CAM messages [11], which are sent in broadcast by all vehicles to advertise their position and movements. Given the periodicity of these packets, the allocation can be performed with a Semi-Persistent Scheduling (SPS) approach: a given portion of time and frequency is chosen and then, used periodically, without further decision making, for a certain time interval. As the presence of a cellular network is not always guaranteed for vehicular users, C-V2X defines transmission and resource allocation modes that may occur over the cellular network or autonomously by the vehicles. These modes are defined as follows [19]:

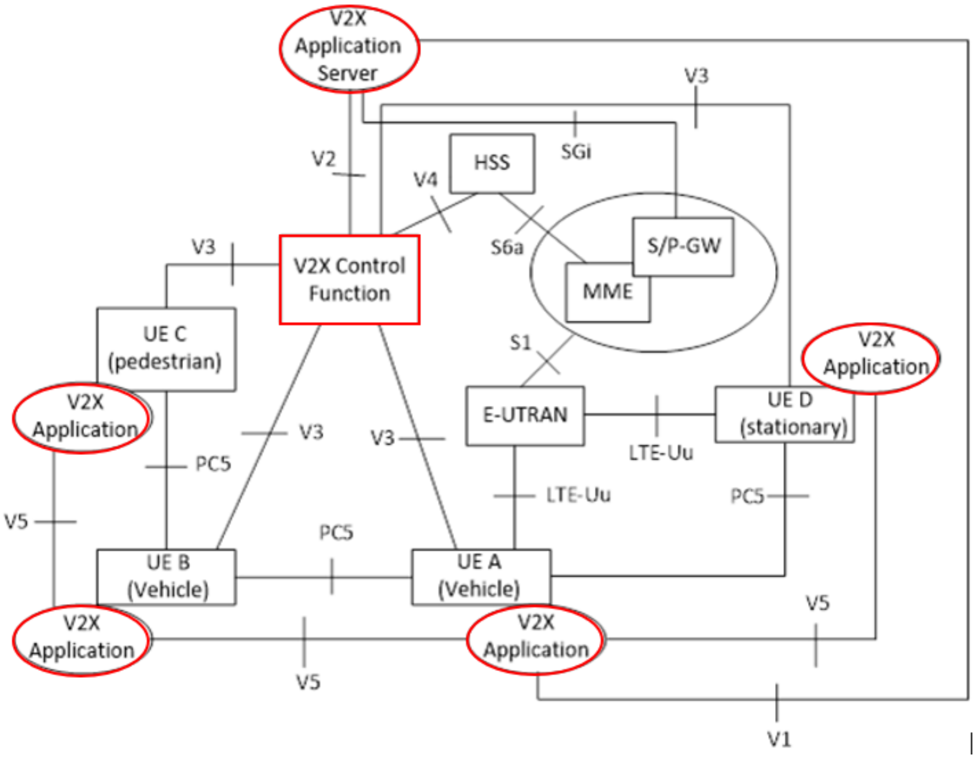


Figure 5: LTE-V2X functional architecture as defined in 3GPP TS 23.285 [20]

C-V2X Sidelink – Mode 3

In C-V2X sidelink mode 3, allocation of resources for sidelink transmissions is handled by the eNB, even though transmissions occur in V2V mode (i.e., they don't go through the eNB). Naturally, this mode is defined for scenarios where eNB coverage is available. The C-V2X sidelink mode 3 uses the following notable mechanisms.

- *Semi-persistent scheduling*: Like in LTE-Uu, eNB supports semi-persistent scheduling for C-V2X mode 3.
- *UE-report based scheduling*: UEs can report their observations on their radio environments to assist the eNB in sidelink resource allocation.
- *Cross-carrier scheduling*: If an operator has two or more carriers at its disposal, the eNB can schedule resources on one of the carriers for sidelink transmissions over the other carrier(s).

C-V2X Sidelink – Mode 4

UEs outside cellular coverage can use C-V2X sidelink mode 4, whereby UEs reserve resources autonomously using the resource reservation algorithm. This resource reservation algorithm requires each UE to sense the channel for 1 second and process the sensing results in order to ensure that neighbouring UEs pick and reserve orthogonal (in time, frequency or both) resources semi-persistently, thereby minimizing packet collisions. This is the only option working in "out-of-coverage" conditions (e.g., urban canyons, tunnels), while it also avoids heavy control load over the LTE-Uu interface. Finally, it overcomes complications due to handover between cells and between networks belonging to different operators.

2.1.1.2 Rel. 15/16 NR-V2X

NR-V2X inherits its key features from the 5G NR [2], while targeted V2X enhancements make it more suitable to address the needs of the challenging VANET applications. The frame structure of 5G NR allows flexible configurations for enabling the support of a majority of C-V2X use cases. Similar to LTE, 5G NR uses orthogonal frequency-division multiplexing (OFDM) whose performance is sensitive to inter-carrier interference (ICI) incurred by carrier frequency offsets and Doppler spreads/shifts. The maximum channel bandwidth per NR Carrier is 400 MHz compared to 20 MHz in LTE [21].

To what concerns the Sidelink (PC5), the main modifications/upgrades of NR-V2X compared to LTE-V2X are the following [18]:

- The communication scope is extended to ***unicast*** and ***groupcast***, besides broadcast that was the focus of C-V2X, to let a transmitting UE target a single receiver and a specific sub-set of UEs in the surroundings, respectively.
- For the aforementioned types of communications, reliability is improved through the definition of the ***Physical Sidelink Feedback Channel (PSFCH)***, which enables feedback-based retransmissions, instead of the blind ones allowed by C-V2X.
- Support for extreme ***low-latency transmission of aperiodic traffic*** through the replacement of the long-term sensing which characterizes Mode 4 with a short-term sensing whenever aperiodic traffic needs to be exchanged.
- Similar to LTE-V2X, NR-V2X primarily uses the 5.9 GHz band, which has been allocated worldwide for automotive use. In addition, ***frequencies above 6 GHz*** are exploited for NR-V2X to accommodate bandwidth-hungry V2X applications.
- Contrarily to the fixed spacing between subcarriers used in C-V2X, NR-V2X supports ***scalable Sub-Carrier Spacing (SCS) and TTI duration***.
- Transmissions are no longer bounded to the subframe duration. NR-V2X allows a UE which has only a small amount of data to send, which can be accommodated in less than 14 OFDM symbols, to occupy only the required number of symbols, the so-called ***mini-slots***.

Compared to the LTE ***numerology*** with subcarrier spacing of 15 kHz, the NR frame structure supports multiple subcarrier spacings including 15, 30, 60, 120, or 240 kHz. A small subcarrier spacing could be configured for V2X use cases requiring high data rates but with low/modest mobility, while a large subcarrier spacing is of particular interest for the suppression of ICI in high mobility channels. In terms of coding, unlike LTE, which uses convolutional and Turbo codes, two capacity-approaching channel codes have been adopted in 5G NR: low-density parity-check (LDPC) codes and polar codes. While the former is used to protect user data, the latter is for control channels in eMBB and URLLC which require ultra-low decoding latency [21].

Like C-V2X, NR-V2X defines two sidelink modes. The NR-V2X sidelink ***mode 1*** defines mechanisms that allow direct vehicular communications within gNB coverage. In this mode, the gNB allocates resources to the UEs. The NR-V2X sidelink ***mode 2*** (similar to LTE-V2X mode 4), on the other hand, supports direct vehicular communications in the out-of-coverage scenario.

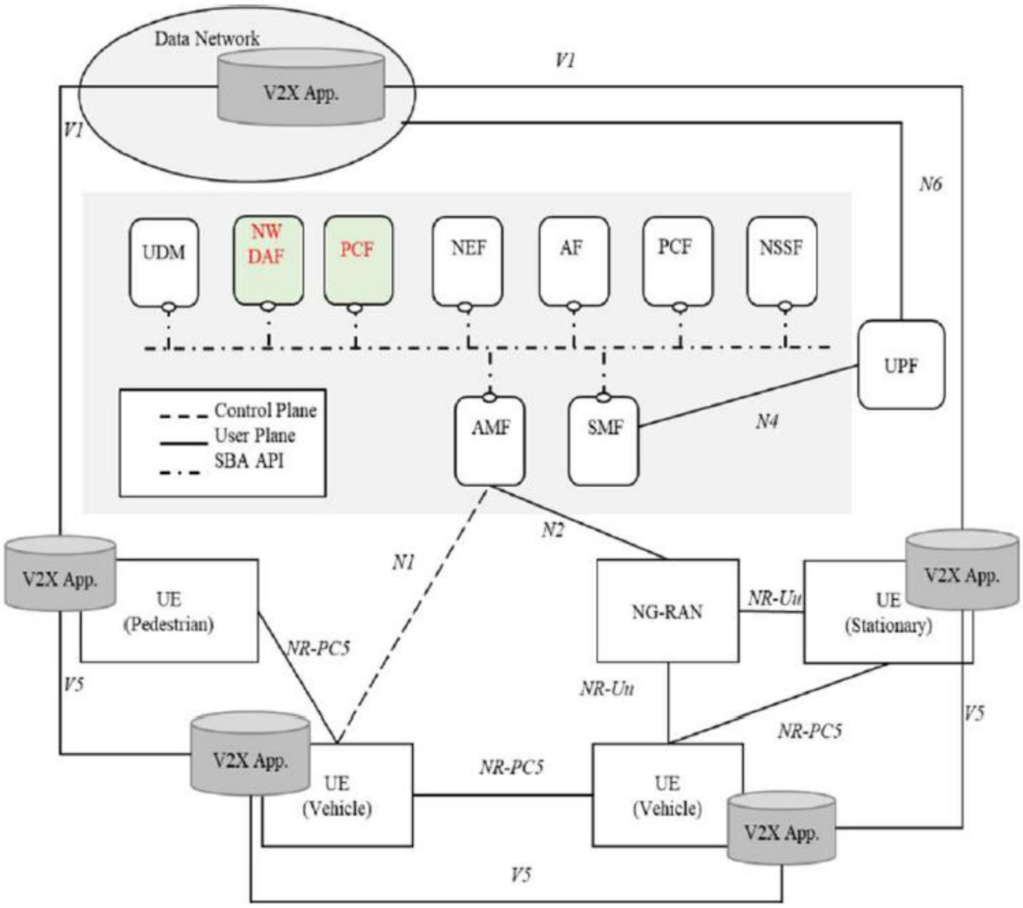


Figure 6: V2X Release 15/16 architecture within 5G system architecture [22]

Besides the traditional slot-based scheduling which is supported in LTE-V2X, NR-V2X also supports ***mini-slot scheduling***, where UEs that have latency-critical messages to send can start their transmissions at any of the 14 OFDM symbols and can occupy any number of OFDM symbols within the slot. Furthermore, slot-aggregation, i.e., combining two or more slots to form a multi-slot, is also supported in NR-V2X to cater to use-cases that require exchange of large-sized packets. Furthermore, the multiplexing in time of the Physical Shared Control Channel (PSCCH) and the Physical Sidelink Shared Channel (PSSCH) is supported in NR-V2X, to accommodate messages with tight latency requirements [19].

In general, the additional features and characteristics inherited from 5G NR, allow NR-V2X to be a much more flexible technology, capable of supporting BSM as well as messages with more stringent requirements for advanced VANET use cases. The NR-V2X architecture and the relationship of the various components with the established 5G system architecture components is shown in Figure 6.

Table 1 provides a comparative overview of the key LTE-V2X and NR-V2X characteristics.

Table 1: Key LTE-V2X and NR-V2X characteristics [21]

Features	LTE-V2X	NR-V2X
Subcarrier Spacing	15 kHz	15 kHz
Carrier Aggregation	Up to 32	Up to 32
Channel Bandwidth	20 MHz	400 MHz
Latency	< 10 ms	< 1 ms
Reliability	95-99%	99.9-99.999%
Channel coding	Turbo	LDPC, Polar
Network Slicing	No	Yes
Modulation	64-QAM	256-QAM
Communication Type	Broadcast only	Broadcast, Multicast, Unicast
Retransmission	Blind	PSFCH
Security and Privacy	Basic	Advanced
Positioning Accuracy	> 1 m	0.1 m

2.1.2 IEEE 802.11

The 802.11p or DSRC standard has been in the works for decades and was the first communication protocol designed specifically for vehicle-to-vehicle communication. IEEE based the design of the early 802.11p version on their successful Wi-Fi standards (e.g., 802.11a) for ad-hoc communications, while specific improvements adjusted the PHY and MAC layers to be more suitable for the high mobility vehicular environment. The IEEE 802.11 standards are very good for ad-hoc, low-cost vehicular communication in low velocity and low-density conditions. Due to the inherited Wi-Fi congestion mechanisms though, their weak points seem to be the operation in high density and high velocity conditions. As these protocols are not infrastructure-based, the communication range has been a traditional challenge for them. The rest of this section provides key information regarding the key features of the 802.11p standard, as well as its evolution and main upgrades imposed during its transformation to the more concurrent 802.11bd standard.

2.1.2.1 802.11p

The IEEE 802.11p standard supports wireless access in vehicular environment of Vehicular Ad-hoc Networks (VANETs) and provides communication for secure and non-secure applications for vehicles on the road. 802.11p is the foundation of the ITS-G5 standard and supports the Geo Networking protocol for V2X communication. Basically, DSRC/ITS-G5 can implement QoS management requirements for VANET applications. DSRC is supported by the US National Highway Traffic Safety Administration (NHSTA), which estimates that V2X-enabled security applications can eliminate or mitigate the severity of up to 80% of non-damaged faults, including collisions at intersections and lane changes. The IEEE 802.11p standard was first proposed by the Federal Communications Commission (FCC) in 1999 and finalized in 2009. However, V2X equipment must be universally installed in automotive and road infrastructure to make V2X effective. NHSTA issued a notice in December 2016 requiring all new light vehicles to use V2V communication. The recommendation also points out the requirement for V2V communication performance which can exchange the bidirectional basic safety message (BSM) by using the onboard DSRC equipment, including the speed, direction, braking state of the vehicle and other relevant information about nearby vehicles [23].

The PHY and MAC layers of 802.11p are largely derived from IEEE 802.11a. Traditionally, Wi-Fi standards have been developed for low mobility applications. However, since DSRC was designed for vehicular networks characterized by high mobility, enhancements were introduced to make it suitable for such environments. DSRC uses an OFDM-based PHY with a channel bandwidth of 10 MHz. As a result, compared to Wi-Fi, DSRC sub-carrier spacing is reduced by a factor of two. The MAC protocol used in DSRC is Carrier Sense Multiple Access (CSMA). However, there is no exponential back-off in DSRC, i.e., the parameter Contention Window used in contention-based MAC protocols remains fixed in DSRC due to two main reasons [19]:

i. because DSRC is designed mainly for broadcast-based systems, there is no acknowledgment frame sent back to the transmitter.

ii. exponential back-off can lead to large Contention Window sizes, thereby leading to high latencies.

2.1.2.2 802.11bd

The 802.11p standard derived its PHY and MAC layers from 802.11a. Since then, however, 802.11a has given way to its successors i.e., 802.11n and 802.11ac. Considering that 802.11p was developed nearly two decades ago, advanced PHY and MAC techniques introduced in 802.11n/ac and even 802.11ax can be leveraged to enhance 802.11p. With this objective, the IEEE 802.11 Next Generation V2X Study Group was formed in March 2018. After an initial feasibility study, the IEEE 802.11bd Task Group was created in January 2019 [19]. The primary design objectives of 802.11bd include support for:

- At least one mode that achieves twice the MAC throughput of 802.11p with relative velocities up to 500 km/h.
- At least one mode that achieves twice the communication range of 802.11p.
- At least one form of vehicle positioning in affiliation with V2X communications.
- Interoperability: 802.11p devices must be able to decode (at least one mode of) transmissions from 802.11bd devices, and vice-versa.
- Coexistence: 802.11bd must be able to detect 802.11p transmissions and defer channel access, and vice-versa.
- Backward compatibility: At least one mode of 802.11bd must be interoperable with 802.11p.
- Fairness: In co-channel scenarios, 802.11bd and 802.11p must get equal channel access opportunities.

In order to address the above-mentioned requirements, the following mechanisms were introduced in the 802.1bd standard [19].

<u>**Alternate OFDM Numerologies**</u>

To increase the OFDM efficiency, TGbd is exploring the use of narrower OFDM numerologies (i.e., sub-carrier spacing) such that the number of sub-carriers is increased while still occupying a 10 MHz channel. These options include twice the down-clock with 64 sub-carriers, four times the down-clock with 128 sub-carriers, and eight times the down-clock with 256 sub-carriers. This mechanism contributes to the increase of the OFDM efficiency, i.e., the ratio of useful symbol duration over the total transmission time.

Re-transmission

An adaptive re-transmission scheme is proposed by the TGbd, where decisions to re-transmit a frame and the number of re-transmissions is based on the congestion level. This scheme makes use of legacy preamble fields such as Legacy Short Training Field (L-STF), Legacy Long Training Field (L-LTF) and Legacy Signal (SIG), meaning that both 802.11p and 802.11bd can benefit from this mechanism to increase their reliability.

Midambles

TGbd has instantiated the use of "*midambles*" in 802.11bd, which are similar in form and function to the preamble except for their location within the frame, to combat the receiver's inability to decode a frame due to channel variations within the frame duration. The preamble, which is at the beginning of the frame, is used for initial channel estimation. However, for fast-varying channels, the initial estimate may quickly become obsolete. In case of fast-varying channels, the initial channel estimate obtained using the preamble may only be valid during the transmission of the first data sub-frame. Thus, if the same channel estimates are used to decode data sequences after Data_1 (see Figure 7), the probability of erroneous reception will increase. Midambles, which are introduced in-between the OFDM data symbol with appropriate frequency, help in channel tracking so that accurate channel estimates are obtained for all data symbols. The frequency of midamble insertion depends on factors like modulation, error control, Doppler spread, etc. Figure 7 shows the use of midamles in 802.11bd.

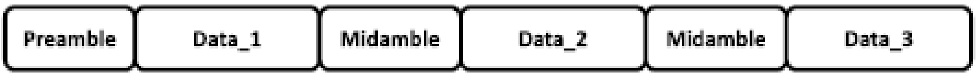


Figure 7: Use of midambles in 802.11bd for improved channel estimation [19]

Dual carrier modulation

Dual Carrier Modulation (DCM) includes transmitting the same symbols twice over sufficiently far-apart sub-carriers such that frequency diversity is achieved. Because each symbol transmission is repeated over two different sub-carriers, the modulation order must be doubled (e.g., from BPSK to QPSK) to maintain the throughput. Despite the increase in modulation order, DCM can help improve the block-error-rate (BLER) performance. Additionally, DCM has the potential to improve the range. The DCM technique was adopted from 802.11ax.

Besides the above-mentioned mechanisms, 802.11bd includes a few more upgrades such as the use of LDPC codes and multiple transmit/receive antennas, the use of a 20MHz channel access mechanism (increased from 10 MHz in 802.11p), the use of mmW frequency bands (26 GHz – 60 GHz) for increased spectrum availability and multi-channel operations to accommodate vehicles with multiple radio devices. Table 2 provides an overview of the key updates in the main characteristics of the 802.11bd technology compared to its predecessor.

Table 2: 802.11p vs 802.11bd key characteristics [19]

Features	802.11p	802.11bd
Radio bands of operation	5.9 GHz	5.9 GHz & 60 GHz
Channel coding	BCC	LDPC
Re-transmissions	None	Congestion dependent
Countermeasures against Doppler shift	None	Midambles
Sub-carrier spacing	156.25 kHz	312.5 kHz, 156.25 kHz, 78.125 kHz
Supported relative speeds	252 km/h	500 km/h
Spatial streams	One	Multiple

2.1.3 3GPP based HO procedures

The main 3GPP document describing 5G's System architecture is the Technical Specification (TS23.501)[2], which includes the architecture and description of the Radio Access Network (RAN) and Core functions, while TS23.502 [3] describes the main procedures of 5G, including session management and HO procedures. The fundamental HO procedure as defined by 3GPP can be seen in Figure 8. The HO process is triggered when one of the periodic *measurement reports* that the UE sends to its Serving gNB (SgNB) indicates that the signal strength towards the SgNB is deteriorating while the signal strength towards a neighbouring gNB (Target gNB a.k.a. TgNB) is improving. As a result the SgNB understands that the UE will soon be out of its coverage range, and issues a HO request towards the TgNB, informing it about the imminent "arrival" of the particular UE within its coverage range. At that point, and assuming that the TgNB has enough capacity left to serve the UE under discussion, the HO procedure is triggered. The main components that comprise the HO Interruption Time (HIT) caused from the HO procedure, are also depicted in Figure 8. Those components are:

- *Time to Break (T_{break}):* Time required for the UE to break its connection with the SgNB.
- *Time to Process (T_{proc}):* Time required for the UE to process the HO command and perform the reconfiguration of its Radio Resource Control (RRC layer).
- *Interruption time ($T_{interupt}$):* Time required for the UE to synchronize to the Target gNB (TgNB) and attach to it.
- *Time to perform RACH (T_{RACH}):* Time required for the UE to perform the Random Access Channel (RACH) procedure in the TgNB.
- *Time to complete HO (T_{HC}):* Time required to acknowledge the newly established connection towards the TgNB.

As it can be seen from the analysis performed in [24] and from other literature[14][25], the average HIT is estimated to be ***49.5 ms***. Leading to a similar service interruption time. Such an interruption can easily be handled by most non-critical applications as their latency requirements are not that stringent and the respective user will not even notice it (i.e. the Quality of Experience -QoE- will remain unchanged).

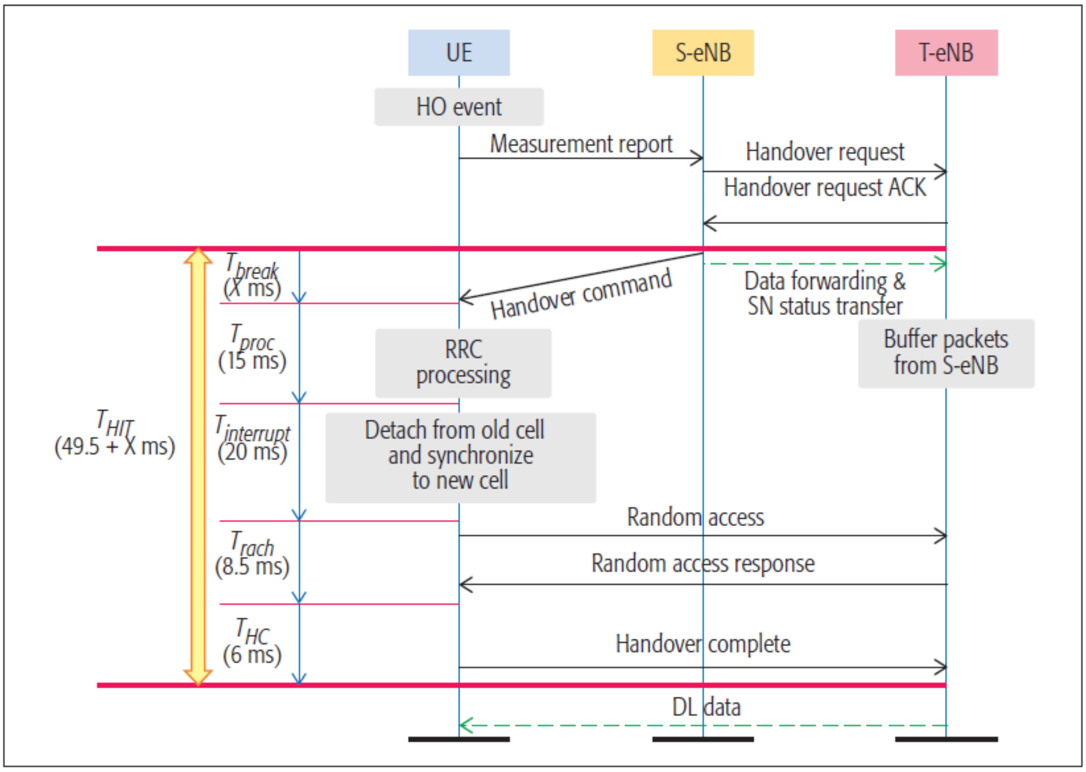


Figure 8: 3GPP HO procedure and HO interruption time [24]

It has to be noted that the HO depicted in Figure 8 describes an intra-MNO / inter-gNB HO, meaning that the UE changes its network attachment point between two gNBs belonging to the same network operator. There are however different types of HO that may occur due to user mobility and they are analysed in [26] and depicted in Figure 9. The different categories of HO depend on which gNBs the serving and target cell belong to, as well as the type of interconnection existing between the two gNBs. As the 5G network architecture is hierarchical two gNBs may be interconnected via the same Access and Mobility management Function (AMF - NG-C interface) or via the same User Plane Function (UPF – NG-U), while eventually all mobility-based updates will go through the Session Management Function (SMF – NG4 or NG11 interface). The "further away" the common attachment point of the SgNB and the TgNB is, the larger the HIT that can be expected.

A promising new feature that has a significant potential of improving the overall HO procedure has been defined by 3GPP, however it is not commercially available in the early releases of 5G networks (i.e. Rel.15 NSA networks that are being currently rolled-out). This feature is called Session and Service Continuity mode 3 (SSC mode 3) and is defined in [2] as follows: "*For PDU Session of SSC mode 3, the network allows the establishment of UE connectivity via a new PDU Session Anchor to the same data network before connectivity between the UE and the previous PDU Session Anchor is released. When trigger conditions apply, the network decides whether to select a PDU Session Anchor UPF suitable for the UE's new conditions (e.g. point of attachment to the network).*". What this practically means is that the UE may follow a Make Before Break (MBB) mechanism and establish a new connection with the TgNB before releasing the connection to the SgNB (also termed as soft HO). Such a solution could potentially even allow for a 0 ms HIT, but it requires the UE to be capable of maintaining multiple connections at the same time (i.e. to have multiple Tx/Rx antenna chains). This feature has not been validated yet in the field, so its real-life performance remains unknown.

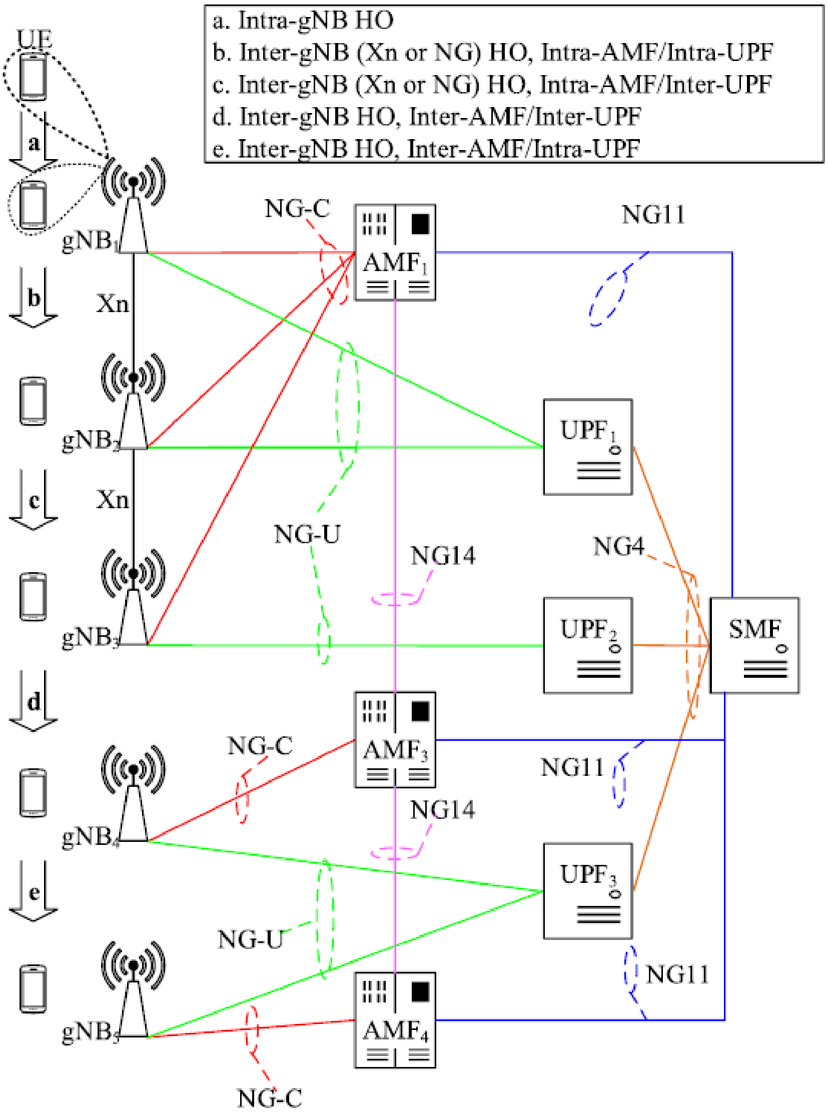


Figure 9: 5G-NR mobility architecture along with relevant interfaces and HO use cases [26]

It can be observed that the inter-MNO HO has not been addressed at all, as it presents the biggest challenge in terms of HO procedures, due to the fact that the SgNB and the TgNB would have no common network attachment point, as they belong to different networks. The inter-MNO HO takes place over whatever interface is available between the networks of the two neighbouring gNBs. Most commonly MNOs of different countries are interconnected via a GPRS Roaming Exchange (GRX) and/or IP Exchange (IPX) interface which steers the data traffic via a third party GRX /IPX operator, which could be located even further away (e.g. the data between a Greek and a Turkish operator may be routed through a GRX hub located in Germany). As it can be understood, the HO delays that are experienced in such cases are in the order of hundreds of milliseconds or even seconds. Certain alternatives to improve this situation exist, such as a direct interconnection between operators or the implementation of a Local Break-Out (LBO) technique, however with limited applicability and scalability due to their increased costs. Even the SSC mode 3 might not be suitable for these type of scenarios as its prerequisite for the two gNBs to "*belong to the same data network*" is violated.

Based on the above analysis, it becomes evident that there are still multiple open challenges regarding the optimisation of the HO procedure and the entire mobility management within 5G networks, while the inter-MNO / inter-PLMN HO is still a significant bottleneck when trying to provision URLLC and CAM services across borders.

Analysis of Rel.15 & Rel.16 roaming schemes

For the 3GPP community, the first full set of standards for 5G cellular communications is part of 3GPP Rel.15, which aims to introduce a 5G new radio (5G NR) system complemented by a next-generation core network that are both designed to address the IMT-2020 requirements of ITU[27]. To better cope with the demand from some of the network operators and vendors for an expedited delivery of 5G services, the initial set of 3GPP Rel.15 specifications were built on existing LTE networks in the form of a "Non-Stand Alone (NSA)" architecture for the early drop in December 2017 before the "Stand Alone (SA)" system was finalized in June 2018. While 3GPP Rel.15 focuses on enhanced Mobile BroadBand (eMBB), the first stage of 3GPP Rel.16 which is called "5G Phase 2" tackles the problems associated with decreasing latency and increasing the number of machines/things in a confined region, namely the Ultra Reliable Low Latency Communications (URLLC) and massive Machine-Type Communications (mMTC) pillars of the IMT-2020 standards. The URLLC feature in particular is of special interest for all automotive applications with stringent latency requirements.

The 3GPP technical report TR 38.801 [28] on radio access architecture and interfaces indicates that the new RAN architecture may consist of gNBs and/or eNBs that provide 5G NR and Evolved-Universal Terrestrial Radio Access (E-UTRA, i.e., 4G) terminations towards UEs, respectively. The new core network defined in 3GPP Rel.15 is the 5G Core Network (5GC), but the standards include several options to allow connectivity to the legacy evolved packet core (EPC), as well. In total, eight options are discussed to cover all possible scenarios, where this number increases more with variants of these options[29]. Non-standalone (NSA) options are those deployment configurations, for which the gNB/eLTE eNB (i.e., 3GPP Rel.15 and beyond eNB) requires an eLTE eNB/gNB as an anchor for control plane connectivity to the EPC/5GC. Standalone (SA) options are characterized by having only a single type of base station connecting to a core network.

The most widely targeted initial deployment option for operators is option 3x for the NSA mode and option 2 for the SA mode, and they are depicted in Figure 10. In **NSA option 3x**, the data bearer is forwarded from both eNB and gNB while all signalling is anchored from the eNB to the EPC. In **SA option 2** a pure 5G network is deployed, having the gNBs connected directly to the 5GC. The advantage of option 2 is that it has significantly less impact and interdependency on the legacy networks, namely the LTE radio access network and the EPC, and it is deemed a final version of the 5G architecture, but where a new core network and 5G UE support is necessary.

The goal of 3GPP Rel.16 (frozen in Q2 of 2020) is to bring overall system advancements to the "5G Phase 1" as well as functions relevant for addressing the specific communication needs of vertical sectors. One of the verticals directly targeted by the 3GPP is the automotive sector, and 5G-supported vehicle-to-everything (V2X) communications considers advanced scenarios that are beyond what is possible with LTE-based V2X, primarily in the area of low latency use cases. The general 5G System architecture for 3GPP Rel.16 is specified by the 3GPP SA2 Group in TS 23.501 [2] while the 3GPP document TS 23.287 [4] targets the 5G system architecture enhancements required to support V2X services in 3GPP Rel.16. The latter specification will largely be based on the 3GPP technical report, TR 23.786 "Study on architecture enhancements for Evolved Packet System (EPS) and 5G System to support advanced V2X services"[6].

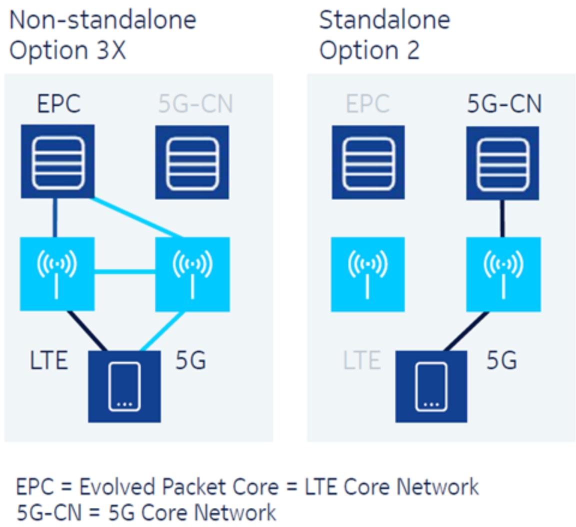


Figure 10: 5G deployment scenarios – option 3x (NSA) and option 2 (SA)

For 5G NSA (3GPP Option 3x) two interfaces are used as roaming interfaces that interconnect the related entities of MNOs. The first one is S6a and the second one is S8. A third interface, S10 may be introduced in certain cases as an additional roaming interface, so that context information of active session is exchanged between two MMEs during handover. The handover procedure will fail, and the UE will be detached from the network, if the S10 interface is not configured. S6a is used for interconnecting MME of V-PLMN with the HSS located in H-PLMN, while S8 is used for signalling and data transfer between SGW/PGW entities.

In 5G Core Specification for 5G SA deployments (3GPP Option 2), the session service continuity (SSC) mode for an application is determined by SSC mode selection policy. With SSC mode 3, the network ensures that the UE does not lose connectivity by making a new connection before breaking the existing one to allow service continuity and this is the most appropriate mode for the seamless roaming. The service provider may provision the policy rules for UE to determine the type of mode associated with an application or a group of applications. This type of service continuity is highly desirable for CAM vehicles realizing advanced functionalities while roaming and is not easily achieved with NSA architecture.

2.2 HO challenges & approaches overview

The authors in [14] attempt to take an end-to-end look at providing URLLC services throughout the life of a 5G session and propose some enhancements to the existing ***Mobility Management (MM)*** procedures. Despite the fact that the information is a bit outdated (2016), the authors touch upon some important aspects of supporting E2E URLLC services as they argue that the entire slice, including ***Application placement and functionality, core functionality placement, mobility anchor optimization, HO process optimization and user plane gateway relocation*** has to be specifically configured to serve this type of services. In this work, there is no attempt to minimize the Handover Interruption Time (HIT), as the HO Detach time (from HO Command from the Serving gNB (SgNB) to HO confirmation from Target gNB (TgNB)) is taken for granted and treated as the lower latency limit that all other network SW/HW have to try and match. Instead, solutions for performing all other necessary tasks within the HO detach time (in order not to waste any more time) are offered.

The Mobility Management Enhancements proposed in [14] include a ***topology aware control plane*** aiming at the selection of the optimal mobility anchor, ***user plane switching*** taking place during the HO detach time, ***more frequent gateway relocations*** (reevaluation of mobility anchor for every HO) and optimal location of application instances to the closest edge nodes as well as ***state information transfer among application instances*** for stateful applications. Despite the fact that the current HIT (~49.5 ms) is treated as the absolute minimum for a HO delay, this article provides a nice overview of all aspects that need to be considered for the provision of seamless mobility to a URLLC user.

In [26] a detailed survey of Handover (HO) Management techniques in 4G (LTE) and 5G from recent bibliography is presented and highlights the main differences in the most common HO scenarios, while also making an overview of open HO management challenges and the various proposed enhancement methods. By taking into account a large variety of metrics such as the ***HO Failure (HOF)*** rate, the ***HO success rate***, the ***HO Interruption Time (HIT)***, the ***frequency of HOs***, the ***HO delay***, the ***Ping Pong (PP) rate***, the ***HO energy*** consumption, the increased ***HO overhead***, the users overall perceived ***QoS/QOE*** and more, all the reviewed HO techniques are categorized according to their approach and an overview of their pros and cons is provided. Additionally, the soft (***make-before-break***) and hard (***break-before-make***) HO approaches are compared and their application in 5G is discussed with their respective pros & cons, while different types of HOs, namely ***Intra/Inter-Frequency, Intra/Inter-cell layer, Intra/Inter-RAT and Intra/Inter-Operator***, are also analysed.

The authors of [26] identify the following main challenges and research directions for HOs in a Heterogeneous Network (HetNet) environment:

- High signalling overhead associated with HOs, mostly due to the ***HO Measurement Reports (MR)*** transmitted by the UE
- Configuration and optimization of HO parameters such as ***measurement gap, Time To Trigger (TTT), Hysteresis thresholds, A3 offset, L3 filter coefficient***, etc. in different cell layers (macro, pico)
- High frequency of inter-layer HOs due to the densification of 5G networks (ultra-dense networks with multiple pico cells)
- HO decision (and performance) affected by the inter-layer optimization of resource allocation load balancing and power control schemes.
- ***Inter-operator HOs*** remain a great challenge as MNOs would have to support other operator's frequency bands, interfaces, protocols, network elements, services, etc.
- ***Multi-connectivity*** is regarded as a promising solution to avoid service interruption and minimize HO latency; however it comes at a cost of increased signalling, complexity and power consumption.

Specifically addressing the HO management and mobility robustness in 5G NR, the authors of [26] identify three major challenges, namely i) the ***increased HOF*** due to the shrinking size of the cells, ii) the increased number of on ***intra/inter-frequency measurements*** affecting UE battery life and iii) the increased overheads due to ***frequent HOs in the mmW bands***, as beam mobility is an added factor in NR. However, 5G NR also possesses some inherent characteristics which help deal with some of these issues or diminish their impact. Such features include i) the ***INACTIVE UE state*** introduced in NR which reduces the transition time to the CONNECTED state and associated overheads and keeps better track of the UE mobility, ii) the possibility for a ***Supplementary UL (SUL)*** to extend the perceived cell coverage from a UE stand-point and reduce HOs and iii) the ***Dual Connectivity (DC)*** capability allowing UEs to be connected to a SgNB and a TgNB simultaneously, thus reducing HIT (potentially to 0 ms). The DC solution is also proposed as a feasible alternative in cases of high user mobility, *while it has also been proposed* in combination with a ***RACH-less approach*** to avoid Random Access CHannel (RACH) overhead towards the TgNB and skip the delay introduced by the RACH process.

Estimating the mobility of a UE and deriving the ***Mobility State Estimation (MSE)*** and ***UE location tracking*** have been used in a few proposed HO scheme improvements, employing predictions regarding the potential HO time and location of a UE and performing HO preparation at the TgNB , before a HO request arrives. Alternatively, in other proposed solutions the ***UL RS signal*** from a UE has been used to estimate the timing of a HO, thus avoiding the measurement and transmission overhead of a MR, while UE initiated HO has also been proposed. Some of the proposed solutions have indicated their potential to achieve a 0 ms HO (with no service interruption) in simulation environments (e.g. DC with RACH-less HO).

Finally, HO management in high-speed scenarios has been investigated where solutions such as ***group HO, mobile relays, mobile-cell, multi-connection and geo-aided fast HO*** have been employed to combat the additional challenges (e.g. large Doppler spread) of high-speed scenarios.

In [24] the authors provide an analysis of the challenges of providing a ***HO Failure (HOF)*** rate and ***HO Interruption Time (HIT)*** close to zero for high user mobility (~120 km/h). Based on 3GPP documentation and definitions it is indicated that the lower the achieved HIT the harder it is to guarantee a HOF below 10^{-5} in order to achieve the URLLC service requirements. A detailed breakdown of the HO process delays is provided where the HO process is broken down to its components and average values are provided per component based on real life measurements (on LTE networks). The components contributing to the HO delay are i) T_{break}: Delay between receiving the last data and receiving the HO Command, ii) T_{proc}: RRC processing delay, iii) $T_{interrupt}$: UE processing time incl. RF retuning, iv) T_{RACH}: RACH process delay for the TgNB and v) T_{HC}: delay to complete the HO, while their average values are given in Figure 8.

The 5G-NR HO process is actually quite similar to the LTE HO process and hence suffers from the same issues (Mobility Interruption Time and mobility robustness) and from the same latency components. Various mechanisms to minimize the above latency components are examined in [24], some of which are already part of 3GPP specifications since Rel.14 [30]. The ***Make Before Break (MBB)*** HO [30] where a connection with the TgNB is formed prior to releasing the connection to the SgNB has been shown to be able to reduce HIT by up to 35 ms, while the optimum timing of data forwarding from SgNB to TgNB should be precisely selected in order to reap the full results. The ***RACH-less HO*** [30] further reduces the HIT by skipping the Random-Access procedure towards the TgNB in case of synchronized networks or networks where the timing advance is zero. This mechanism could reduce the HIT by another 8.5 ms, with the additional challenge of provisioning the UL grant allocation to the UE at the exact right point. *The authors claim that a combined use of MBB and RACH-less HO can drop the HIT down to 6 ms, while if the TgNB could send the DL data to the UE without receiving the HO Complete command, that would reduce the HIT close to 0 ms*. The misalignment of subframe boundaries between the SgNB and TgNB is to blame for not being able to reach an absolute 0 ms of delay.

Additional solutions are examined including a 2 Tx/Rx MBB HO, which guarantees a 0 ms HO as the UE maintains a live connection with both base stations for a certain period of time. A ***Conditional HO (CHO)*** mechanism is proposed to improve mobility robustness where the HO preparation is network controlled but the HO execution is UE controlled. In this case the SgNB issues a HO preparation command towards the UE when the signal conditions are still good (avoiding a HOF due to RLF) and the UE triggers the HO execution when a certain threshold condition is met. A *HO Indication* is provided to both the SgNb and TgNB at this point to alert them of the pending HO. Multiple TgNBs can be considered in this solution increasing the chances of a successful HO but also increasing the overhead. Simulation measurements provided by the authors indicate the trade-off between low HIT and HOF rates (close to zero) and the PP occurrences (high PP visible) for HetNets with small size pico -cells. However, the results indicate that near-zero HIT and HOF are possible for highly mobile users with the proposed solution, while the ***UE measurement period*** is exposed as another critical factor for achieving these results.

2.2.1 Inter-operator (inter-PLMN) HO approaches

As mentioned before, little work has been done targeting the improvement of inter-MNO HO, however a few researchers have started touching upon this important issue. Perhaps the most prominent and relevant work on this field are two papers written by the same authors which present the original concept of an improved inter-MNO HO and its evolution and evaluation in [31] and [32] respectively.

In [31] a ***latency reduction mechanism in case of inter-operator HOs*** is proposed, which only requires UEs with a single Tx/Rx chain and is targeting time-critical messages (e.g. in case of V2X communication). The proposed solution addresses the V2X scenario where a stretch of road is covered by multiple operators (Op.A and Op.B) with regional splitting applied, i.e. kms 1-3 are covered by Op.A and kms 3-6 are covered by Op.B. In the addressed scenario if a vehicle covered by Op.A located close to the region border (between Op.A and Op.B) issues a time-critical message (e.g. break due to accident), then *vehicles close to the border area served by Op.B would be forced to switch serving networks to Op.A (forced HO) in order to receive the time-critical message* without the inter-operator transmission delays (intra-operator communication is faster than inter-operator communication). After the time-critical message is received the vehicles can be handed over back to their original serving operator (in this case Op.B). In order to increase the speed of this HO process, the devices are assumed to be matching the active times of the Discontinuous Transmission/Reception (DTX/DRX) process in the connected operator (e.g. Op.A) with the non-active times of the DRX process in the idle operator (e.g. Op.B), and vice versa. In principle, this would allow UEs with one Tx/Rx chain to transmit/receive via Op.A while listening in for messages in Op.B, but the SW/HW latency of RF re-tuning has not been properly taken into account.

The proposed solution is quite interesting, but it has some significant *drawbacks*. First of all, an almost complete coverage overlap between Op.A and Op.B is assumed, as UEs are expected to communicate with both operators seamlessly. This might be sufficient for cases of national roaming, but *it is not valid for international borders* where roaming conditions apply, and the overlap among neighbouring operators is close to zero (due to regulations). Furthermore, *the authors make extremely favourable assumptions for the evaluation of the proposed solution, without properly justifying them*. The solution is only evaluated for *non-critical CAM messages with a periodicity of 100 ms* (despite the opposite claim in the text), while *the values for the various latencies* for intra-operator (38-58 ms), inter-operator (58-78 ms) and HO delay (20 ms) are arbitrarily set by the authors and used as input for the simulations, instead of being the output of the simulations. As indicated by the rest of the bibliography an assumption of a 20 ms HO is extremely favourable. The above assumptions significantly diminish the credibility of the provided evaluation, while the proposed solution only seems applicable under very specific conditions.

The authors improve and elaborate on their work in [32] where the challenges of *inter-operator HO* are addressed in an effort to provide low E2E communication for CAM services, taking *national roaming / regional split* as the main driver behind this research. The authors identify the 3GPP based E2E latency requirements for various CAM services ranging from 100 ms (non-critical) down to less than 10 ms (critical) as well as the expected latency for the communication of a critical message between different MNOs, which is set at 20 ms [5], and propose a scheme which would facilitate and reduce the latency in inter-operator communications. The selected *Regional split* scenario addresses multi-operator functionality in the same area where a split between the serving areas of the two MNOs is enforced, i.e. in a specific area all vehicles are served by the same MNO irrespective of the MNO they have a subscription with, as depicted in Figure 11. This approach presents certain advantages such as ***i)*** simplifies the multi-operator environment limiting the HO events to specified HO areas between the operators, ***ii)*** vast majority of communications will be intra-operator, ***iii)*** Local Break-Out (LBO) is enabled when serving all vehicles from the same MNO's network, ***iv)*** no common spectrum resources needed among MNOs, thus simplifying spectrum management as well, ***v)*** more cost efficient operation as only UEs with a single Tx/Rx chain are needed and ***vi)*** the selection of the artificial inter-operator border may be optimized and dynamic to increase the performance experienced by users (i.e. select a low traffic segment, with direct Line of Sight (LoS) to gNBs of both operators).

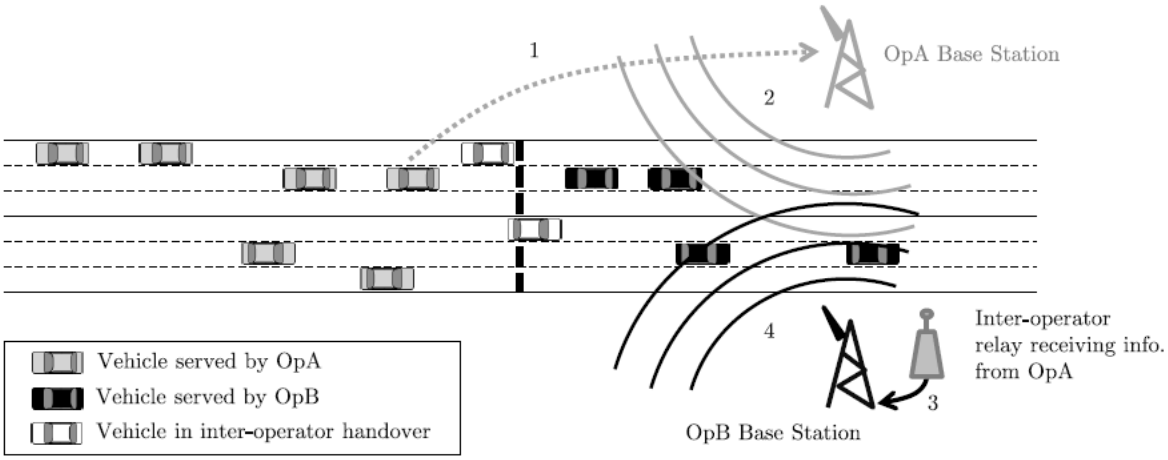


Figure 11: Illustration of the proposed approach in [32] including an inter-operator Relay

The proposed solution of this paper, whose *main goal is to reduce the latency of inter-operator communications especially for time-critical messages*, is comprised of two parts. First an advanced inter-operator HO scheme is proposed based on pre-registration to the V-PLMNs, decreasing the total inter-operator HO time and secondly a MEC approach is proposed for all participating gNBs bringing the ITS functionalities closer to the users. More specifically, the authors propose *three new network entities* (could be housed in existing network functions) in order to achieve a fast inter-operator HO. First a *Mobility Server* is needed (role could be played by the AMF[5] or SMF[6] in 5G) tasked with bearer activation and deactivation and authentication, secondly a *Subscriber Server* is needed tasked with requesting the attachment of a specific UE to other MNOs and thirdly a *Mobility Server Gateway* is needed in each participating operator in order to receive the attachment messages from the Subscriber server of the Home-PLMN (needed for obfuscating the underlying network topology). Using these entities, a mobile user may be pre-registered in all participating operator's networks (request sent by subscriber Server of H-PLMN), thus saving the tim*e for network re-attachment during inter-operator HO.* As Single Cell – Point to Multi-point (SC-PTM) broadcasting scheme is assumed as the main communication strategy, a further enhancement is proposed in order to eliminate the delays introduced by the MBMS gateway and other broadcasting entities, which includes a local application server, a local broadcasting system and a new node called *inter-operator Relay*, to be housed in MECs in all participating gNBs. The inter-operator Relay is an additional measure to reduce the E2E latency of critical messages, as critical messages transmitted by e.g. Operator A or Base Station A are captured by the relay which is attached with fibre to Operator B or Base Station B, and are hence quickly retransmitted by operator B as well or by Base Station B.

In order to evaluate their proposed solution, the authors in [32] perform a literature survey to identify the latency components contributing to intra and inter operator HOs, both in the UL (UE→ gNB→Serving Gateway→PDN Gateway→ITS server) and the DL (ITS server→BM-SC[7]→MBMS

[5] Access and Mobility Management Function
[6] Session Management Function
[7] Broadcast Multicast Service Center

Gateway→gNB→UE). The outcome of their survey has resulted in the latency assumption mentioned in Table 3, which are used to numerically evaluate their proposed solution. Based on these values the authors arrive at the assumption that a typical intra-operator communication experiences an E2E latency of approximately **40 ms**, while an inter-operator communication (message transmitted by UE served from Op.A and received by UE served by Op.B) experiences a latency of approximately **60 ms**, including sub-frame alignment delays (no scheduling delays are assumed as critical messages get prioritized). Moreover, a service interruption of ***300 ms*** is assumed every time a transmitting or receiving UE is performing an *inter-operator HO*, based on input from [33], resulting in a worst case scenario E2E latency of ***660 ms*** (1 inter-MNO HO for the transmitter + 1 inter-MNO HO for the receiver + worse case message latency). An *intra-operator HO* on the other hand is assumed to impose a ***20 ms*** service interruption time

The authors perform an evaluation of their proposed scheme via numerical analysis and network simulations. Based on the numerical analysis outcome the authors claim that their solution significantly decreases the E2E communication latency experienced by automotive users in relevant scenarios as they show a decrease from 40 ms to 20 ms for intra-operator communication, from 60 ms to 26 ms for inter-operator communication and from 660 ms down to 66 ms in the worst case scenario (two inter-operator HOs included). The simulation results indicate more or less a similar performance, although also during the proposed solution implementation not all critical packets were delivered in time (reduced Packet Reception Ratio - PRR) depending on the exact scenario.

Table 3: Assumed Values for User Plane delay components [32]

Component	Value
t_{UL}	≥ 9 ms
t_{DL}	≥ 1 ms
t_{UE}	1 ms in transmission ($t_{UE \rightarrow TX}$) 4.5 ms in reception ($t_{UE \rightarrow RX}$)
t_{BS}	1 ms in transmission ($t_{BS \rightarrow TX}$) 1.5 ms in reception ($t_{BS \rightarrow RX}$)
$t_{BS \rightarrow \text{ITS Server} \rightarrow BS}$	20 ms
$t_{\text{ITS Server} \rightarrow \text{ITS Server}}$	20 ms

The work presented in [32] is definitely a good first attempt at analysing the challenges of inter-operator HO and their impact on automotive communication, accompanied by a detailed solution targeting the reduction of E2E communication latencies, *however the work also suffers from certain oversimplifications and flawed assumptions, that skew the evaluation results and/or make the solution non-universally applicable*. First of all, the proposed solution is only applicable in national roaming cases, where overlapping coverage of the gNBs of the two operators can be assumed. In actual cross-border conditions, where significant *coverage gaps* may exist among the two operators, such a solution would break down. Secondly, *the signalling and computational overhead* imposed by the proposed solution is very significant, making such an implementation unfeasible from a financial perspective. The constant signalling among all BSs of all involved operators (for mobility monitoring), and the constant registration of UEs that may never use the assigned resources, have not been properly evaluated. Moreover, the fact that a MEC node is assumed at *ALL* participating BSs acting both as an MBMS server and a localized ITS server, makes the proposed solution extremely expensive and the implementation extremely localized, forfeiting the benefits of a global ITS server view.

Besides the above-mentioned omissions, the latency assumptions used in this paper are very favourable in certain cases. Certain delay components have been completely disregarded such as the ITS server processing latency or the inter-operator processing latency, while the effect of mobility on the experienced SINR, QoS and the potential retransmissions that this may lead to, have also not been taken into account. Moreover, an immediate attachment of the UE to a Visitor-PLMN is assumed when a pre-registration has occurred, not taking into account any Random Access (RA) procedure delay for the UE to start communicating with the new BS and to receive its UL assignment allocation. Perhaps the most notable erroneous assumption is the fact that an intra-operator HO's duration is taken to be 20 ms, while as shown in section 2.1.3, a more accurate estimation for the minimum duration of an intra-operator HO has been placed at 49.5 ms through multiple sources and corroborated by measurements[34][24]. Finally, the performance evaluation via simulation is also unreliable, as the delay components of each type of HO were provided as input into the algorithm by the authors, instead of modelling the 5G network HO procedure according to 3GPP and extrapolating the actual HO latencies. The selection of skewed scenarios and improper modelling is also evident from the fact that in one of the used metrics, the currently used HO mechanism of 3GPP yields a result of 0% of successful delivery of critical messages, while the proposed solution yields a result of 100% of critical message delivery, thus impacting the credibility of the provided results.

Besides the HO latency there are other factors contributing to the E2E latency experienced by vehicular users (Vehicular UE - VUE) when changing 5G networks, such as the *service migration from one MEC server to another*, which is the subject under investigation in [35]. The authors highlight the importance of MEC deployment alongside 5G networks for proper CAM service provisioning, as it minimizes the amount of data traversing the core network and brings important functionalities closer to the vehicular users. However, as VUEs experience inter-PLMN HOs and change their network attachment points they will also have to change the Mobile Edge (ME) Host from the H-PLMN to one in the V-PLMN. Since such a service migration has the potential to cause additional service interruption, ETSI[8] has already proposed a *service pre-relocation* in [36] where vehicular application running on MEC take advantage of the estimated trajectory of the served VUE to relocate to the target ME host, before the actual MEC HO. The authors of [35] work towards a first implementation of this theoretical concept with a few proposed enhancements.

The proposed solution includes the concept of a *Virtual Vehicle (VV)* located at the MEC server acting as a digital twin of the actual VUE, i.e. collecting and storing all measured and received information from the UE. This VV complements the V2X Application at the VUE with additional functionalities (i.e. data analytics, aggregation etc.) and is deployed as a docker container just before the V2X Application Server (AS). Based on the VUE mobility pattern the *ME Orchestrator* may take the decision to relocate the VV from an origin ME host to a target ME host, in order to keep up with the requested QoS. Once such a decision is taken the target hosts needs to be decided as well as the migration timing in order to keep service interruption to a minimum. When the service migration is triggered, the VV at the origin ME host is deactivated while a *Data Volume (DV)* is created in order to buffer the data missed, until the VV can be re-activated in the target ME host. Once the VV is re-created (based on image files) at the target ME host, the DV transfers its buffered data to the new instance of the VV, at which point normal operation proceeds.

The timing of the service re-location procedure has to be exact, as early triggering will lead to the buffering of a significant amount of data from the DV which then need to be transferred to the VV, adding additional delay, while the late triggering of the process may result in the VUE handing-over from the origin ME host to the target ME host, before its VV is recreated. Some basic experimental results (Proof of Concept - PoC) indicate that indeed this solution can reduce the service migration time among MEC hosts. The actual RAN HO interruption time (HIT) has not been taken into account in this

[8] https://www.etsi.org/

study, however the MEC service migration time even with the proposed solution is in the order of seconds, making any discussion about the ms duration of service interruption caused by the RAN HO irrelevant. Nevertheless, the work presented in this paper is a good reminder of the fact that guaranteeing service and session continuity while performing an inter-PLMN HO, is a multi-aspect challenge which goes beyond RAN latencies.

2.2.2 HO based on multi-connectivity

To ensure service continuity while roaming, roaming agreements must be signed between operator networks to define the policies necessary to control network access for roaming subscribers and manage roaming services. Operator network connections must be established, and this can be achieved either directly or through a GPRS Roaming Exchange (GRX) or IP exchange (IPX) network as depicted in Figure 12.

- **Direct Interconnection** is simple and if established through private lines or VPNs (ex. MPLS) can solve QoS and security Issues. Nevertheless, it greatly increases cost especially if many international point-to-point private lines are necessary. It is noteworthy that using the Public Internet and establishing secure tunnels with IPSec can be regarded as a viable option for fulfilling pilot and prototype deployments' requirements, but not for carrier-class communications. Direct Interconnection is relevant to friendly operators with shared responsibilities.
- **GRX based Interconnections** are operated and managed by third parties. An MNO, through a GRX connection endpoint can be connected to multiple operator networks establishing corresponding roaming agreements and enjoys the service scalability offered through this point-to-multi point interconnection. Private lines do not need to be individually established, greatly reducing roaming costs. Nevertheless, GRX networks provide no QoS guarantee and typically leverage SS7 signalling focusing on the transmission of GPRS, EDGE, 3G, and HSPA roaming data and MMS service data.
- **IPX based Interconnections** is an evolution of the GRX framework towards an open and flexible environment and assumes an all-IP transformation better suited for LTE service requirements. MNOs need to find GRX services that can offer E2E SLA for future service growth and only GRX services provided by IPX networks can offer E2E SLA.

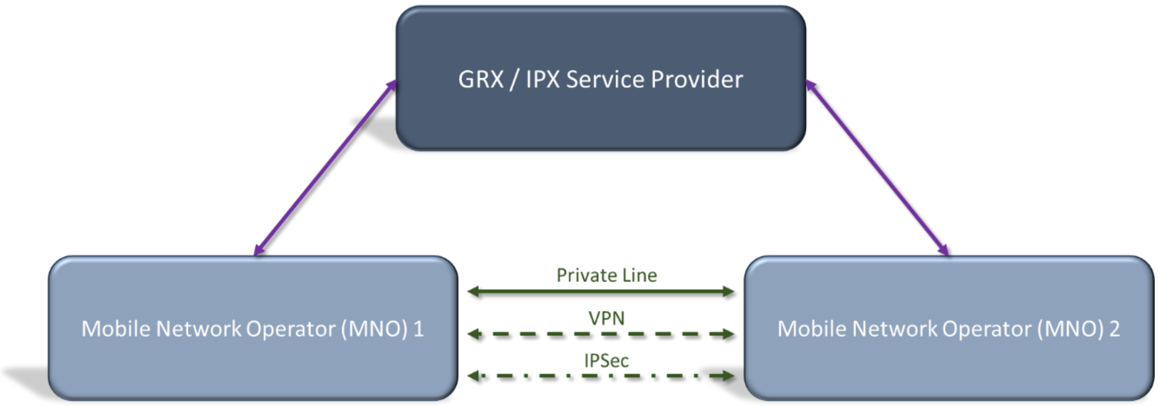


Figure 12: Roaming Interconnection Options

The concept of multiple connectivity or most often Double Connectivity (DC) has been proposed as a potential mitigation solution for the impact of HO on session and service continuity, multiple times. Such solutions tend to overcome the latency and service interruption issues at the expense of more complicated and expensive end devices which need to be equipped with multiple Tx/Rx chains to maintain communications with at least two base stations. The most prominent solutions employing the theme of DC are presented in this sub-section.

In [37] the concept of Dual/Multiple Connectivity is explored targeting a mobility with zero interruptions and zero failures. It is claimed (with no proper reference however) that *3GPP has even accepted the fact that in order to achieve a 0 ms HO a terminal (UE) with at least 2 Tx/Rx chains is needed, as a single Tx/Rx chain UE would have to detach from the SgNB before attaching the TgNB*. The authors propose modifications to the well-known Dual Connectivity 3GPP solution [38] (supported since Rel. 12) so that UEs can be attached to at least two gNBs at any given time and to maintain a live connection to at least one during HO, thus arriving to a zero interruptions/zero failures HO.

More specifically the proposed solution is comprised of the following steps: **i)** add one or more TgNBs to the candidate list for a Slave/Secondary gNB (SgNB) based on measurement reports (this should happen earlier than usual, i.e. add TgNBs even if they are currently worse than the serving MgNB), **ii)** the best candidate is nominated as SgNB and the UE moves in DC state (the SgNB can act as a backup), **iii)** as the UE moves towards the SgNB the roles of MgNB (Master gNB) and SgNB are swapped and **iv)** the former MgNB (now SgNB) is released when its signal becomes too weak (another gNB is selected as SgNB). The proposed solution is shown in Figure 13. In order to further optimize performance, the concepts of SRB duplication and SgNB survival are also proposed. The *Signaling Radio Bearer (SRB) duplication* means that the UE control messaging (DL & UL) is reported through both the MgNB and SgNB instead of only via the MgNB (MgNB forwards the control messages to SgNB and from there to the core network), which avoids RLFs. The *SgNB survival* scheme refers to the definition of a Radio Link Failure (RLF) in 5G. In 3GPP based DC an RLF is declared when the radio link to the MgNB fails, even if there is in place a high-quality radio connection to the SgNB. This results in the costly process of the UE entering Random Access (RA) process. In the proposed solution an RLF is not declared if a solid radio connection is in place with the SgNB as control and user-plane messaging may still continue with the network via the SgNB, thus avoiding the RA process. This is referred as the SgNB survival.

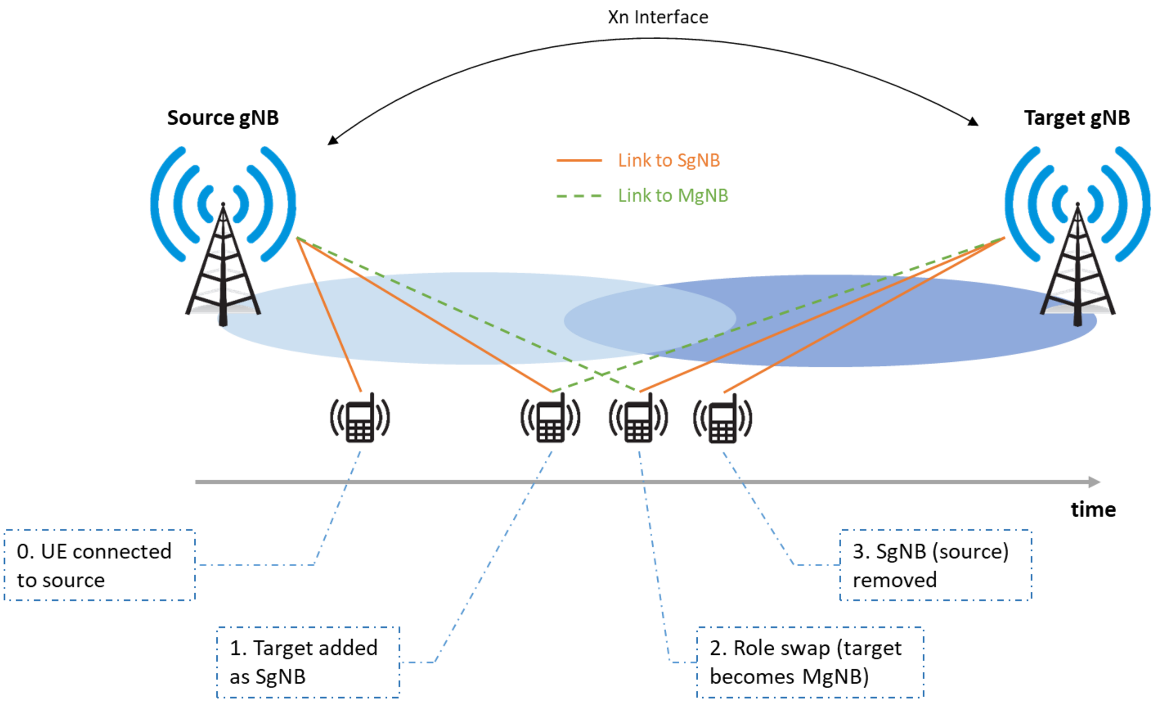


Figure 13: Illustration of the multi-connected HO proposed in [37]

The authors also touch upon the drawbacks of implementing such a solution which include *the increased UE complexity/cost (multiple Tx/Rx chains needed), the increased interference due to DC and the* *uncertainty and additional signaling caused by the existence of multiple potential TgNBs*, however they still claim significant improvements in terms of reported RLFs and consequent outages per UE, based on simulation results. It has to be noted that simplistic simulation assumptions were used and only low mobility users (up to 30 km/h) were considered, while no insights on potential reduction of the HIT (and to what levels) are offered.

In [39] the authors analyse the *shortcomings of the 3GPP proposed RACH-less and MBB HO schemes* [40] and propose an enhanced HO mechanism combining parts of both. More specifically, it is highlighted that the 3GPP proposed RACH-less HO only works for synchronized networks, while the MBB HO requires UEs with advanced capabilities so as to simultaneously perform UL Tx towards both the SgNB and TgnB. The HO Interruption Time (HIT) and HO Execution Time (HET) are defined and broken down to their individual components, as shown in Table 4 and a hybrid scheme of RACH-less and MBB HO is proposed to achieve seamless mobility in non-synchronized networks.

Table 4: HO Interruption Time (HIT) and HO Execution Time (HET) definitions

Term	Start Event	End Event	Equivalent Latency
HIT	RF retuning	UL grant & TA value reception	User Plane latency
HET	RRC Reconfiguration Request	RRC Reconfiguration Complete	Control Plane latency

The proposed mechanism in [39] employs *a partial, DL-only MBB* in which the UE monitors both the SgNB and the TgNB but only in the DL, which doesn't require a structural UE change (no UL Tx required). In this way, the common System Information from the Target cell can be acquired (i.e. the general LTE RRC connection reconfiguration can be acquired) excluding delays such as RF synchronization to TgNB, RF baseband re-tuning and security updates, as well as the RACH procedure delay, as RACH is not used. As RACH is not used, the *Cell Radio Network Temporary Identifier* (C-RNTI), the *UL grant* and *TA value* of the TgNB have to communicated to the UE in a different manner. The C-RNTI is forwarded to the UE via the SgNB within the HO command, while thanks to the fact that the UE is already monitoring the TgNB DL (partial MBB), the TgNB may directly allocate and control the UL grant to the UE by embedding it in the Physical Downlink Control Channel (PDCCH).

The *UL timing alignment* is achieved via measurements of the UE to/from both SgNB and TgNB and a comparison of the reported values. More specifically, the *Round-Trip Delay* (RTD) is measured between the UE and the SgNB and broken down to its individual components. Taking into account the channel reciprocity, the measured DL timing difference between the SgNB and the TgNB and the reported internal reference clock of the two BSs an alignment is performed to the UL frame timing of the TgNB. The *Timing Advance* (TA) difference is calculated by the UE using the inter-cell timing difference value between the SgNB and the TgNB, that is provided to it via the network. In a similar fashion the initial *UL Tx power* of the UE is indirectly estimated by the UE using the current UL Tx power level towards the SgNB and the differences measured (by the UE) between the RSRPs and SINRs of the SgNB and TgNB.

The proposed scheme seems to outperform both the standards RACH-less and MBB schemes in terms of achieved HIT and HET, despite the slight increase of complexity that it incurs.

The authors in [25] propose to use *Device to Device (D2D)* communication to achieve seamless mobility with a target HIT of 0 ms and an increase of experienced user throughput during the HO. In the proposed mechanism the SgNB attempts to identify the best UE within its coverage area to act as a relay for a UE about to initiate the HO procedure. Any UE in RRC_Connected or RRC_Inactive mode is a viable candidate and if the calculations of the SgNB indicate that a D2D connection between the HO UE and the Relay UE is better than a direct forwarding of data to the HO UE, then the buffered data for the HO UE are forwarded to the Relay UE, which in turn forwards them to the HO UE, while it goes through the HO procedure. The authors have used the 3GPP defined HO execution delay components (depicted in Table 5) and attempt to minimize most of them by allowing parallel D2D communication while these steps are executed.

This solution presents certain advantages such an increased user throughput experience for the HO UE, as data is still received during an otherwise empty period of HO. This also contributes to an almost 0 HIT as data is being received in a D2D fashion while the SgNB and TgNB finalize the HO procedure. Finally, this solution can be configured before the HO UE enters the cell edge territory, hence the *HOF* due to RLF can also be reduced. However, the presented solution also has some disadvantages, as it significantly increases the computational overhead in order to calculate the best relay UE for all UEs about to have a HO, while it also deteriorates the energy consumption (and consequently decreases the battery life) of the relay UE. Moreover, this solution only works for an adequate density of UEs (i.e. not suitable for rural environments or low traffic hours).

Table 5: LTE HO Latency components [25]

Message	Time (ms)
RRC HO command (1)	15
UE processing time for RF/baseband re-tuning (2)	20
Acquiring first available RACH in target cell (3)	2.5
PRACH preamble transmission (4)	1
UL allocation and TA transmission (5,6)	5
Processing RRC message and TTI assignment (7)	3
RRC message encapsulation and transmission (8)	3
Minimum / Typical total delay	**49.5**

It also needs to be highlighted that the authors [25] have made some quite favourable assumptions during their simulations for the evaluation of the proposed solutions. First of all, the UEs are assumed to have multiple arrays of Tx/Rx antennas in order to be able to receive data in D2D fashion, while they are simultaneously performing RF re-tuning to the TgNB. This would significantly increase the UE cost. Moreover, extremely simplistic models of the E2E HO process and the V2X functionality have been employed during simulations, without considering all the appropriate HW and SW delays and without providing an evidence of performance validation for the simulator. Hence the conclusion that the proposed solution can deliver a HIT of 0 ms is extremely doubtful.

In [41] the authors explore cell clustering and Cooperative Multi Point – Joint Transmission (CoMP-JT) as a way of reducing HO Failures and to increase the throughput of mobile users in HetNets comprised of multiple small-cells (urban scenario). The authors identify the frequent HOs of moderate and high-speed mobile users in small cell environments as the leading cause of degraded performance in such environments, while also pointing out that recent studies on user mobility and their respective mitigation measures only focus on low mobility users (up to 30 km/h). The proposed scheme utilizes the inherent benefits of Dual Connectivity (DC) and Control/Data Plane Separation Architecture (CDSA) and by utilizing dynamic clustering, it attempts to reduce the HOF and increase the throughput of mobile users with moderate speeds (up to 60 km/h) in Het-Net urban environments.

The proposed solution identifies mobile users with moderate speeds (between 30 and 60 km/h) based on the Mobility State Estimation (MSE) estimated as indicated in *Equation (1)*, and instead of allowing them to perform single HOs every time they change a small-cell, it directs them to a CoMP based DC served by dynamic clusters of small cells. During CoMP transmission the UEs control plane remains attached to the macro cell while the user/data plane communication takes place over the small-cells, hence reaping the benefits of small-cell connectivity (higher throughput) without the frequent HOs. The clusters serving each UE are dynamically adapted based on its mobility pattern, while the UE is directed back to normal (single transmission) once its velocity drops below a certain threshold.

$$r_{MSE} = \frac{N_{HO}+N_{reselect}}{T_{MSE}} \tag{1}$$

Where:

- N_{HO} : number of HOs in period T_{MSE}
- $N_{reselect}$: number of cell reselction in period T_{MSE}
- T_{MSE} : adjustable measurement period (sec)

Based on relatively detailed simulations, the proposed scheme presents moderate improvements in terms of reduced HOFs and increased experience throughput for moderately mobile users, however it has a few drawbacks as well. Most notably, this scheme leads to a significant increase of signalling as CoMP-JT needs tight synchronisation among the participating cells, while the clustering algorithm itself also consumes considerable resources due to its dynamic nature. Moreover, this scheme has no effect on macro-to-macro HO, which are performed in a typical manner, while the HO latency and HIT are not affected at all by this scheme meaning that users will experience short service interruption. This aspect of the proposed algorithm, along with the fact that the scheme is irrelevant for rural/ highway environments and inapplicable in cases of inter-PLMN HO (CoMP and clustering do not work across different MNO domains), makes this scheme unsuitable for V2X applications in cross-border conditions, where inter-PLMN HOs may take place.

2.2.3 Additional aspects

Besides the reduction of the HIT and HOF, some other aspects of the HO process should be taken into account when looking to improve the E2E communication time and the overall efficiency. In [42] a HO cell selection optimization mechanism is proposed for Software Defined Networks SDN-based 5G networks. The proposed scheme aims at selecting the most appropriate cell for a HO based on the UE mobility pattern and a variety of metrics to determine the suitability of each neighboring cell, such as the cell size, the received RSRP and its current load. More specifically, a prediction of the mobility pattern of a UE takes place based on its trajectory data (GPS, speed, etc.) and the most appropriate neighboring cell is selected (in the direction that the UE is moving, large serving area, etc.) for a HO such as the sojourn[9] time of the UE in that cell is maximized. The scheme is further enhanced by attempting to perform load balancing at the same time by using the cell load data for all candidate cells. Finally, a channel pre-allocation by the SDN Controller (SDN-C) at the TgNB, helps with reducing the HO latency. By using linear programming, the decision for the selection of the optimal cell for a HO among all the neighboring candidate cells, comes at a lower computational cost.

The authors of [42] claim their solution significantly reduces the control signaling associated with a HO (compared to traditional 3GPP HO) by eliminating part of the signaling between the UE and the network core (MME, S-GW), as all HO decisions are taken and communicated from the SDN-C. However, the signaling cost of SDN-C collecting all necessary information from the gNBs and the UEs, is not

[9] Total time the UE will remain at the target cell thus avoiding frequent HOs

addressed. The (relatively simplistic) simulation-based evaluation of the solution, only takes into account low mobility users (average speed of 13 km/h) and indicates that indeed the proposed solution can lead to the selection of a more appropriate TgNB depending on the UE's mobility pattern (direction), the cell's load and cell-specific measurements leading to less frequent HOs for the UE and to a reduction of control signaling. A claim is made that the solution also assists in reducing the HO delay, however this is never justified nor backed up by any simulation data.

The issue of efficient HOs from 5G networks towards legacy 4G networks is addressed in [43]. More specifically the transitional period of migration from 4G to 5G networks is investigated, where 5G and 4G networks will co-exist without all the proper mechanisms and interfaces up and running, hence significantly impacting the HO performance and latency. The authors focus on the inter-RAT HO between 4G and 5G networks (and vice versa) wherein a dedicated interface between the Mobility Management Entity (MME) in the EPC and the Access and Mobility management Function (AMF) in the 5G NGC, i.e., N26 as specified by 3GPP[2][3], is non-existent. The goal of the work in [43] is to minimize the HO preparation time by considering a fully SDN based network utilizing Distributed Mobility Management (DMM) for enhancing HO signalling procedures.

The authors consider the three major phases of the 3GPP proposed HO preparation signalling procedure, i.e. Tracking area update, Initial attach procedure and UE requested Packet Data Network (PDN) Connectivity and focus on improving the last two phases. The smooth transfer of PDU sessions from 5G NGC to the EPC during the HO process and maintaining the IP address/prefix will be extremely critical for guaranteeing service continuity and increased QoS during mobility events, so this paper presents a novel approach for PDN connectivity procedure based on a SDN enabled Mobility Management unit (SeMMu) with the parallelization of Control Plane (CP) messaging and the elimination of time consuming handshakes. The enhanced procedure is depicted in Figure 14, and is comprised of the following main steps: i) the SeMMu parallelizes the execution of the create session request message to the S-GW and the PDN-GW, ii) the response messages have been eliminated from the legacy signalling mechanism, hence the newly developed message P2a and P2b and iii) the bearer is modified in such a way that a handshake involving four messages in the legacy procedure is now compressed in messages P7a and P7b.

The authors apply an analytic approach for the evaluation of their solution, using data sets from a Japanese telecom operator [44] and link delay values adopted from [45], while the main metrics used for the performance evaluation of their proposed solution are latency, transmission cost and processing cost. Both scenarios of inter-RAT HO are evaluated, i.e. from 5G NGC to EPC and vice versa, and the results indicate that a latency improvement of more than 24% may be achieved, while at the same time the transmission and processing costs are reduced by up to 34.4% and 27,78% compared to the legacy procedure, respectively. With regards to latency the achieved performance was down to 89 ms for an inter-RAT HO, which seems to be a significant improvement over the legacy 181 ms, but it still remains very far from the necessary 0 ms HIT goal needed for service provisioning to the automotive sector and CAM applications.

Interference in 5G networks when serving a large amount of nodes in a specified environment (such as the vehicles in a vehicular environment) is another significant issue that needs to be taken into account. Vehicular environments may have the characteristics of mMTC services and as such the study of the impact of interference caused by mMTC connections, becomes an important factor. The authors in [46] provide a comparative SOTA survey of the challenges and proposed solutions in literature regarding inter-cell interference (ICI) minimization in (B)5G networks for two main schemes, namely Orthogonal Multiple Access (OMA) technique and Non-Orthogonal Multiple Access (NOMA).

Several works have studied the OMA / NOMA schemes and their suitability in 5G and B5G systems. For example, in [47], the authors intended to minimize the total energy consumption subject to the computation capacity and execution latency limits. They obtained an optimal transmit power and computation resource allocation based on the Karush-Kuhn Tucker (KKT) conditions. Their results showed that the total energy consumption for both NOMA and OMA schemes increases with the number of NB-IoT user equipment (UEs). However, when compared to OMA, NOMA reduces the total energy consumption by 53:23%. Critically, it should be noted that the authors neglected the impact of inter-cell interference (ICI).

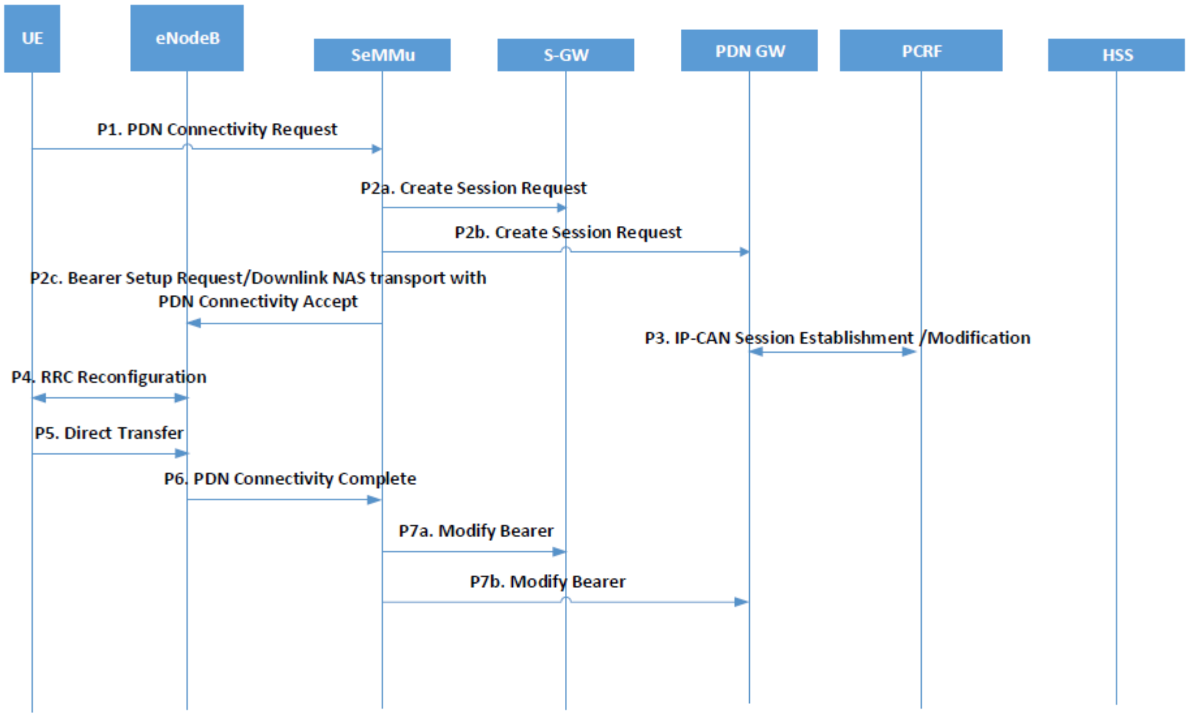


Figure 14: Enhanced UE requested PBN Connectivity request procedure [43]

In [48], the authors investigated the downlink performance of NOMA with randomly deployed cellular users. From the presented analytical formulations, it is shown that the NOMA scheme leads to significant performance gains in terms of ergodic sum-rate. However, the allocated power and the targeted data rate could directly influence the outage performance, i.e., if the allocated power is lower than the required power for successful transmission, the UE will suffer from the outage. In [49], the authors dealt with the connection density maximization problem in NB-IoT networks by using NOMA. The authors used the bottom-up power filling algorithm and proposed item clustering heuristic approach which allows any number of devices to be multiplexed per sub-carrier. It should be noted that the authors suggested multiplexing any number per sub-carrier without considering the impact of ICI, which is a potential threat to meeting the performance requirements of NB-IoT massive connectivity.

In [50], the authors proposed two cooperative relaying schemes i.e. ON/OFF - full-duplex relaying (ON/OFF - FDR), and ON/OFF - half-duplex relaying (ON/OFF - HDR) schemes. Either of the proposed schemes is applied to the cell-centre user (with good channel conditions) to help relaying the direct NOMA transmissions on the downlink of cell-edge users. In this regard, the ON/OFF relaying decision depends upon the quality of direct and relay links from the base station to the cell edge user. From the results, it is shown that the proposed cooperative scheme significantly improves the outage performance and the sum rate of both cell-centre and cell-edge users. However, for mMTC devices such as in the LPWAN category, relaying of information leads to an increase in device complexity and cost, which is the limitation for most massive IoT use-cases. In [51], the authors proposed a novel resource allocation technique for NOMA, based on cooperative cellular networks. In their proposed framework, the NOMA users with good channel conditions act as group heads, hence can relay information to NOMA users with bad channel conditions. Despite the gains of the proposed scheme for high complexity devices, it should be noted that the reduced complexity of NBIoT devices, power-saving mode, and extended discontinuous reception (eDRx) make relaying of information (i.e. at the low complexity device) unfeasible.

2.2.4 Comparative Study of HO solutions

Based on the above analysis, the main characteristics of each solution along with some other critical elements are extracted and comparatively presented in Table 6, in order to offer immediate insights into the applicability, cost and effectiveness of each of the proposed solutions.

Table 6:Comparative table of surveyed HO solutions

Ref.	Proposed Solution	Target KPIs	Used Technologies	UE Tx/Rx chain(s)	Target Service	Evaluation Method	Advantages	Disadvantages
[34]	Parallelization of multiple steps during HO Detach time	E2E latency	SDN, Topology aware CP	Single	URLLC	PoC	• Good overview of E2E latency components • Simple method	• Weak evaluation (PoC) • outdated information (2016)
[26]	Overview of HO Management techniques & HO challenges	HOF, HIT, HO success rate, PP, overhead, energy consumption, latency	MBB, BBM, intra- vs inter- HO procedures (gNB, frequency, RAT)	Single & Multiple	None	Numerical analysis / Overview comparison	• Very good overview of open HO challenges & proposed solutions	N/A
[24]	Overview of HO Mechanisms for URLLC & enhancement based on MBB + RACH-less → CHO	HIT & HOF	MBB, RACH-less (hybrid controlled HO)	Single & Multiple	URLLC	Simulation / Trade-off analysis	• Improved mobility robustness • Reduced HOF & PP	• Increased overhead from multi-HO preparation • Increased signalling • Increased computational complexity
[14]	Forced HO in cases on National Roaming / Regional split	E2E latency (inter-MNO)	MBMS, DTX/DRX cycles	Single	CAM	Simulation	• First work addressing inter-MNO HO	• Coverage overlap assumed (not suitable for cross-border) • Favourable sim. assumptions
[32]	Inter-MNO HO based on Regional split and MBMS	E2E latency of time critical messages (inter-MNO)	MBMS (SC-PTM), MEC pre-registration	Single	CAM	Simulation + Numerical analysis	• Elaborate work addressing inter-MNO HO • Thorough analysis of HO mechanism	• Coverage overlap assumed • Signalling & computational overhead • Very high cost • Ignored mobility effect • Favourable sim. assumptions
[35]	Inter-MNO MEC Service migration based on service pre-location	Service migration time, QoS	Virtualization (VV), Docker containers	Single	CAM	PoC	• Concept of VV reduces N2V traffic • Reduced service down-time	• Service migration time in the order of seconds (unsuitable for critical CAM messages)
[37]	Zero HIT through radio bearer duplication for both MgNB and SgNB	HIT & HOF	Dual Connectivity, SgNB survival	Multiple	URLLC	Simulation	• Increased mobility robustness • Reduced HIT	• Increased UE complexity & cost • Increased interference • Increased signalling • Low UE mobility considered

[39]	Enhanced HO mechanism based on MBB & RACH-less (No RA and UL grant procedure needed)	HIT & HET	MBB, RACH-less	Single	URLLC	Simulation	• Alleviates need for synchronized network • Alleviates need for multi Tx-Rx chains	• Increased complexity • Sensitive to estimation errors
[25]	Relay info during HO (eliminate HIT) via D2D with another UE	HIT, HOF & increased Throughput	D2D, Relay node	Multiple	URLLC	Simulation	• Reduced HIT • Increased Throughput • Dynamic selection among D2D and network communication.	• Increased computational overhead • Increased energy consumption / decreased battery life • Simplistic modelling
[41]	Address high mobility UEs via cell clustering and Joint Transmission (DC)	HOF & Throughput	CoMP-JT, CP/DP separation, MSE	Multiple	CAM / small cells	Simulation	• Addressing Het-Net dense deployments • Dynamic algorithm • Increased mobility robustness	• Increased signalling • Tight network synchronization needed • Increased computational resources
[42]	Maximization of sojourn time of UE per cell (cell selection), based on predictive UE mobility + Load Balancing	HIT, sojourn time, number of HOs	SDN, mobility pattern prediction, channel pre-allocation	Single	None	Simulation	• Reduced HO delay • Improved TgNB selection based on UE mobility • Reduced num. of HOs	• Ignored SDN-C - gNB signalling • Simplistic modelling assumptions • Only low mobility users
[43]	Optimization of inter-RAT HO without N26 interface with enhanced HO preparation phase	Latency, processing & transmission cost	SDN, Distributed Mobility Management	Single	None	Numerical Analysis	• Reduced HO signalling • Reduced HO delay • Use or realistic dataset	• Obscure scenario of limited applicability • Inter-RAT HO time in the order of seconds (unsuitable for critical CAM messages)

2.3 V2X Use cases & requirements

2.3.1 Key V2X characteristics & requirements

Based on the description of the expected VANET applications that will need to be supported, a few key characteristics of VANETs and vehicular traffic in general can be extracted [52]:

- A huge number of vehicles needs to be supported, especially during high traffic hours.
- The applications developed for VANET have very specific and well-established objectives, such as the provision of safe and intelligent transport systems.
- Instead of requesting a specific facility or route, there are many safety applications connected with VANET attempting to include information related to the traffic to all available nodes in a particular geographical area.
- Nodes in VANETs move in the predefined road network. Accordingly, this predefined network topology allows the vehicle location to be determined. Likewise, vehicles will probably disconnect because of various obstacles on the road.
- The dynamic network topology due to the high movement of vehicles, causes the connections in the comparative rapid movement of vehicles to be highly insecure.
- Power supply is not considered a major issue in VANETs.

These characteristics highlight the very dynamic nature of the vehicular environment which causes unstable connectivity, thus reducing the reliability of communications and causing issues with the expected QoS in terms of latency and throughput. On top of that, provisioning basic safety applications alone is unlikely to meet the requirements of self-driving autonomous vehicles. For example, while existing applications such as left turn assist and emergency electronic brake lights are beneficial for vehicle safety, autonomous vehicles require vehicles to be capable of transmitting messages indicative of manoeuvre changes, trajectory alignments, platoon formations, sensor data exchange, etc. Besides, even for human-driven vehicles, processing of data received from sensors of surrounding vehicles - for example, where one vehicle shares its live camera feed with a vehicle behind it - is expected to increase the safety benefits well beyond what can be achieved by basic safety applications [19].

Table 7: Key Vehicular/VANET application requirements [53]

KPIs / Use Case	Max E2E Latency	Data Rate	Reliability	Position Accuracy
Vehicles Platooning	20-40 ms	50-100 Mbps	99.999%	20-50 cm
Advanced Driving	< 10 ms	50 Mbps	99.999%	10-20 cm
Extended Sensors	10-100 ms	up to 1 Gbps	99.99%	20-50 cm
Remote Driving	5 ms	up to 100 Mbps (Uplink)	99.999%	10-20 cm
Vehicle QoS Support	20-100 ms	up to 100 Mbps	99.99%	10-100 cm

Requirements of some advanced vehicular/VANET applications have been studied by the 3GPP in [5]. These advanced V2X use-cases, which are summarized in Table 7 along with their respective requirements, not only improve road safety but also assist in better traffic management and cater to the infotainment needs of passengers. The definition of these Use cases is provided below [22][54]

- ***Vehicles platooning*** refers to vehicles traveling together in very close distance and their management. All vehicles part of the platoon obtain information from the leading vehicle and act accordingly (autonomous driving instructions). This information allows vehicles travelling together to drive closer than normal in a more coordinated manner.

- ***Extended Sensors*** enables exchange of raw or processed data gathered through local sensors or live video images among vehicles, Road Site Units (RSU), devices of pedestrians and V2X application servers. Vehicles can increase perception of their environment beyond what their on-board sensors can detect, thus providing a more broad and holistic view of the local situation. High data rate is one of the key characteristics of this use case.
- ***Advanced Driving*** enables semi-automated or fully automated driving. Each vehicle and/or RSU shares perception data obtained from its sensors with vehicles in proximity allowing synchronizing and coordinating their trajectories or manoeuvres and driving intention.
- ***Remote Driving*** enables the handling of a vehicle by a remote driver located far away thus helping those passengers who cannot drive by themselves, or remote vehicles located in dangerous environments. For a case where variation is limited and routes are predictable, such as public transportation, driving based on cloud computing can be used. High reliability and low latency are the main requirements for remote driving scenario.

From Table 7 it can be observed that most CAM use cases require extremely low end-to-end latency and very high reliability, as it was expected, since the connectivity interruption or the delayed delivery of a critical message could lead to an accident, especially when taking into account the high mobility of the vehicles. In terms of throughput (data rates) most use cases are not that demanding, as usually the content exchanged among vehicles and infrastructure are small packets containing sensor information or driving directives. There are however certain scenarios belonging to these cases that have extremely high demands in BW (such as video sharing, raw data sharing) which also need to be accommodated. Finally, the position accuracy delivered by todays GPS systems (approximately 1-2 meters in most realistic scenarios) appears to not be enough for most of the CAM use cases and that is an area where 5G is expected to have a significant impact (once the position accuracy features of 5G become available).

2.3.2 Periodic vs aperiodic traffic

A big portion of the communication of the above discussed V2X use cases is based on the periodic exchange of messages among the vehicles and/or between a vehicle and a remote (ITS) server over the network. This periodic communication is key for most CAM application as it provides the groundwork for the collection of information from multiple vehicles and based on its fusion and processing, it allows for the generation of the "big picture" of a certain vehicular environment which drives any autonomous driving decisions. The type of data usually exchanged with periodic communication are the location, trajectory and velocity of each vehicle which allows for the creation of such vehicular environment cooperative maps. Other types of data may also be exchanged such as engine temperature and revolutions.

As it is critical for every vehicle to receive this information from all the surrounding vehicles, especially the ones that are located outside its Line of Sight (LoS), e.g., behind a corner, in order to be able to operate in autonomous mode without the risk of an accident, ETSI has standardized these types of messages which are called ***Cooperative Awareness Messages (CAMs)*** [11]. CAMs are now adopted by all vehicular and equipment manufacturers facilitating the interoperability of the various vehicular components and applications. The transmission frequency of CAMs is set to 10 Hz which is deemed enough even for the most challenging vehicular environments with high velocity. The continuous reception of these messages is critical for VANET applications, as the high velocity environments means that the position, speed and trajectory of every other vehicle on the road is very dynamic, hence information from older CAMs can easily be outdated.

However, periodic traffic is not the only traffic that should be supported for the successful deployment of CAM services. Actually, the messages warning of an accident ahead, which are generated based on events on the roads, are potentially the most critical ones as they need to be quickly propagated to the rest of the vehicles on the road, to avoid further accidents. ETSI has also standardized this type of messages, in order to guarantee universal reception and understanding of these messages across vehicular manufacturers and application developers. These aperiodic messages are called ***Decentralized Environmental Notification Messages (DENM)*** and are defined in [12]. Both CAM and DENM messages are instrumental for the correct operation of every VANET application and through them, vehicles are fully aware of their surroundings and may construct a Local Dynamic Map (LDM) with all the vehicles on the road and potential hazardous locations/events.

Despite the importance of both of these types of messages, some of the features of LTE-V2X and IEEE 802.11p may not provide full support for the transmission of DENMs. This is mostly due to the fact that both "*Listen before Talk*" (802.11p) and "*Semi-Persistent Scheduling*" (LTE-V2X) have an inherent waiting period that each message needs to wait for, before being transmitted. As DENM messages are extremely important as they carry information on sudden or potentially dangerous road events, they should not be delayed by such mechanisms, and they should be granted immediate priority by the scheduler (prioritized over CAMs). On top of that, the currently used channel sensing scheme for channel estimation (which results in the selection of the transmission scheme and coding) which averages the channel over observations of 1 second, is not considered accurate enough for highly dynamic vehicular environments where channel fading is very fast and could lead the dropping of important messages (such as a DENM message) which could result in accidents.

It becomes clear that aperiodic event-driven traffic is more troublesome for the vehicular communication protocols while the loss of a DENM message is much more severe than the loss of a CAM message, highlighting the importance of addressing those issues. Solutions in terms of short-term sensing with sensing windows down to 100 msec and the repetition of DENM messages without waiting for a NACK, have been investigated in literature [55], and have produced promising results indicating a significant performance improvement (lower latencies and lower drop rates for DENM).

2.4 Relevant R&I activities and Performance Evaluation

In this section, a performance evaluation of the four discussed communication technologies (802.11p, 802.11bd, LTE-V2X and NR-V2X) for V2V communication is presented based on simulation results as well as early field trial results (for 802.11p an LTE-V2X which are mature enough), available in literature. A benchmarking of their performance for various scenarios is performed based on these results, while insights regarding the suitability of each technology under specific circumstances are drawn. Furthermore, the most prominent challenges in VANETs and the respective research directions are discussed, while some first results from simulation-based evaluation for some of the researched improvement mechanisms are also provided.

Moreover, this section provides an overview of the most relevant R&I EU funded projects, that recently engaged in the research and validation of technologies for 5G Enabled Mobility in cross-border conditions. There are multiple R&I efforts from European and global consortia on relevant 5G enabled Autonomous Mobility challenges, addressing for instance pure automotive aspects (e.g., [56]) or researching the application of 5G enabled CAM solution in the Transport and Logistics sector, with the additional help of Network applications (e.g., [57][58]). However, for the purpose of this thesis, only the specific project focusing on cross-border CAM provisioning will be analysed.

2.4.1 Comparison of C-V2X vs 802.11 performance

In this section both variants/versions of the two key technologies (C-V2X and 802.11) are evaluated based on available simulation results in the literature. As this is a study for the evaluation of the ad-hoc V2V communication capabilities, only the PC5/SL variant of LTE-V2X and NR-V2X are taken into account (no communication via the gNB(Uu Interface)). Starting from the more mature technologies, i.e., 802.11p and LTE-V2X where more experimental results are available, initial simulation studies have been available for some time, indicating the expected performance under specific V2X scenarios. Authors in [60] have examined the effect of the longer expected communication range of LTE-V2X compared to 802.11p, by simulating two scenarios/use cases. In the first scenario, a disabled vehicle behind a blind curve is transmitting alerts to approaching vehicles under both icy and normal road conditions. The simulation results for this use case regarding the reception distance and consequently the supported vehicle speed were analysed. If DSRC (802.11p) is used, an approaching vehicle must maintain a speed below 28 mph (45 km/h) and 46 mph (74 km/h) for icy and normal road conditions, respectively, to stop in time to avoid accident after receiving an alert. With LTE-V2X, the incoming vehicle receives the alert earlier at a longer distance away. Therefore, it can stop before reaching the disabled vehicle even if it is traveling at higher speed, (for example, 38 mph (61 km/h) and 63 mph (101 km/h), for icy and normal road conditions, respectively) [59][60].

Qualcomm also simulated a do-not-pass use case scenario where a vehicle following a large truck has limited visibility of the opposite traffic. At the same time, a second vehicle is approaching the first vehicle from the adjacent lane. The higher the vehicle speeds, the faster the two vehicles approach each other and the more dangerous is the situation if the first vehicle chose to overtake the truck. With V2V communication, the second vehicle can send warning alerts, which are used by the first vehicle to decide whether it should overtake the truck or not. Similarly to the previous use case, the longer C-V2X range (443 m) allows the first vehicle to receive the alerts earlier, thus allowing it to safely overtake the truck even if it is traveling at a higher speed compared to the case where 802.11p is used (240 m) [59].

Besides the simulation-based evaluation, Qualcomm also proceeded to test the two technologies in real-life trials with actual vehicles. These trials were only focused on LTE-V2X and 802.11p protocols, as they are the only technologies mature enough to have real-life implementations and commercial HW capable of supporting them. The real-life tests focused on the performance of the two technologies under Line of Sight (LoS) and Non-Line of Sight (NLoS) conditions, and the Packet Reception Rate (PRR) vs the distance between transmitter and receiver was the main metric used for the evaluation. For the NLoS case, a big truck was constantly placed in front of the transmitter in order to create a significant (and constant) line of sight obstruction.

The results indicated that for both LoS and NLoS cases the LTE-V2X outperforms the 802.11p (DSRC) in terms of how far the ITS messages were transmitted (communication range), for both sub-scenarios where a different transmission (Tx) power was used (5 dBm and 11 dBm respectively). As expected, when a larger Tx power is used by the transmitter the achieved communication range for which 100% of the messages are received increases from about 600 m to 900 m for the LoS case and the DSRC technology and from 950 m to about 1250 m for the LTE-V2X technology. What is very interesting to observe is that for LoS conditions, the LTE-V2X achieves a larger communication range with the low Tx setting (950 m with 5 dBm) compared to the communication range achieved by DSRC with the high Tx setting (900 m with 11 dBm). This is a clear indication of the superiority of LTE-V2X over DSRC with regards to the communication range of the two technologies.

The exact same behaviour was observed in the NLoS case, where the communication range has dropped significantly for both technologies (as expected due to the obstruction), but the relative performance remains the same, i.e., LTE-V2X significantly outperforms 802.11p.

After this first look into the relative performance of the two legacy technologies, the more interesting question of the performance improvement achieved with the new releases of 802.11bd and NR-V2X is raised. A very thorough simulation campaign was performed by the authors in [61] where all four technologies (802.11p. 802.11bd, LTE-V2X, NR-V2X) are benchmarked against each other, and even a variation of 802.11bd is included in the study where Dual Carrier Modulation (DCM) is activated, and range extension mode is enabled. This variation is denoted as 802.11bd^{DC}. The following four main KPIs are used for the performance evaluation:

- Packet Error Rate (PER) vs Signal to Noise Ratio (SNR)
- Packet reception rate (PRR) vs distance
- Data Rate (Mbps) vs distance
- Packet Inter-Arrival time vs distance

Two sub-scenarios were examined, addressing use cases where small data packets (100 B) and large data packets (1500 B) are transmitted as well as different Modulation and Coding Schemes (MCS). The results of this simulation campaign were presented in detail in [61].

The PER is potentially the most common metric to evaluate the performance of a receiver in terms of reliability. Especially for cases of URLLC applications (as some VANET applications) a PER < 10^{-5} may be expected. From the simulation results it was observed that for small payloads of 100 Bytes and a modulation of ½ QPSK, the 802.11p has the worst performance while the 802.11bd^{DC} has the best performance, outperforming even NR-V2X. This is due to the fact that the range extension option of 802.11bd^{DC} offers a gain of about 3 dB and a gain of about 5 dB due to the diversity gain of frequency selective channels (i.e., a total gain of ~8 dB compared to 802.11bd).

In case of 2/3 64QAM, LTE-V2X has a worse PER due to the fact that the channel estimation at high Doppler shifts becomes outdated. However, NR-V2X has a slightly better PER performance due to its four times lower subcarrier spacing compared to LTE-V2X, and its better performing LDPC codes compared to Turbo codes. The 11p also suffers as a reason of its preamble-based channel estimation. Nevertheless, 11bd outperforms all other technologies due to the use of midambles for channel estimation. Another reason behind the bad performance of C-V2X is the flat fading, as only few number of RBs are used for data transmission compared to 11bd which uses whole bandwidth [61].

When the performance of high throughput applications (1500 Bytes packets) is examined, it is observed that the PER of 802.11p is even worse due to the bad channel estimation, highlighting the importance of midambles which significantly improve the performance of 802.11bd. Similarly to the performance observed for the small data packets, 802.11bd^{DC} outperforms all other technologies, but this time the difference with LTE-V2X and NR-V2X is much smaller. Both LTE-V2X and NR-V2X perform better for large packet sizes due to the increased error correction capability of both Turbo and LDPC decoders, and frequency diversity due to the use of more RBs.

By examining the PRR performance of the different technologies a shift in favour of LTE-V2X and NR-V2X is noticeable as they clearly outperform their 802.11x competitors. By focusing on the small data packets performance for 2/3 64 QAM it can be observed that even though all four technologies perform reasonably well for a distance up to 50 m, as they all achieve > 90% PRR, the performance quickly degrades for 802.11p and 802.11bd as the distance increases, while LTE-V2X and NR-V2X maintain a much better performance (e.g. > 65% PRR up to 100 m compared to ~20-30% for 802.11p/bd). Similar performance is observed for all technologies when the lowest possible coding rate is used (MCS 0), while the advantage of LTE/NR-V2X over 802.11p/bd even increases as a 90% PRR can be achieved even at distances of 450 m for LTE/NR-V2X compared to a PRR of <10% for 802.11p/bd, for the same distance. This clear superiority of LTE/NR-V2X is due to the very low coding rate used for MCS 0 (~0.1 compared to about 0.5 for 802.11). The 802.11bdDC variant presents a significantly improved performance compared to 802.11bd but is still no match for LTE/NR-V2X.

The performance of the four communication protocols is very similar for the case of larger data packets (1500 Bytes), as LTE/NR-V2X outperforms the 802.11 protocols. The only notable exception is that for the case of 2/3 – 64QAM 802.11bd now presents a similar performance with NR-V2X. It is interesting to note, that the expected communication range of all protocol decreases by about 60 m for larger data packets, except for 802.11p which is experiencing an even greater impact in its performance (lose about 100 m of range). Overall, considering both packet sizes (100 bytes and 1500 bytes) NR-V2X is the most reliable technology reaching higher range. In addition to that, performance of NR-V2X can be further improved by utilizing HARQ process [61].

NR-V2X and LTE-V2X have a clear advantage when it comes to average data rates for small packets as well. For smaller distances (<100 m) NR/LTE-V2X significantly outperforms 802.11 delivering much higher throughputs while also for larger distances (up to 500 m) NR/LTE-V2X manages to deliver up to 1 Mbps when 802.11 is already almost to zero. This is mostly attributed to the non-negligible preamble of 802.11 technologies which plays a big role when small packets are used. NR-V2X is the clear winner as it outperforms all other technologies, due to its lower overhead and higher reliability, while 802.11bd is slightly better than 802.11p. The 802.11bd^{DC} variant presents some improvement for large distances due to its extended range preamble.

For the case of larger packets a similar behaviour is observed, for the most part, as NR/LTE-V2X outperforms 802.11 especially for larger distances. One noticeable difference is the significantly improved performance of 802.11bd for small distances (<50 m) mainly attributed to the decreased overhead ratio, caused by the use of larger packets, which leads to its performance being superior even to NR-V2X for extremely small distances (10 m). It is however obvious from both sub-scenarios (100 B / 1500 B) that NR-V2X constantly delivers much higher data rates with high reliability at small and longer distances [61].

Another critical metric for the performance of a V2X communication protocol is the packet inter-arrival time (t_{IAT}) which describes the elapsed time between two successive packet arrivals and depends on the packet transmission time and on the reliability of the link. Results show that for distances <350 m, the t_{IAT} of 802.11 based technologies is very small due to their slot-less transmissions and it increases with distance due to the outage. The t_{IAT} in case of LTE-V2X remains between 1-2 ms due to its fixed Transmission Time Interval (TTI) of 1 ms. However, NR-V2X performs better than LTE-V2X due to its smaller TTI of 0.25 ms and remains close to $11bd^{DC}$. It can be concluded that for distances <300m all technologies can meet 1 ms update interval apart from LTEV2X. Nevertheless, if the update interval is set to 10 ms (which is a more reasonable assumption for the vast majority of V2X applications) then NR-V2X, LTE-V2X, and $11bd^{DC}$ can satisfy this requirement up-to a range of 500 m.

The packet size of 1500 B is deemed more appropriate for high throughput applications, where extreme low latency is not necessary, hence the latency requirements for such applications can be relaxed. A latency of 10 ms seems to be easily attained for NR-V2X even for very long distances (up to 500 m), while LTE-V2X also performs very well maintaining this requirement for up to 400 m. 802.11 based technologies on the other hand, only seem to be able to meet this requirement for up to about 250 m, while some improvement (up to 350) is observed with the $802.11bd^{DC}$ variant.

Based on the above presented results, for the small packet transmission case, it can be said that $802.11bd^{DC}$ and NR-V2X are both good choices for the considered range, while in the case of high throughput applications (packet of 1500 bytes), NR-V2X is the only choice for higher range [61].

2.4.2 Sota on Field validation attempts of inter-PLMN CAM

A few attempts to validate the performance of CAM functions in cross-border conditions have already taken place as summarized in [62]. In the case of cross-border operation, maintaining a high Quality of Service (QoS) from the network perspective becomes extremely challenging as multiple factors play a role, e.g., the type of border (soft vs hard), the channel conditions (Line of Sight or Non-Line of Sight), the application server placement, the kind of inter-PLMN connectivity, etc. The main 5G PPP R&I projects funded by the European Commission (EC) have provided an overview of the key cross-border challenges that need to be addressed to enable CAM cross-border operation in [63]. These challenges include cellular coverage aspects, Service and Session Continuity (SSC) settings including inter-PLMN data routing and roaming schemes, data management, security aspects and more. The projects also discuss the key technological enablers to resolve these challenges which include, new 5G interfaces, the extensive use of edge computing, MNO collaboration framework and more. A multitude of R&I projects under the umbrella of 6G-IA, have taken this a step further and provided a view on the CAM services and aspects that will be addressed by 5G as well as the remaining challenges and technological enablers that are expected to be addressed by 6G in [64].

A more thorough analysis of the most prominent CAM use case requirements, the cross-border mobility management challenges, and the way they impact the CAM application performance is presented in [53], highlighting the importance of the data roaming scheme, the inter-PLMN interconnection and the CAM server placement. An initial attempt to quantify the cross-border effect on connectivity and to obtain initial estimates of the 5G network performance across neighbouring PLMNs is presented in [65], where it is showcased that with previous generation networks and without additional measures, vehicles performing an inter-PLMN HO will experience service interruptions in the order of minutes, which is unacceptable for CAM applications. 5G network performance on the other hand with targeted mobility countermeasures seems promising for CAM applications, according to the authors.

Some attempts to evaluate the performance of certain 5G enabled CAM use cases in cross border conditions have already taken pace. In [66] the authors evaluate in a test track the performance of High Definition (HD) mapping in cross border conditions when using Mobile Edge Cloud (MEC) and find that 5G may offer acceptable performance in these conditions for this use case, while a 15% reduction in download times is offered when using MEC. Similarly, the authors in [67], evaluate 5G enabled CAM performance in an edge-based environment in the Spain-Portugal CBC, on one hand highlighting the increased 5G performance but on the other hand noting the experienced significant delays (especially in Uplink traffic) during the inter-PLMN HOs.

2.4.3 Overview of 5G PPP ICT-18 corridor projects

As it is the vision of the European Commission (as described in Section 1.2) to provide such advanced CAM services along the major European transport paths/corridors by 2025 [7] mainly enabled by 5G networks, smooth and uninterrupted CAM service provisioning must be guaranteed across the entire corridors irrespective of the network provider, vehicle and equipment manufacturers, cloud/edge and application providers and On Board Units (OBU)/RSI developers. To that end, the EU has funded three pioneer collaborative research projects with the participation of hundreds of relevant EU stakeholders with the mandate to investigate the challenges and test suitable solutions to mitigate any issues and performance degradation cause by the cross-border environment. These projects are 5G-MOBIX [14], 5G-CARMEN [15] and 5GCroCo [16], and their overview is presented here.

A big part of the scientific work, field testing, results collection and analysis and extraction of insights presented in this dissertation, took place in the context of the 5G-MOBIX project.

5G-MOBIX

5G-MOBIX has the objective to align the benefits of both 5G technology and CAM use cases and align EU stakeholders. By using 5G key technological innovations, 5G-MOBIX develops and tests vehicular functionalities along several cross-border corridors (Greece-Turkey and Spain-Portugal) and urban pilot sites. Besides economic, legal, and social aspects different from region to region, further conditions of automotive traffic, network coverage and service demand are considered throughout the test phase.

5G-MOBIX has built 2 cross-border corridors (CBC) in between Spain and Portugal (ES-PT) and between Greece and Turkey (GR-TR), while additional experiments have taken place in five 5G enabled test sites in Europe namely in Germany (DE), Finland (FI), France (FR) and The Netherlands (NL), while results and insights exchange has also taken place with 2 affiliated sites in China (CN) and Korea (KR). 5G-MOBIX has focused on the five Use Cases proposed by 3GPP [54], and has defined specific “User Stories” to be tested at each of the CBC and test sites. Table 8 provides an overview of the 5G-MOBIX user stories and Use cases that were tested in each of the project’s CBCs and trial sites.

Table 8: 5G-MOBIX User Stories to tested at each CBC/trial site

Trial Site	Advanced Driving	Vehicles Platooning	Extended Sensors	Remote Driving	Vehicle QoS Support
ES-PT	Complex manoeuvres in cross-border settings (*Lane merging, Automated Overtaking*) Automated shuttle remote driving across borders		Complex manoeuvres in cross-border settings (HD maps) Public transport with HD media services and video surveillance	Automated shuttle remote driving across borders (Remote Control)	Public transport with HD media services and video surveillance
GR-TR		Platooning with "see what I see" functionality in cross-border settings	Extended sensors for assisted border-crossing Platooning with "see what I see" functionality in cross-border settings		
DE		RSU-assisted platooning	EDM-enabled extended sensors with surround view generation		
Fi			Extended sensors with redundant Edge processing	Remote driving in a redundant network environment	
FR	Infrastructure-assisted advanced driving				QoS adaptation for Security Check in hybrid V2X environment
NL	Cooperative Collision Avoidance		Extended sensors with CPM messages	Remote driving using 5G positioning	
CN	Cloud-assisted advanced driving	Cloud-assisted platooning		Remote driving with data ownership focus	
KR				Remote driving using mmWave communication	Tethering via Vehicle using mmWave communication

5G-CARMEN

Focusing on the Bologna-Munich corridor (a 600-km-long highway crossing three EU countries – Italy, Austria, and Germany), the objective of the 5G-CARMEN project is to leverage the most recent 5G advances to provide a multi-tenant platform that can support the automotive sector delivering safer, greener, and more intelligent transportation, with the ultimate goal of enabling self-driving cars. To this end, 5GCARMEN employed different enabling technologies such as 5G NR, C-V2X, Multi Access/Mobile Edge Computing (MEC), and a secure, multi-domain, cross-border service orchestration system to provide end-to-end, 5G-enabled CAM services. In particular, the 5G-CARMEN project aimed at investigating the following four cross-border use cases targeting automation levels ranging from SAE Level 0 to Level 4:

- Cooperative Manoeuvring
- Situation Awareness
- Green Driving
- Video Streaming

5GCroCo

5GCroCo performed tests and trials on 5G technologies for CAM use cases along the borders of France, Luxembourg, and Germany with the main focus on the technical validation of cross-border and cross-mobile network operator (MNO) handovers to ensure service continuity. Furthermore, 5GCroCo attempted to identify new business models which can be established based on the exceptional connectivity and service provisioning capacity. Relevant standardization committees were impacted by the automotive and telecommunications industry by this project. The use cases examined within the context of 5G CroCo were:

- Tele-operated Driving (ToD)
- High definition (HD) map generation and distribution for automated driving
- Anticipated Cooperative Collision Avoidance (ACCA)

2.5 Current Sota notes (April 2025)

As the Sota part of this dissertation took place in the early phases of this research effort (circa 2021), it was deemed necessary, to perform a complementary Sota research on mechanisms and features that have been standardized or are being investigated for further MM and (inter-PLMN) HO improvements, in the past four years, in order to obtain a true estimation of the added value of the findings of this dissertation. Over the past years, 3GPP has introduced and enhanced several features in its Releases 17 and 18 (towards 6G networks) to improve mobility management, particularly benefiting autonomous vehicles and CAM applications that require seamless network connectivity during handovers.

Enhanced Handover Mechanisms:

- Xn-Based Inter NG-RAN Handover: This procedure allows a User Equipment (UE) to move between Next Generation Radio Access Network (NG-RAN) nodes using the Xn interface without changing the Access and Mobility Management Function (AMF) [3]. There are variations of this handover, namely:
    - Without User Plane Function (UPF) re-allocation, maintaining the existing UPF
    - With insertion or re-allocation of intermediate UPFs, providing flexibility in user plane routing.
- N2-Based Inter NG-RAN Handover: This mechanism supports handovers between NG-RAN nodes via the N2 interface, involving coordination between the source and target AMFs [3]. It is particularly useful when the UE moves across different PLMNs or when Xn connectivity is unavailable.

Both of these mechanisms, refer to a 5G SA, where its improved and simplified architecture would allow for a more streamlined process during inter-PLMN HOs. Especially the N2-based Inter NG-RAN HO is one of the targeted features that are expected to significantly improve the CAM application experience during inter-PLMN HO as the latency and interruption times are expected to be significantly reduced (as also mentioned in Section 3.5). To this day, there is no real-world implementation of interconnected 5G SA networks using this mechanism, so it is not yet possible to verify its expected advantages in the field.

AI and ML Integration for Mobility Optimization:

Artificial Intelligence (AI) and Machine Learning (ML) are poised to play a transformative role in the evolution of 5G Standalone (SA) networks and the future 6G architecture, particularly in the domains of mobility management and inter-PLMN handovers. These technologies address the increasing complexity and dynamic nature of modern mobile networks, where traditional rule-based mobility mechanisms may fall short in optimizing performance for high-mobility use cases like CAM applications, high-speed trains, and drones. More specifically the following developing features should be highlighted:

- Predictive Handover Management: Traditional handover mechanisms in 4G and early 5G rely on reactive thresholds like signal strength and quality. AI/ML introduces predictive capabilities based on historical mobility patterns (e.g., a vehicle's common routes), real-time network conditions (e.g., load, interference), environmental data (e.g., road topology, weather, congestion) and more. By training models on this multidimensional data, networks will be able to pre-select the most suitable target cells, perform conditional handovers (CHO) more intelligently, and even reduce ping-pong effects and handover failures, especially in dense urban and ultra-dense networks [68].

- Adaptive Mobility Parameter Tuning: AI/ML can dynamically optimize mobility parameters (like Time-to-Trigger, handover margins, hysteresis values) in response to live network or environmental conditions such as changes in UE velocity, detected interference patterns and cell load and user distribution. This capability is foundational to Self-Organizing Networks (SON) and Zero-Touch Network Operations, allowing networks to automatically fine-tune mobility strategies in real time without manual reconfiguration [68].

- Reinforcement Learning for Policy Optimization: AI-based agents can use reinforcement learning (RL) to continuously improve handover decision policies based on reward functions such as minimizing handover interruption time, maximizing throughput and quality of experience (QoE) and reducing signalling overhead. This is especially useful for multi-connectivity scenarios and inter-PLMN HO scenarios, where the agent can learn optimal link-switching behaviours [68].

AI/ML in Inter-PLMN Handover Optimization

AI/ML mechanisms are also envisioned to significantly assist with inter-PLMN HO optimization in the upcoming Rel.18 and Rel. 19 of 3GPP. The two most promising such mechanisms can be noted as:

- Dynamic PLMN Selection: In inter-PLMN scenarios (such as cross-border mobility or multi-operator network sharing), AI/ML can predict which PLMN the user should connect to, based on application QoS, expected coverage duration, and current network congestion. The optimal time and method for executing the PLMN switch will also be affected, allowing for smoother transitions for CAM applications, when the conditions for a HO are optimal [2][68].

- Context-Aware Session Continuity: AI/ML can help maintain service and session continuity (SSC) during inter-PLMN handovers by predicting whether to retain, release, or migrate session anchors (like the UPF). Ensuring the optimal SSC mode (1, 2, or 3) is applied based on service requirements and network state, will help guarantee low-latency and uninterrupted service — a core requirement for autonomous driving and real-time communications.

Looking further ahead to 6G networks, AI/ML will move from being an optimization tool to becoming a core architectural component, enabling intent-based networking, where UEs specify desired outcomes (e.g., "low latency for HD video", "low interruption time"), and the network self-configures accordingly. Moreover, federated learning, will allow for distributed training of mobility models without compromising user privacy, while digital twins of the radio environment will simulate and test mobility strategies before real-world application. Such advancements would significantly improve the user experience of a CAM user in cross-border areas, as HO and MM settings will be optimised individually for each autonomous vehicle [69].

Efforts in the academic / research world, also seem to heavily focus on AI/ML enabled mechanisms and features for improved MM and HO optimization in future cellular networks. The "Deep-Mobility" model employs deep learning neural networks, including Recurrent Neural Networks (RNN) and Long Short-Term Memory (LSTM) networks, to analyse network KPIs for efficient handover decisions [70]. By continuously monitoring RF signal conditions and system-level inputs, this approach aims to enhance handover reliability in ultra-dense 5G networks.

In another research effort machine learning-based solutions have been introduced that concurrently optimize inter-frequency and intra-frequency handover parameters [71]. By leveraging models like XGBoost and Random Forest, these solutions aim to maximize KPIs such as edge user signal strength, handover success rates, and load balancing across frequency bands. Recent studies have proposed using Proximal Policy Optimization (PPO), a reinforcement learning algorithm, to develop adaptive handover protocols. These protocols dynamically adjust to varying user equipment speeds and network conditions, outperforming standard 5G NR handover procedures in terms of data rates and reducing radio link failures, as explained in [72].

Following a slightly different direction, S. Jun et.al. propose a multi-radio multi-connectivity (MR-MC) technology to overcome the challenges of high path loss and directionality in the sub-THz band in 6G networks, The presented MR-MC architecture that simultaneously connects to LTE, NR, and sub-terahertz (THz) bands, allows the usage of Conditional HO (CHO) to support reliable mobility enhancements. Simulation results indicate that the proposed structure effectively reduces signal delay and service outage issues through multi-connectivity.

Finally, major global stakeholders continue to investigate approaches to further optimize the HO performance of B5G networks, however these investments are mostly focused on major population centres as the revenue is expected to be larger, rather than remote cross-border areas. For instance, Nokia has explored multi-connectivity strategies to enhance mobility robustness in standalone 5G networks. By configuring and managing sets of serving cells for each user, their approach aims to reduce connection failures and signalling overhead, ensuring ultra-reliable communication without relying on macro cells as mobility anchors [74]. On the other hand, Ericsson is focusing on reducing handover interruption times through L1/L2 triggered mobility mechanisms in 5G Advanced. By initiating handovers at lower protocol layers, this method aims to minimize service disruptions, which is critical for URLLC applications (such as CAM applications). Even though these solutions are not targeted at cross-border environments, they are expected to improve the overall user experience during handovers and may pave the way for further developments that will also affect cross-border operations.

3 Mobility Management Challenges & Cross-Border Considerations

3.1 Functional & Non-functional requirements for cross-border operations

In order to properly set-up and configure the RAN and core parts of the 5G network to support CAM functionality at cross-border conditions, the main functional and non-functional requirements of such a system need to be identified. The *functional requirement*s practically specify "what a system should do", i.e. the behaviour of the system when certain conditions are met, while the *non-functional requirements* specify "how the system performs certain functions", i.e. the expected behaviour of a system and the limits of its functionality. In the context of this dissertation a survey was performed among 5G network experts from the 5G-MOBIX project [14], comprising five major European MNOs, two major European vendors and other experts, who have identified and prioritised the most prominent functional and non-functional requirements 5G networks should fulfil in order to support CAM functionality in cross-border conditions.

These requirements range from the support of specific functionalities in the radio, core and transport parts of the network down to SLA and roaming agreements. The prioritisation of each of the functional and non-functional requirements is based on the MoSCoW method of requirements prioritization [76], which is a well-established management method, prioritising the requirements of any system into the following categories:

- (M)ust-haves (highest priority),
- (S)hould-haves,
- (C)ould-haves, and
- (W)ould-haves (lowest priority).

By assigning a numerical value to the MoSCoW grades (M=2, S=1, C/W=0), and by aggregating the responses of the experts around Europe (see [77] for exact details) a clear requirements prioritisation was established on a scale of one to ten (1 (low priority) – 10 (high priority)). The resulting classification per functional requirement is shown in Figure 15, while the classification of the non-functional ones is depicted in Figure 16.

Based on the above analysis the support for core eMBB functionality and the support for virtualization are the most critical functional requirements for delivering high quality CAM services in cross border conditions. Both these features should become available with the deployment of 5G core solutions (i.e. SA implementations). Closely behind, mobility support and URLLC functionality will allow for further CAM applications to be supported. In terms of non-functional requirements there does not seem to be a clear winner, as multiple requirements are deemed critical for the successful provisioning of CAM services by 5G networks. Scalability, upgradability, physical and cyber-security, commercial feasibility and reliability are considered key factors that must be present for 5G networks to be able to realistically extend their functionality and reach to a state where they would successfully support the stringent CAM applications.

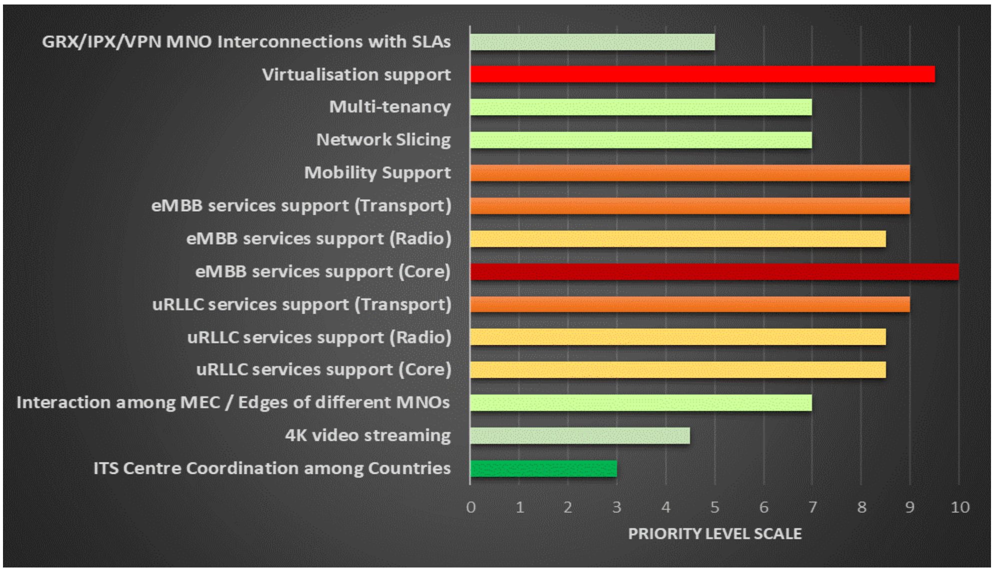


Figure 15: Prioritisation of functional requirements for support of CCAM functionality

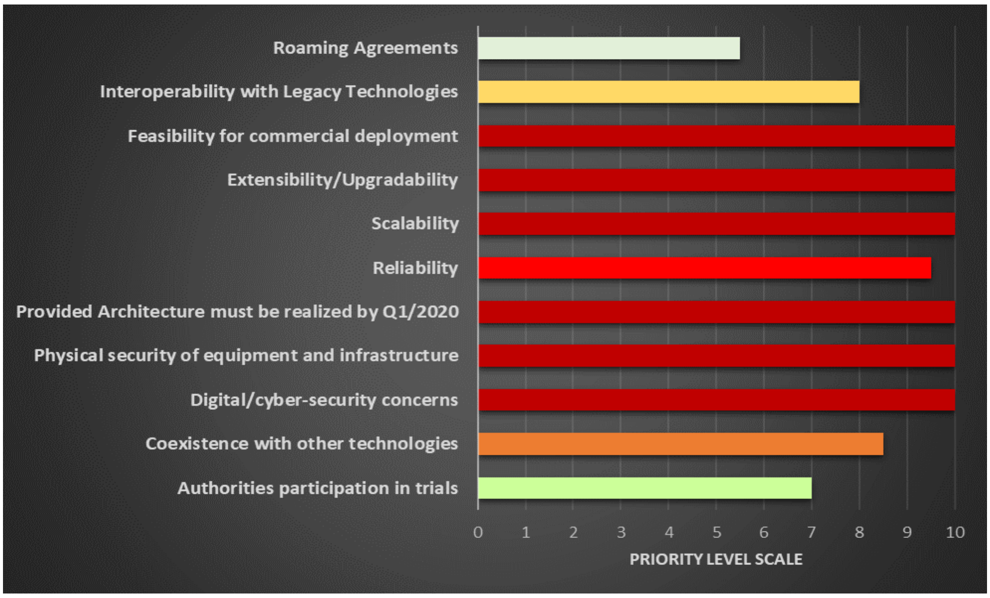


Figure 16: Prioritisation of non-functional requirements for support of CCAM functionality

3.2 Inter-PLMN Mobility Challenges

The cross-border CAM applications operate in a challenging environment where different issues for connected and automated mobility must be addressed to ensure a timely, continuous and seamless operation. Specifically, different EU member laws, stakeholders, industries, operators and economies take place at the EU bridged by a common transit regulation. Thus, the cross-border functionality promotes integration and interoperability taking into account the coexistence and common usage of public and private resources. The core idea behind this study is to investigate the potential cross-border issues and their potential impact, that arise from trying to provide CAM functionality over 5G networks at cross-border conditions. Taking into account the detailed State of the art research presented in Section 0, the issues addressed so far, the remaining pain points as well as the specificities of the cross-border environment (never before considered at this scale), an identification and analysis of the challenges and their potential perspective solutions has been performed. Specifically, the considered issues pivot around four main dimensions for the most common CAM use cases presented in Table 7, namely:

i) *Telecommunications issues* regarding issues arising from the implementation of core technological innovations from 5G, such as new frequency bands, Cloud Radio Access Network (C-RAN), Mobile Edge Computing and network virtualisation infrastructures.
ii) *Application issues* regarding the proper deployment, execution and interconnection of CAM services across different technological, administrative and management domains.
iii) *Security and privacy issues* spanning the communication and application threats at cross border environments, as well as concerns regarding proper data management and ownership.
iv) *Regulatory issues* encompassing all potential road, traffic and bureaucratic regulations that CAM functionality needs to consider.

In the following sub-sections, the most prominent issues of the four identified categories are presented and their potential impact to the proper CAM functionality provisioning at cross-border conditions is discussed. Potential solutions to resolve or mitigate the issues of each category are also discussed. The most promising of the presented solutions, are then implemented in the real-life cross-border corridor of Greece-Turkey, and their impact and ability to improve the observed performance is evaluated under realistic conditions, as shown in Sections 4 and 5.

3.2.1 Telecommunication issues

3.2.1.1 Roaming

International roaming support for V2X communication cases is required when vehicles travel to other countries. Specifically, when a User Equipment (UE), e.g., automated vehicle, crosses the borders, the switching to the new PLMN operated by the neighbouring MNO needs to be performed in an optimum way aiming to fulfil the strict requirements of the CAM use cases and applications in terms of latency and service continuity. Roaming agreements between the MNOs is a prerequisite. Three distinct cases of roaming can be foreseen:

- *Roaming between MNOs with 5G Evolved Packet Core – Non-Stand Alone (EPC- NSA) network solutions support:* Taking into account vendors' roadmap, this scenario seems to be the most likely to happen at the first phase of 5G deployments, exploiting the existing LTE roaming agreements.
- *Roaming between MNOs with 5G SA core network solutions support:* Taking into account vendors' roadmap & the standardization status, this scenario will occur at a later phase.
- *Roaming between a 5G EPC (NSA) network and a 5G SA network:* Interworking functionalities need to be supported at this scenario; roaming extensions or new roaming interfaces (i.e., N26 interface) will be required.

Long roaming latency is expected since the current LTE roaming traffic is Home Routed (HR), meaning that subscribers always obtain service from the Home Packet Data Network (PDN) gateway (H-PGW) and through their home network. As the service is always managed through the same PGW (the H-PGW), service continuity while roaming can be ensured, but nevertheless with increased latency due to the user plane traffic being routed through the GRX (GPRS Roaming Exchange) / IPX (IP exchange) networks to the Home PLMN (H-PLMN). In addition, the Visited PLMN (V-PLMN) does not normally guarantee QoS for roaming UEs using home routing.

In order to deal with the above presented issues a number of *potential solutions* can be envisioned. In certain cases, Ultra Reliable Low Latency Communication (URLLC) resource discovery and allocation may take place within the V-PLMN before the roaming takes place [78], hence partially dealing with the latency concerns (valid for any use case with low E2E latency requirements – see Table 7). In a different more proactive approach, proper selection of roaming network mode (MNOs interconnected via GRX or direct connection) may take place to fulfil the latency requirements. In this case, a direct interconnection for instance could be useful for a border-passage with heavy traffic as it would by-pass the latency-intense GRX interconnection (although this solution is not very scalable). Finally, flexible network configuration may be considered to improve the QoS of services/users, probably considering a proper slice management with 5G SA Core solution. Zero-touch Service Management (ZSM) solutions have the potential to significantly improve roaming performance by assisting with the autonomous (and potentially predictive) allocation of resources in the visited network, thus reducing the total roaming latency.

3.2.1.2 Handover (HO)

The HO process during which a UE changes its network service point (eNB/gNB) is perhaps the most critical one of the entire roaming process and defines in a great degree the service continuity and latency capabilities. The current 3GPP HO procedure is analysed in Section 2.1.3. Three distinct cases can be defined for potential HO scenarios.

HO with overlapping coverage

A bad or uncoordinated cellular planning can induce overlapping coverage issues, where the gNBs radio coverage are highly overlapping. In cross border scenarios (inter-PLMN HO) this scenario is very likely as the MNOs from both countries want to guarantee coverage in their country's territory and as a result a 'spill-over' of coverage from both sides creates unpredictable radio conditions, where the actual HO may take place well before or after the actual border. A high level of overlapping coverage may lead to:

- Interference among gNBs and consequently low SINR (Signal to interference and Noise Ratio) leading to QoS degradation.
- Signal levels are too close to each other leading to disturbance of the UE connection stability, especially, during handover (ping-pong effect).
- The connection drop rate will increase depending on handover rate
- Unjustified signalling traffic load increases.
- At cross border conditions, excessive radio coverage can generate unwanted roaming.
- Cells unbalanced traffic load
- Uplink/Downlink unbalanced cell radio coverage.

Consequently, CAM applications will suffer negative impacts from the resulting QoS degradation. In order to deal with the above presented issues a number of *potential solutions* can be envisioned. The use of intelligent algorithms (e.g., Artificial Intelligence (AI)/ Machine Learning (ML) based resource allocation / slicing mechanisms) may help to anticipate the handover and trigger the relevant processes. In this case a request for HO parameter optimisation may be issued to the network and in case where ZSM is applied, such updates may be effectuated seamlessly and with minimal latency. In a dual SIM scenario, an intelligent switch will decide for the handover and manage this process to be as stable as possible. This solution may lead to increased performance but is not very scalable, as multiple SIM cards from multiple MNOs would be required. As a more generic solution, network mobility solutions should be properly adopted for mobility-agnostic applications, while radio access network parameters configuration, such as transmission power, antenna tilt and height, frequency band, etc. should be thoroughly investigated and agreed upon among neighbouring MNOs, which currently seldom happens among neighbouring MNOs (potentially as part of a common framework).

HO with coverage gaps

The distance among the neighbouring countries eNBs/gNBs or the radio planning of the two neighbouring MNOs, results in areas close to the border where no MNO can provide service, or UE connection to a network is not even possible. These areas of no coverage are identified as coverage gaps and result in complete service interruption, until connectivity can be re-established with one of the networks.

In order to deal with this issue a number of *potential solutions* can be envisioned. Satellite communications may be used to provide service in the areas that 5G connectivity experiences gaps. The moment the network parameters for the other MNO are met, the connection will change from satellite communication back to 5G. During the handover process all data flows will be considered. Such a solution would guarantee service continuity, however, delay sensitive applications (such as CAM applications) may not be satisfied with the satellite provided latency. Handover to 4G if required, may be considered in order to at least guarantee minimal service provisioning. This solution is feasible in cases where the footprint of 4G coverage is different than that of 5G (due to network planning, antenna configurations, utilised spectrum, etc.) but will only result in basic connectivity and will not be able to meet the requirements (in terms of BW or latency) of the most stringent CAM applications Proactive resource allocation may be considered to try and mitigate those issues, while once again detailed network planning & optimization processes for all neighbouring MNOs are considered critical to mitigate this issue.

Hybrid HO

This issue involves the handover between cellular network communication technologies with different performance capabilities, i.e., different RAN and core technologies. This will be particularly common when combining 5G New Radio (5G-NR) with currently available 4G LTE networks. Both cases of HO between a 5G NSA (5G NR + EPC) and a 4G LTE and 5G SA (5G NR + 5GC) and a 4G LTE network need to be considered. Performance degradation in terms of throughput (impact on enhanced Mobile Broadband (eMBB) services), delay (impact on URLLC services) and potential period of disconnection in the HO are some of the most severe anticipated consequences of such a HO.

In order to deal with the above presented issues a number of potential solutions can be envisioned. A Redundant connection using dual SIM has the potential to resolve this issue, however a proper management of data flows in the same end node, using an intelligent router or Software Defined Networking (SDN) capabilities, for instance, would be required. In general, the softwarization of 5G network functionalities (e.g. orchestration functions) have a significant potential to assist the HO management in such cases [79]. In the absence of this capability, the allocation of maximum resources in the target 4G network could be considered to reduce the impact on the CAM services (overprovisioning). In a different approach, network mobility solutions could be applied to make applications mobility-agnostic. In this paradigm, applications should be developed considering network disconnections (e.g., re-direct to visiting country IP-based platform, option of connection-less mode, etc.). This especially applies to IP-based applications in which re-addressing can be present in the handover. Finally, the use of intelligent algorithms may help to anticipate the network change and trigger the HO once the resources are prepared.

3.2.1.3 Inter-MEC connectivity

The interconnection of Edge nodes/MECs deployed at different MNOs network across borders is not trivial. The main problem is the high latency that can be expected between MECs as neighbouring MNOs are usually interconnected through 3rd party GRX/IPX networks. MECs interconnected through GRX/IPX networks or directly interconnected but with international traffic routed to the centre of the IP network, result in significant latencies, not suitable to serve stringent CAM applications / functions. High latency introduced by GRX/IPX networks impacts the QoS of applications requiring URLLC. The traditional routing via the MNOs core which may be located hundreds or thousands of km away becomes problematic as well. The lack of security in such interconnections also poses a significant issue.

In order to deal with the above presented issues, the following approach can be envisioned. In cases where the neighbouring MNOs PLMNs are connected via a physical direct interconnection then their respective MECs may also benefit from this solution, as the traffic may be directly routed between them. This solution, although effective is not particularly scalable as all MNOs of one country would need to have direct connections with all other MNOs of all their neighbouring countries. A direct interconnection with IP network configured with border link (international traffic not routed to centre of MNOs IP network) may be another solution to improve the experienced latency without the need for a physical direct interconnection.

Figure 17 provides an overview of the discussed telecommunication cross-border issues along with their respective considered solutions.

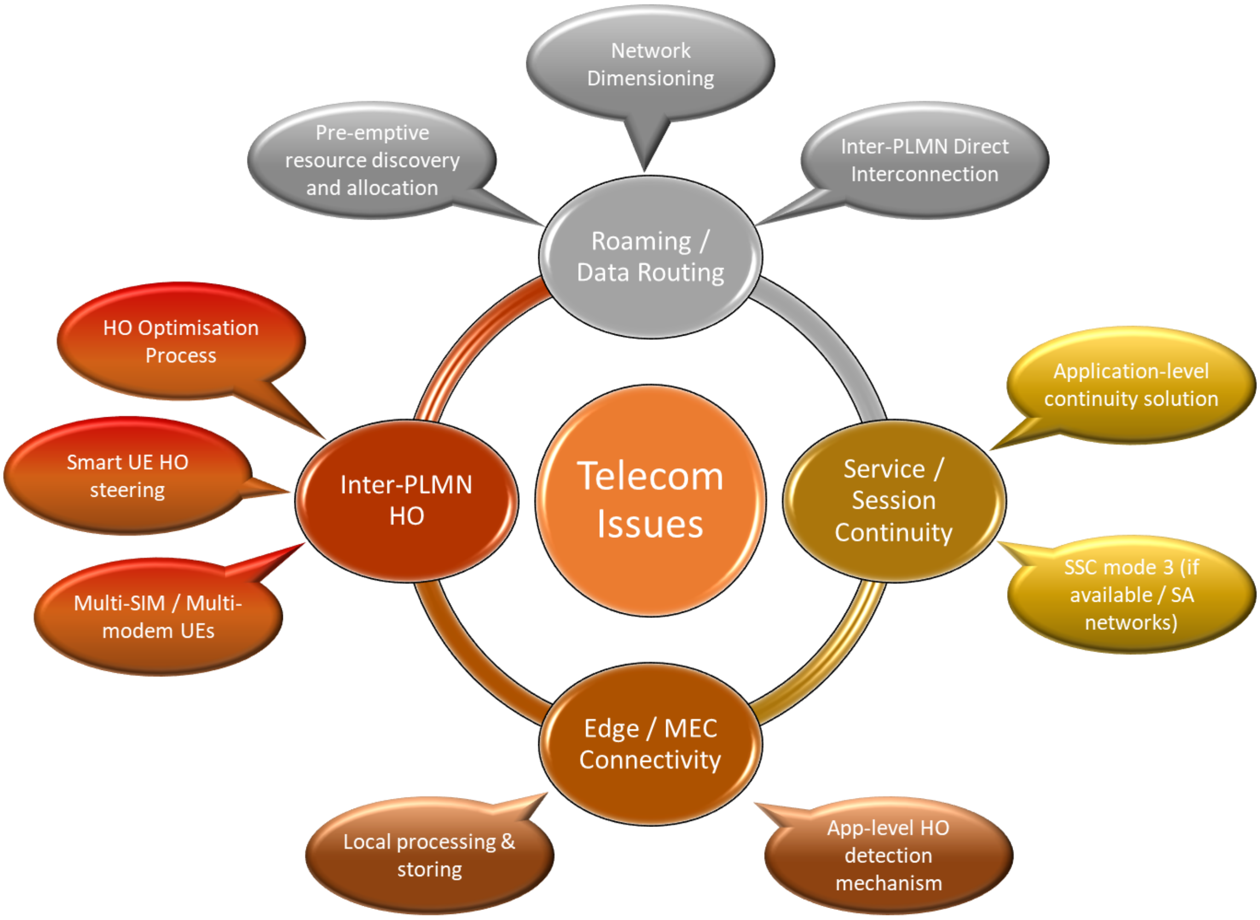


Figure 17: Schematic overview of Telecom issues & their respective considered solutions

3.2.2 Application issues

3.2.2.1 V2X service continuity

Service continuity for CAM applications is of paramount importance especially in safety relevant use cases. Potential unstable communications performance among vehicles, servers and network functions during HO may lead to severe degradation of the application performance and to potential human injury. For instance, in cases of remote driving over a remote-control centre, service continuity must be ensured when roaming from one PLMN to another irrespective of whether the same or different remote-control centres are used (i.e., vehicle needs to be controlled without interruptions even when a change in the control room occurs). In the border surrounding area, V2V communication should be able to be supported for all vehicles irrespective of the PLMN they belong to (e.g., in V2V mode 3 the resources to be used for V2V communication are dictated by the gNB, which could be problematic as vehicles belonging to different PLMNs are controlled by different gNBs). The most common consequences of failing to guarantee this needed V2X continuity are data loss and delay due to roaming and handover, while autonomous manoeuvres may remain unknown, increasing the collision risk which will also be unknown. This type of performance is unacceptable for all safety critical CAM applications.

In order to deal with these issues a number of *potential solutions* can be envisioned. Special measures can be put into place to deal specifically with roaming safety critical applications, while for the rest of the applications the HO delay may be customized through resource pre-allocation and proactive planning [78], to meet their respective performance requirements. For critical applications it is important to have a "fail-safe" strategy in place, where the driver is immediately alerted, the autonomous CAM functionality is disengaged and the control of the vehicle is passed back to the driver, for the duration of the HO. Pro-active measures can also be of help in this case, as information about known events in the handover area may be transmitted prior to the vehicle entering this area where potential HO effects may apply. In a similar spirit, if connectivity among vehicles is not continuous, on-board SW may assist by extrapolating the neighbouring vehicle position based on past trajectory to predict its potential position during handover. Finally, completely autonomous operation of a vehicle (not based on connectivity but rather its own sensors) and Vehicle-to-Vehicle (V2V) based operation should be feasible at least for the duration of the HO process.

3.2.2.2 Data interoperability

A major concern when large amounts of data is exchanged across multiple vehicle vendors, network domains, infrastructure systems or federated service providers is the inconsistent data schemes. In order to avoid issues during handover between different sides of the border, the various Intelligent Transport Systems (ITS) applications need to exchange a multitude of information on the border area, thus creating an overlapping area of concern. Due to different information sources (e.g., from equipment from different manufacturers or different application / functionality developers) two integrated applications or even the two countries' ITS centres may have different information at a given time. Such a mismatch may lead to inconsistent view of the border area, where the number of vehicles or their exact location and trajectory may not be certain. In turn this creates an additional trust issue (which of the two "views" should be trusted?).

The following *potential solutions* can be envisioned for these issues. A rather simplistic but straight-forward solution would be that one of the ITS centres would be nominated (pre-configured) as "Primary", and in case of inconsistent information, all vehicles would trust the information originating from that ITS centre, by default. In an alternative approach, techniques for difference resolution of Decentralized Environmental Notification Messages (DENM) in case of V2V communication could be re-used, i.e., existing techniques for dealing with the reception of DENM messages providing different information about a certain situation [13]. Perhaps the most thorough and complete solution would be the synchronization of neighbouring ITS centres, where such data values discrepancies would be immediately detected, and effective conflict resolution techniques would be applied. In this way, a common view of the border area could be decided among the two ITS centres and communicated to all relevant vehicles.

3.2.2.3 Protocol/APIs interoperability

Inconsistent Edge cloud Application Programming Interfaces (APIs) across different technology vendors and network domains may lead to significant interoperability issues, resulting in problematic CAM application operation or even complete breakdown of their functionality. These CAM applications expect a consistent data format in order to be able to process the incoming data. Other applications / functions, such as the extended perception function expect a homogeneous protocol to access and publish (API) sensor streams. Incompatible solutions in vehicles for raw sensor streams or processed data (events) will lead to malfunctioning of the CAM applications with potentially catastrophic results.

The following *potential solutions* can be envisioned to address this issue. The most straightforward and effective solution would be to standardize the used protocols and data formats, as was the case for Cooperative Awareness Messages (CAM) and DENM messages. Unfortunately, standardization efforts in such a diverse environment comprising infrastructure, platforms and SW development stakeholders are quite complicated. However, a step in this direction could be to involve MEC or centralized functionality which may be tasked with the translation of different messages to a unique format ensuring compatibility. Adoption of standardised messages in such an ecosystem such as the Manoeuvre Coordination Messages (MCM) for Advanced Driving, Collective Perception Message (CPM) for Extended Sensors and map message set, should become a priority.

3.2.2.4 Additional application challenges

Apart from the above-mentioned key issues, some additional challenges need to be noted. *Clock Synchronization* is a critical issue for delay-stringent CAM applications at the border, not only for the potential drift among the clocks of two neighbouring MNOs, but also because of the possibility of a different time zone between neighbouring countries. A clock misalignment or the failure to manage the different time-zones may result in loss of autonomous control of the vehicle. This is especially the case for platooning where the vehicles need orchestration actions with a common timeline and response time of each member. Additionally, *Geo-driven discovery* is a significant aspect that needs to be taken into account. For efficient and effective CAM functionality, all relevant vehicles around a certain area need to receive all up-to-date information based on their geo-location, thus including all relevant vehicles and excluding non-relevant vehicles which would overload the communication channels. Vehicles, roadside infrastructure, MEC and centralised systems need to support this type of geo-driven discovery, which becomes even more challenging in cross-border conditions.

Regarding the synchronization issues some *potential solutions* could be the use of a common time-reference source among all stakeholders and manufacturers, which is hard to enforce. Predictive analytics could also be used in this case, to anticipate the HO to a visiting network and obtain its timing information in advance to prepare and adjust the timing of the relevant CAM applications (account for the drift). Regarding the Geo-driven discovery, the most prominent solution would be to make sure that geo-distribution mechanisms are supported in Roadside, MEC and centralised network systems, both between these systems potentially belonging to different ITS centres, or MEC systems belonging to neighbouring networks. Vehicles should also be able to retrieve geo-location-based information of a predefined area potentially based on standardised V2V communication and pass the knowledge of the surrounding environment onto the participating network components (e.g., MEC) in order for all participating entities to form a single digital image of the immediate environment around the borders.

Figure 18 provides an overview of the discussed application cross-border issues along with their respective considered solutions.

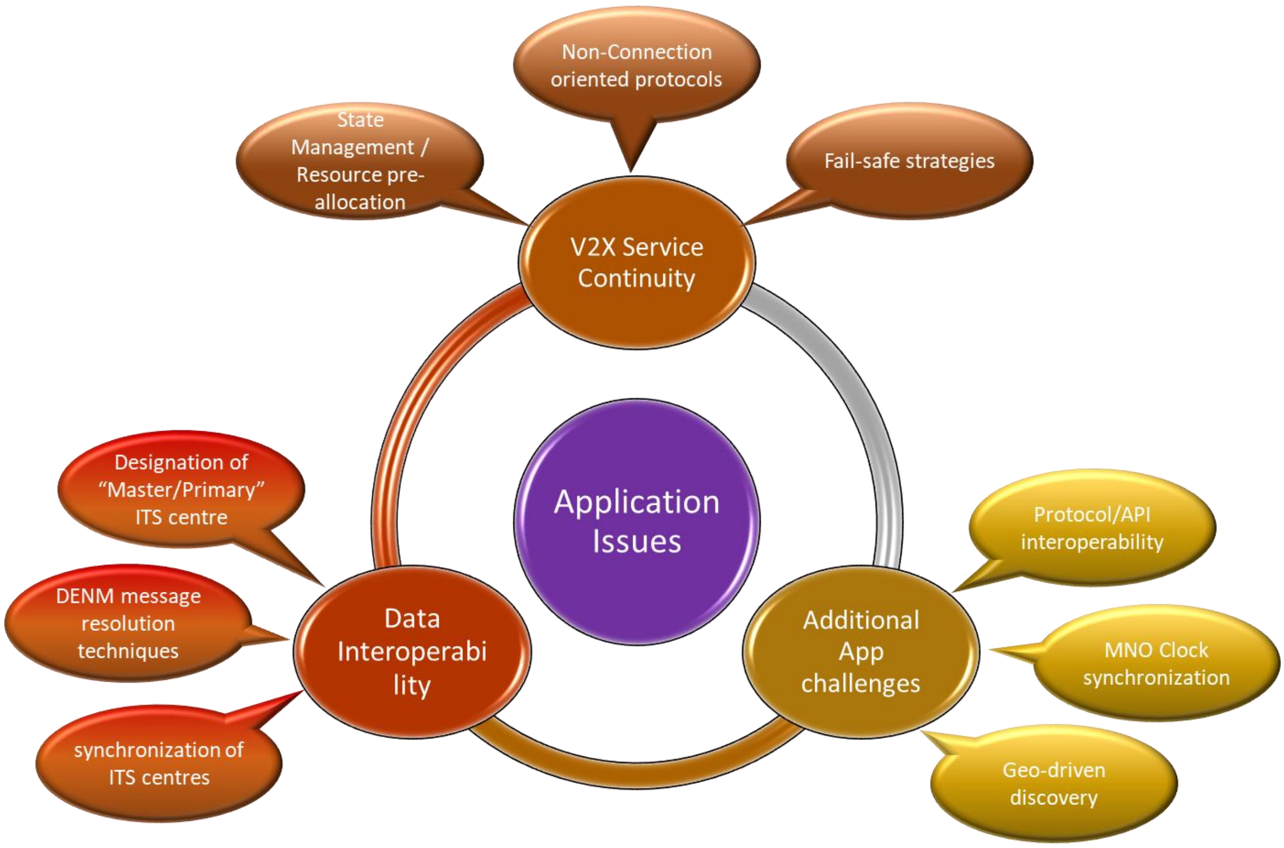


Figure 18: Schematic overview of Application issues & their respective considered solutions

3.2.3 Security & Privacy issues

3.2.3.1 Different personal data protection regulations in non-EU countries

Different data protection regulations apply when processing personal data subject in EU and non-EU countries, depending on the legal framework of each country. Therefore, many legal, organisational, and technical challenges need to be overcome for lawful processing of these data. Different level of data protection may cause services to be unavailable, which could require personal data protection. As a result, certain CAM application may not work properly once a border is crossed, diminishing the trustworthiness and penetration of said applications (e.g., data sharing for Extended Sensors including license plate video recognition may be more/less limited across the borders).

To counter-act this effect, harmonization of data protection regulation, or establishment of agreements between involved countries is necessary. The General Data Protection Regulation (GDPR) framework[10] applicable in EU countries would be a valid starting point, as already many countries that perform transactions and are in business with EU-based parties are forced to address similar concerns. Such negotiations would have to be extended in the CAM domain as well to guarantee the uninterrupted functionality of CAM applications and services.

3.2.3.2 Organizational procedures between different countries

CAM applications supporting cross-border functionality will eventually have to process data from citizens of different countries (e.g., license plate recognition when crossing the border). To this end, proper organisational procedures need to be put in place to handle data protection of the neighbouring country's citizens. These include (but are not limited to):

- Data processing cartography
- Systems' training
- Privacy risk assessment
- Data breach procedures

The management of personal data leaking incidents increases the complexity of this issue which could cause severe security concerns and render a CAM application unsuitable for cross-border functionality. As with the previous issue, any technical solution should be complimented with strong policy decisions in this case, resulting in a legal framework for harmonization of data protection regulation, or establishment of commonly acceptable agreements between participating countries.

3.2.3.3 Technical difficulties for cross-border lawful data processing

The technical mechanisms that are applied in order to support the legal requirements on lawful data processing could encounter difficulties in a cross-border scenario, as neighbouring countries may need to comply to different legal frameworks regarding the capabilities and permissions of these mechanisms. These mechanisms include (but are not limited to):

- Data encryption
- Anonymization/ pseudonymization
- Informed consent
- Privacy by design and by default

These protection mechanisms could be incompatible between EU and non-EU countries, which could result on more difficult handover procedures or limited functionality of a CAM application, once the border is crossed. Similar to the previous solutions a framework of collaboration among neighbouring MNOs needs to be established while it can be assisted by Artificial Intelligence (AI) mechanisms and predictive analytics where autonomous negotiations algorithms may agree on a minimum set of commonly agreeable configurations / settings for the

[10] https://gdpr-info.eu/

functionality of the applications in questions (e.g. list of encryption mechanisms that are considered acceptable in the respective countries, minimum capability negotiations, etc.).

Figure 19 provides an overview of the discussed application cross-border issues along with their respective considered solutions.

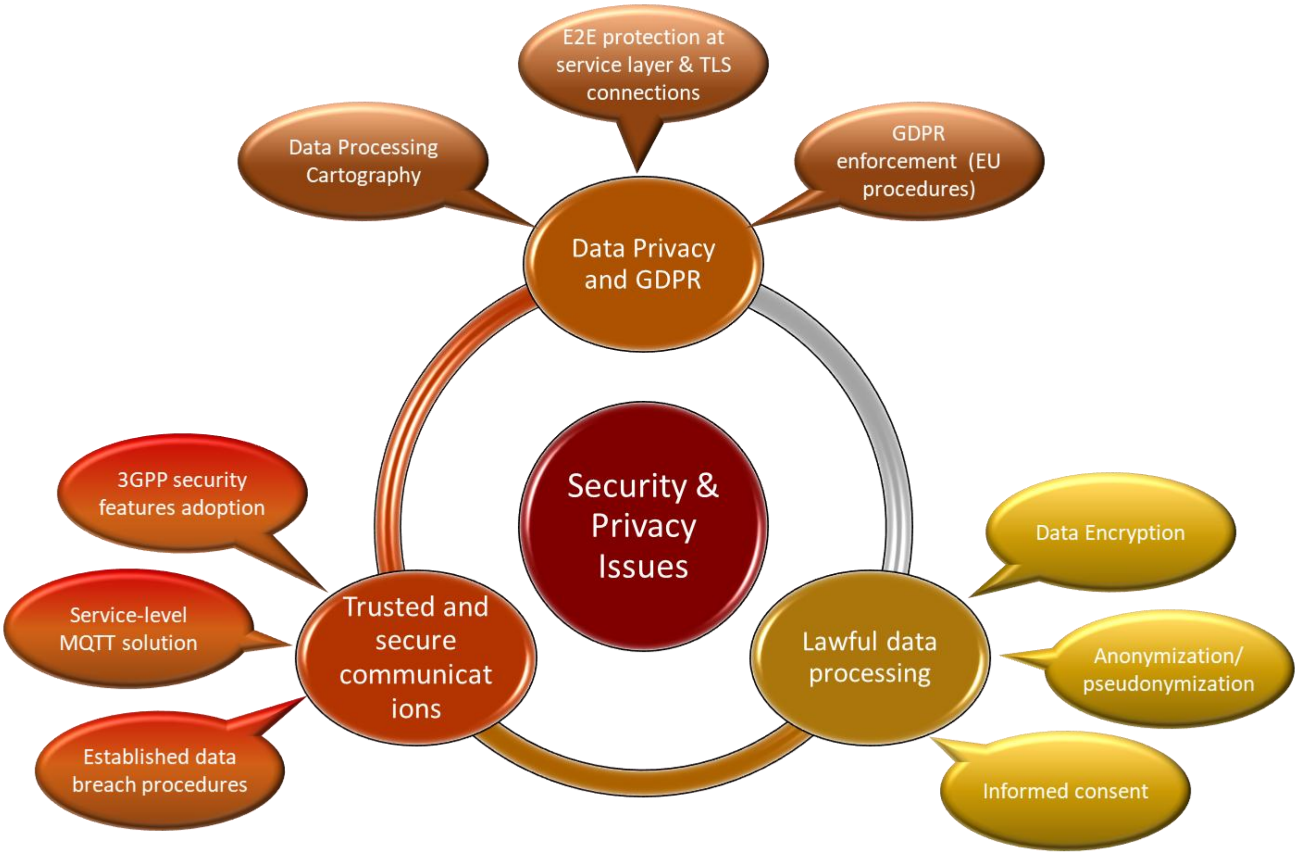


Figure 19: Schematic overview of Security & Privacy issues and respective considered solutions

3.2.4 Regulatory issues

3.2.4.1 Autonomous vehicle regulation compliance

There are no national or international regulations specified for the roads and the corresponding autonomous vehicles moving on these roads. For instance, different vehicles will have different safety distance levels for emergency braking situations. In case of handing over the control of the driving from vehicle to driver, there should be standardized driver warning systems (which are not in place currently).

A situation where a connected and automated vehicle (CAV) has been homologated for the source country but not for the destination country may occur. As an example, an Autonomous vehicle A has successfully passed the minimum tests required to drive in autonomous mode in country A, but it has not passed the tests on country B, or the tests are different in the two countries; and therefore, autonomous vehicle A is not authorized to be driven in autonomous mode in country B. These tests ensure that the CAV is safe on that country, e.g. it takes into account the local laws, it has installed the maps for the route, etc. Lack of regulations may affect the vehicular hardware selection and its specifications; hence, compliance to several different systems of different brands can be costly from the perspective of OEMs.

In order to deal with the above issues, there should be a regulation in terms of hardware specifications and capabilities per country as well as border-conditions for cross-border functionality. By using a standardized software algorithm, an adaptive behaviour in each CAM application can be defined for each vehicle according to their capabilities and status. Additionally, driving license trainings can be rearranged according to SAE levels of autonomy of the vehicles and also for specific applications such as platooning.

In an alternate approach, geo-fencing or GPS may be used to restrict the operation of the vehicle in autonomous mode to the areas where it is legally approved. In case the destination of the travel is an area outside of the approved domain the vehicle shall ask the user to take control and then deactivate its autonomous driving or even perform a safe stop autonomously.

3.2.4.2 Road & traffic regulation compliance

Neighbouring countries may have different traffic rules. This means, the CAV software needs to be adapted to the target location, so that it knows how to behave to respect local traffic law. In addition, roadside units of a specific region may need to supply different message types/content that may not be understandable by the foreign vehicles. In such cases the vehicle might break the law if this has not been taken into account in the design of the algorithm, or the autonomous driving function might be restricted to certain road types, e.g., highway chauffeur. The lack of understanding in safety related messages may lead to dangerous traffic conditions for all road users.

Different approaches can be envisioned to deal with the above-mentioned issues. The legislation of the destination markets shall be well known by developers so that the Autonomous Driving (AD) algorithm may (re)configure its behaviour depending on the vehicle location. This adaptation can be done in several forms:

- Create High Definition (HD) maps that consider all countries where the vehicle will be allowed to drive and store not only the road but also all the traffic signs. Add the information about the type of road (urban, highway, etc.) to the onboard map database so that the vehicle does not depend on the road code to determine the road type.
- Traffic management centre and RSU at the border shall inform vehicles that they enter another country and also inform them about the traffic rules. Autonomy level of the vehicle can be changed accordingly.
- The CAV shall check its current location before AD can be activated to ensure it is prepared to drive autonomously on that location and type of road.

Alternatively, in a less technical approach, neighbouring country Road Administration Authorities may exchange a commonly agreed format of expected behaviour of CAVs on common international level traffic legislations and laws, in order to standardise the traffic rules.

3.2.4.3 Law enforcement interaction

The rapid deployment of autonomous vehicle technology will undoubtedly have a significant impact on public safety services, including law enforcement agencies. In fact, CAV's will reshape the nature of the interactions concerning police authorities. Police officers and other law enforcement authorities must be able to interact with CAVs on the road. To do this, new police interaction protocols have to be designed to communicate with CAVs. As an example, a police officer may need to stop a CAV for a security check, and to do that it has to send a stop request to the vehicle.

Besides the obvious solution of the police making use of autonomous vehicles capable of communicating (over the same protocols) with other CAVs, a common message set/protocol dedicated to public safety/emergency response interactions should be standardised at European Level (and potentially even in international level). All security authority interactions with CAVs should be protected with highly graded encryption algorithms and should allow authorities to intervene to prevent dangerous situations (e.g., police officers having the capability to force stop a vehicle not obeying orders). Emergency bands and message sets may be defined for this purpose.

Figure 20 provides an overview of the discussed application cross-border issues along with their respective considered solutions.

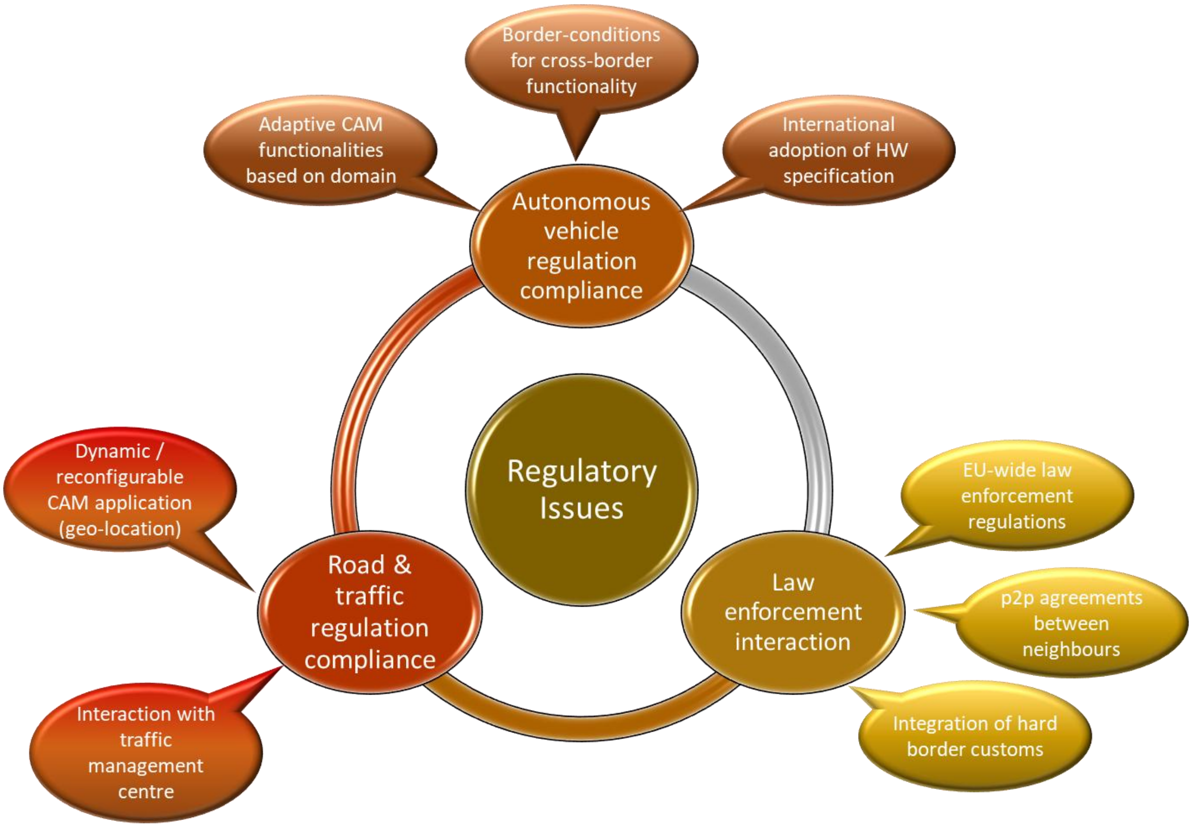


Figure 20: Schematic overview of Regulatory issues and their respective considered solutions

3.3 Technological enablers for cross-border solutions

In order to support URLLC functionality over 5G networks, the 3GPP has upgraded the existing MM mechanisms with certain features that are either trying to minimize (or even completely eliminate) the interruption time introduced by (inter-PLMN) HO or attempting to optimize the data routing across the different networks (PLMNs) targeting a more efficient use of resources and reduced end-to-end latencies. These mechanisms/optimizations termed *Session and Service Continuity* and *Home Routing vs Local Break-Out*, respectively, are presented and discussed below. Moreover, the different options for the deployment of MEC/Edge servers and their respective advantages and disadvantages are also discussed.

3.3.1 Service & Session Continuity (SSC)

Session continuity is defined as the capability of a node to maintain its ongoing IP sessions while changing its (IP) point of attachment (when changing network). The simultaneous switching of the application server and host as well, while maintaining full operational capacity for the application is termed service continuity. Maintaining session and service continuity in cross-border conditions (i.e. when changing PLMNs) is perhaps the biggest challenge of the CAM stakeholders at this time, proven by the commissioning of three Innovation projects from the EU tasked with researching CAM functionality at cross-border conditions, namely 5G-MOBIX[14], 5G-CARMEN [15] and 5G-CROCO[16].

3GPP has defined three Session and Service Continuity (SSC) modes [2] for the 5G system, caring for different situations. With SSC mode 1, the Home User Plane Function (UPF) acting as a Packet Data Unit (PDU) Session Anchor is maintained throughout session lifetime regardless and the UE's session IP address does not change. Such a choice provides IP continuity (i.e., minimal to zero interruption) but it leads to increased end-to-end delays due to the sub-optimal UE-UPF path. In SSC mode 2, the network may trigger the release of the PDU session and instruct the UE to establish a new PDU session from its new location. In this scenario, the IP address changes and a new PDU Session Anchor UPF may be selected. In this case, there is an interruption of connectivity (IP change), but an optimal UE-UPF path is selected, providing optimum latency.

Finally, SSC mode 3 introduces the Make-Before-Break (MBB) mechanism, where the network ensures that there is no loss of connectivity, while at the same time optimizing the UE-UPF path based on UE mobility. The network allows the UE to establish connectivity via a new PDU Session Anchor UPF before connectivity between the UE and the previous PDU Session Anchor is released. Consequently, there is a time at which the UE maintains two parallel PDU sessions with different Anchors in the network. SSC mode 3 involves changing the IP address but supports service continuity through the MBB mechanism. Table 9 summarizes the three SSC modes and provides the main advantages and disadvantages of each one.

Table 9: Definition and pros/cons of the Service and Session Continuity modes

SSC mode	Definition	Pros	Cons
Mode 1	The Home Packet Gateway (H-PGW) is maintained throughout the session lifetime and the UE's session IP address does not change.	IP continuity (i.e., zero interruption)	Increased E2E latency due to suboptimal path
Mode 2	UE established a new PDU session with the Visiting PGW, acquiring a new IP address.	Optimum E2E latency due to short data path	Interruption of connectivity (IP change)
Mode 3	Make-Before-Break (MBB) mechanism → network ensures that there is no loss of connectivity, while at the same time optimizing the data path.	Service continuity + optimal E2E latency (short data path)	Only available with 5G-SA architecture + Complex/ expensive UEs

The SSC3 approach seems ideal for stringent CAM applications where both service and session continuity and low latencies need to be guaranteed when changing PLMNs, however such a solution requires a 5G SA architecture, i.e., utilizing a 5G Core (not EPC) on both sides of the border and it also requires more expensive and complex UEs with multiple Tx/Rx chains, capable of maintaining two parallel connections. Figure 21 depicts the steps involved in an inter-PLMN HO for a vehicle with SSC mode 3 activated.

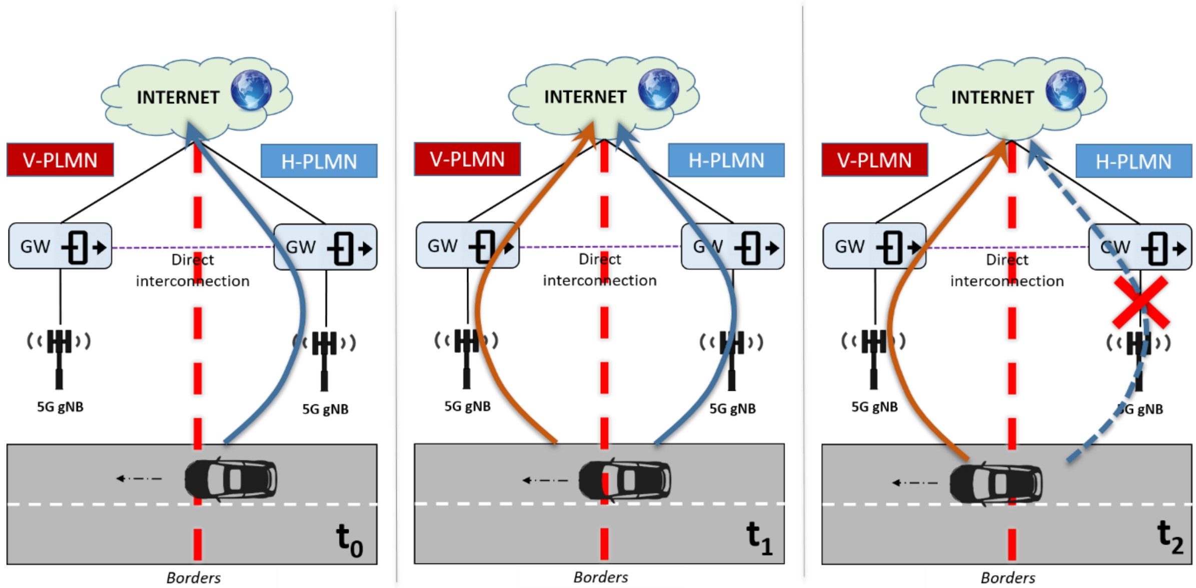


Figure 21: Depiction of vehicle inter-PLMN HO with SSC mode 3

3.3.2 Data routing options (HR vs LBO)

Based on the analysis presented in [53] and according to the 3GPP defined roaming service access policies used by mobile terminals [2], two main roaming types exist:

- ***Home Routing (HR)***, where subscribers always obtain service from the home PDN gateway (H-PGW) and through their home network. As the service is always managed through the same PGW (the H-PGW), service continuity while roaming is ensured, but with increased latency and resources utilization due to the routing of user plane traffic through the GRX/IPX network to the Home PLMN.
- ***Local Break-Out (LBO)***, where subscribers obtain service from the visited PGW (V-PGW). In effect, this provides better user experience and significantly reduced roaming service delay (payload traffic does not traverse through GRX but rather stays in V-PLMN network), at the expense of service control, policy control, charging and service continuity that will be disrupted as the sessions must be released and re-established during the handover. LBO, which is a spec compliant functionality, requires re-establishment of PDN session. For LBO to operate the involvement of Home Subscriber Server (HSS) and Mobility Management Entity (MME) modules is required.

In case of a 5G SA architecture using a 5G Core, the Access and Mobility management Function (AMF) determines if a PDU Session is to be established in LBO or HR. In the case of LBO, the procedure is as in the case of non-roaming with the difference that the AMF, the Session Management Function (SMF), the UPF and the Policy and Control Function (PCF) are located in the V-PLMN [3]. The Service Based Architecture (SBA) of the HR and LBO solutions over 5G NSA and 5G SA networks are depicted in Figure 22 and Figure 23, respectively.

These two options have their respective advantages when it comes to supporting CAM cross-border functionality. With Home Routing, the session continuity is ensured (SSC mode 1) as the vehicle may maintain its anchor point in the Home-PLMN (H-PLMN) and as such there will be no session interruption during the inter-PLMN HO. However, such a solution is not particularly scalable when traversing multiple nations, as could be the case when travelling over the TEN-T corridors, as the anchor point of a vehicle could end up thousands of km away from its physical location, while at the same time increased end-to-end latency is introduced (unacceptable for critical CAM use cases).

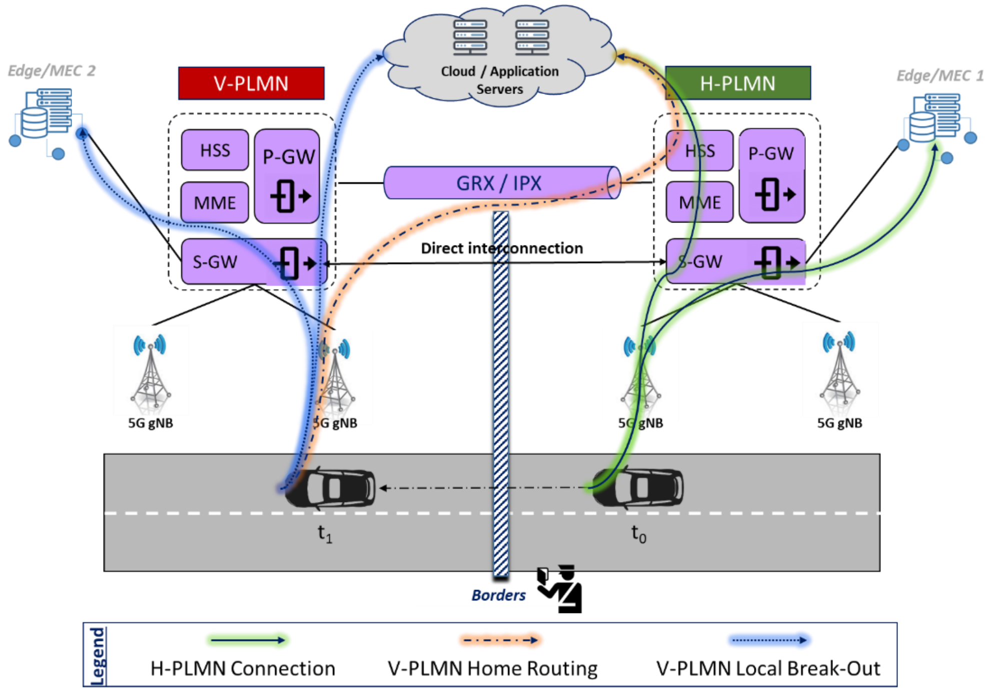
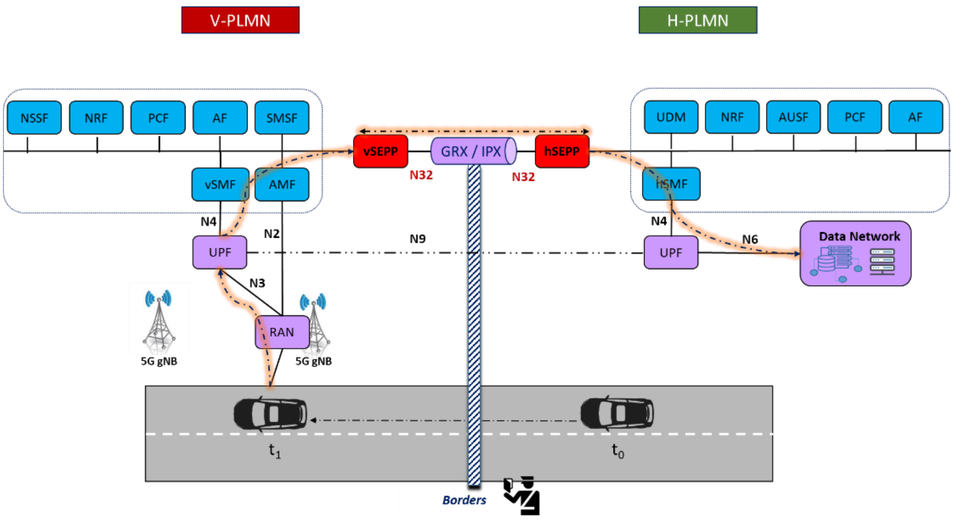
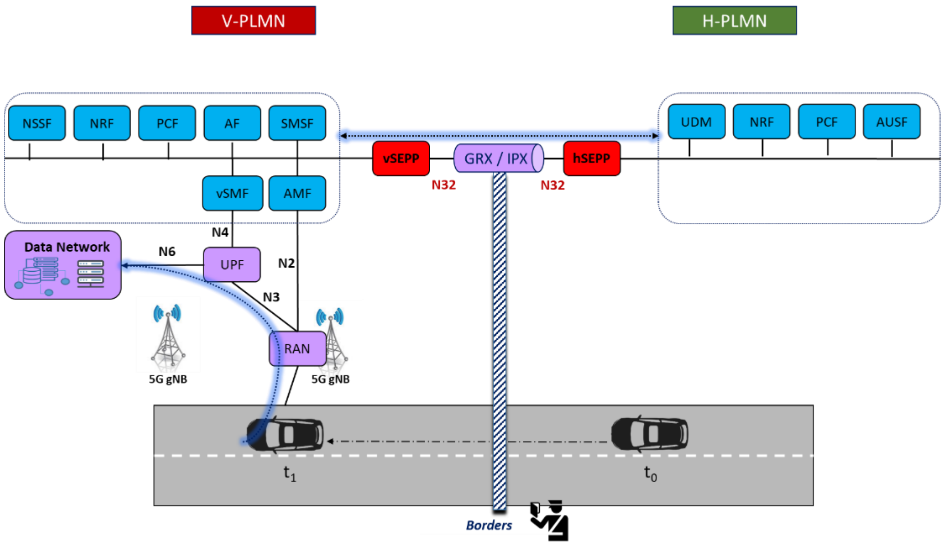


Figure 22: HR vs LBO routing over 5G NSA networks

With LBO on the other hand, an always optimum path to the desired data network is ensured, guaranteeing minimum latency and presenting a scalable solution when traversing multiple PLMNs, however the unavoidable session interruption during the inter-PLMN HO will be problematic for CAM applications. In case of 5G SA network deployment from both sides of the borders, the SSC mode 3 could prove to be the best solution for cross-border CAM support (assuming that it works seamlessly in an inter-PLMN environments), but as the full penetration of 5G SA network across Europe is still a long way from happening, interim solutions will be needed.



a)



b)

Figure 23: 5G SA roaming architecture with a) Home-Routing (HR) and b) Local Break-Out (LBO)

3.3.3 Edge computing / MEC

For the proper provisioning of CAM functionality while roaming, the type of MEC deployed as well as their interconnection among neighbouring MNOs also plays a major role. For the 5G NSA architecture, the resulting MEC deployment options as well as interconnection possibilities to support user mobility are summarised below:

- **Bump in the Wire:** In this scenario, to support low latency communications, the MEC host is placed on the S1 interface of the system architecture in between the eNB/gNB and the core network components (SGW, PGW, MME etc), and the MEC host's data plane must process user traffic encapsulated in GPRS Tunnelling Protocol – User plane (GTP-U) packets. This scenario poses challenges to operations such as lawful interception and charging, possibly mandating a dedicated solution such as a MEC GW to be implemented.

- **Distributed EPC:** In this scenario, through its data plane the MEC host is placed on the SGi interface, connected to the distributed EPC components, where the Home Subscriber Server (HSS) is co-located with the EPC, and the MEC applications can also be positioned next to the EPC functions in the same MEC host. The advantage of the distributed EPC scenario is that it requires less changes to the operator's network and leverages standard 3GPP entities for session management and charging operations.

- **Distributed S/PGW:** This scenario is similar to the Distributed EPC except that only SGW and PGW entities are deployed at the edge site, whereas the control plane functions such as the Mobility Management Entity (MME) and HSS are located at the operator's core site.

- **Distributed SGW with Local Breakout (SGW-LBO):** Local breakout of the MEC data at the SGWs to achieve a greater control on the granularity of the traffic that needs to be steered such as to allow the users to reach both the MEC applications and the operator's core site application in a selective manner over the same access point name (APN).

- **CUPS MEC:** The deployment options above with distributed EPC gateways at the edge, can also be built using the Control and User Plane Separation (CUPS) paradigm standardized in 3GPP Rel.14 and have the new User Plane built in the MEC host allowing the traffic to be locally steered.

As mobility management affects the service continuity it is considered especially critical for CAM applications, and since MEC functionality is an inherent part of most advanced CAM application, *inter-MEC mobility / HO* is equally critical to meet the necessary requirements. In order to provide service continuity to a roaming UE, the MEC system needs to relocate the service delivered to the UE from the source to the target MEC. In the distributed EPC, distributed S/PGW, SGW-LBO and CUPS MEC deployment options, the MEC handover is supported using 3GPP standard "*S1 Handover with SGW relocation*" by maintaining the original PGW as anchor (HR option). Nevertheless, it is the MEC application's responsibility to synchronize at application level and maintain the session in the case of a stateful application. Such a solution suffers from the inherent issues of the HR option discussed above and cannot support demanding CAM application. In cases of direct network interconnection, the available MECs may also utilize this connection inheriting however both the increased performance and scalability concerns.

3.4 Cross-Border Issues Analysis & most promising solutions

According to the latest GSMA report [80], 1 billion 5G devices will be in circulation worldwide by 2024, while by 2025 the penetration of 5G subscriptions will reach 46% in North America, around 40% in China, Japan and South Korea and 30% for Europe. In terms of coverage, a third of the world population will be 5G covered by 2025, however the surface area coverage will be more limited than that, as initial deployments will focus on heavily populated urban areas. This aspect might be quite relevant for the provisioning of CAM services, as 5G coverage will not be ubiquitous, especially in rural and cross-border areas. Unresolved challenges when attempting to roll-out ubiquitous 5G services all over Europe may act as a deterrent for any further investments and may slow down the adoption and penetration of CAM solutions. Hence, it becomes critically important to address currently unresolved as well as future cross-border challenges.

In the previous sections, several prominent cross-border challenges have been identified and categorized into four main categories, which jeopardize the CAM roll out and adoption at cross border areas, both technical and non-technical in nature. Some of the most prominent challenges include the proper interconnection of operator networks and edge computing sites across countries (neighbouring PLMNs), the significant role of service and session continuity, the optimization of inter-PLMN handover and data routing across different data networks, and more. Additional non-technical challenges include the data management and security situation, as well as the existing concerns regarding privacy, GDPR and regulatory compliance for CAM operations in multi-disciplinary/multi-stakeholder cross-border environments. An important insight is that besides the technical and operational aspects, there are also significant nonfunctional, business and regulatory (beyond standardization) aspects which need to be resolved to enable smooth and sustainable cross-border CAM functionality.

Various potential solutions to these challenges were also discussed, based on available technological enablers and the insights shared by key stakeholders. In order to avoid the service continuity problems, the components from different entities need to collaborate for mutual exposure of data and events, such as radio network information, decisions to re-configure the network, or the re-location of the complete MEC/Edge platform and service instances. For inter-domain and cross-border service continuity, the coordination between the different 5G control- and management planes needs to be enabled both locally and federated, based on clear MNO-collaboration guidelines and SLAs. Table 10 provides an overview of the key cross-border challenges discussed in this section and the corresponding considered solutions for each of them.

Table 10: Overview of key cross-border challenges and considered solutions.

Category	Challenge	Description / Overview	Considered Solution
Telecoms / Networking	Roaming / Data Routing	Home Routing vs. Local Break-Out: service/session disruption vs. service degradation.	Network dimensioning with experimental assessment of trade-off in both SA and NSA deployments; direct (leased line) interconnection.
	Inter-PLMN HO	Insufficient network and UE steering capabilities for HO; local UE behaviour not tailored for service continuity.	Meticulous HO optimization process; Smart UE HO steering; Imminent HO detection; multi-SIM/multi-modem UEs.
	Service / Session Continuity	SSC mode 3 with make before break not supported in NSA networks	Application-level solution for interaction with both the UE and the network, stateful application transfer mechanisms.
	Edge / MEC connectivity	Vehicle state lost when changing Edge/MEC servers	Application-level HO detection mechanisms & local processing and storing.
Application / Service	V2X service continuity	Need for application-level support against service disruption.	Non-connection-oriented protocols; state management; “fail safe strategies”
	Data interoperability	Inconsistent data schemes among different network/vehicle domains	Designation of “Master/Primary” ITS centre; DENM message resolution techniques; synchronization of neighbouring ITS centres.
	Additional application challenges	Protocol/API interoperability; MNO Clock synchronization, Geo-driven discovery	Use of standardized message formatting such as CAM/DENM with extended fields; compulsory common time source; Geo-distribution mechanisms.
Security / Privacy	Data Privacy and GDPR	Data privacy through anonymization, data ownership, personal data processing under	GDPR enforcement through common EU procedures, end-to-end data privacy protection at service layer; TLS connections; DPIA, Data processing cartography

		different regulations, common data processing procedures.	
	Trusted and secure communications	Confidentiality, authenticity and authentication features. Lack of trust domain definition results in non-authenticatable information exchange	3GPP security features; service-level MQTT solution using TLS to support message exchange between domains, established data breach procedures
	Lawful data processing	Legal requirements on lawful data processing and interaction are not harmonized across borders.	Data encryption, Anonymization/ pseudonymization, Informed consent,
Regulatory	Autonomous vehicle regulation compliance	No national or international regulations specified for the roads and the corresponding autonomous vehicles (non-homologated vehicles)	International adoption of Hardware specification regulations, border-conditions for cross-border functionality, adaptive behaviour in CAM functionalities based on domain.
	Road & traffic regulation compliance	Different traffic rules per country may require different functionalities / levels of autonomy / behaviour.	Dynamic / reconfigurable CAM application based on geo-location & UHD maps; interaction with traffic management centre;
	Law enforcement interaction	Communication procedures and protocols needed for law enforcement across countries.	EU-wide law enforcement regulations and p2p agreements between neighbours, Integration of hard border customs

3.5 Improvements expected with 5G SA

The 3GPP has also established interfaces and mechanisms that will enhance the roaming procedures among 5G SA networks (using 5G cores) as depicted in the guidelines presented in [79], both in case of HR and LBO. The exact protocols, message flows and APIs for procedures on PLMN interconnection as well as the dedicated interface *N32*, are specified in 3GPP specification TS29.573 [82]. The N32 interface, which is comprised of the Control plane interface (N32-c) and the Forwarding interface (N32-f), is used between the Security Edge Protection Proxies (SEPP) of the H-PLMN and V-PLMN during roaming scenarios. The initial handshake between the networks and the negotiation of the roaming parameters to be applied on the actual messages going over the N32 interface, is performed over the N32-c interface, which is then torn-down to give its place to the N32-f interface over which the actual communication between Network Functions (NF) of the two networks takes place. The N32-f connection uses HTTP/2 and is end-to-end between the two SEPPs and may use an established IPX path between the networks, or in case such a path does not exist an IPsec VPN will be established.

Besides the N32 interface, the *N9* interface is also established in [2] to facilitate the direct communication among the UPF of the H-PLMN and the V-PLMN. As in LBO mode the SMF and all UPFs sessions are under the control of the VPLM UPF, while in HR both instances of the SMFs and UPFs are utilized, the N9 reference point for user plane traffic is only applicable to the HR scenario [82]. Both the N32 and N9 interfaces (depicted in Figure 23) aim to facilitate the direct communication among the necessary NFs of the two neighbouring PLMNs and as such streamline the roaming process between two 5G SA networks, improving the experienced QoS and the relevant KPIs. Such an improvement could be extremely beneficial for the operation of CAM services in cross-border conditions; however, it requires the almost full penetration of 5G SA networks, thus pointing to future deployments and highlighting the need for interim solutions to accommodate 5G NSA and mixed NSA/SA deployments by different MNOs.

4 Technological Considerations & Trial Structure

Some of the most promising solutions examined and highlighted in the previous section, have been put to the test using one of the first available 5G Cross-Border Corridors (CBC) in Europe at the borders between Greece and Turkey. The previously presented state of the art study and theoretical analysis of the challenges, opportunities and potential solutions for the provisioning of 5G enables CAM services at cross-border environments, have paved the way to progress the most suitable and promising solutions for such environments. The work presented in this thesis, is among the first in the world to obtain real life experimental data based on real deployments of 5G NSA networks. This provides the unique opportunity to be among the first global efforts to experimentally verify (or refute) the expected performance based on theoretical analyses and simulation results.

This section presents the details and specifications of the 5G NSA networks, autonomous vehicles, on board units and CAM applications used in the Greece-Turkey (GR-TR) corridor, for the real-life trials that provided the experimental results. Moreover, the specificities of the specific CAM Use Cases including the scenarios, information flow diagrams and targeted functionality are also analysed.

4.1 5G Network Aspects (High Level)

4.1.1 5G Network architecture & Inter-PLMN connectivity

The Greece-Turkey (GR-TR) CBC is located at the Kipoi-Ipsala border region between the two countries. It is comprised of a 10 km stretch of road covered by four Ericsson 5G gNodeBs (three on the TR side and 1 on the GR side) provided by COSMOTE on the Greek side and Turkcell on the TR side, as is depicted in Figure 24. The four gNBs provide 5G Non-Stand Alone (NSA) 3GPP Rel. 15 (option 3x) coverage on both sides of the border. A 100 MHz channel with Time Division Duplexing (TDD) is used with a 20 MHz anchor channel in LTE, on both sides. The three gNBs deployed on the TR side offer clear Line of Sight (LoS) to the trial route (highlighted route in Figure 24) while the GR gNB is significantly further from the trial route (~2.8 km) and does not offer LoS conditions (NLoS), which affects the 5G performance experienced on the GR side.

Figure 24: The GR-TR CBC layout.

Both MNOs already have commercial networks covering the CBC with 4G/LTE at the B7 band (2600MHz), used in this case as the anchor band, while the overlay 5G NR that was deployed on both sides used the n78 band at 3500-3600 MHz for Greece and 3650-3750 MHz for Turkey. All deployed gNBs are equipped with AAS (Advanced Antenna System), a solution that provides cell shaping and Massive MIMO capabilities. A detailed description of the GR-TR CBC may be found in [81].

4.1.1.1 Radio Access Network Planning and Coverage

The existing 4G site locations around the GR-TR borders were also used for the gNBs of the 5G overlay network, however a fine-tuning of the Radio Access Network (RAN) was necessary to ensure coverage at the crossing point where the inter-PLMN HO took place, i.e., no coverage gap and to minimize inter-cell interference between the two networks.

Ericsson's network planning tool was used to estimate the coverage of all four gNBs around the border area, based on Reference Signal Received Power (RSRP) measurement, which are depicted in Figure 25. Good coverage conditions (RSRP > -110 dBm) can be observed along the GR-TR CBC for the most part, however the area where the inter-PLMN HO takes place among the two countries is closer to the lower end of RSRP, due to the larger distance to the gNBs (constrained by the physical location of the existing MNO sites). These conditions create a challenging environment for the provision of CAM Services.

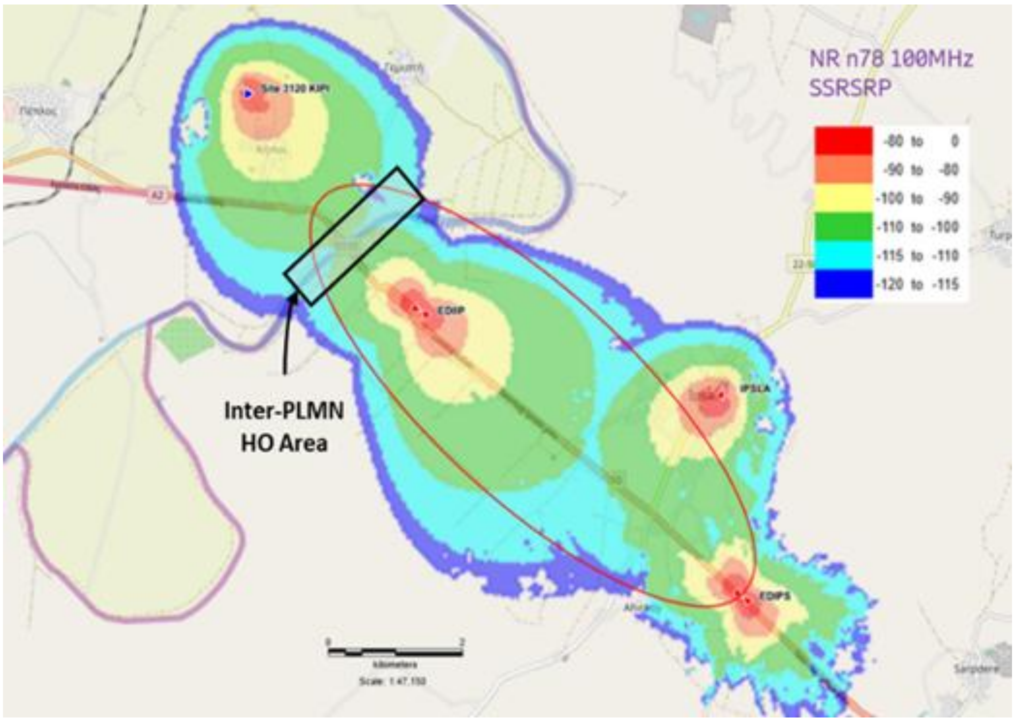


Figure 25: The GR-TR CBC coverage map with RSRP measurements

An <u>interesting insight</u> that was already gained during the initial network configuration and RAN fine-tuning, was the significant effect that environmental factors and dynamic surroundings have on the delivered network performance. Significant variations in delivered throughput and experienced latency were observed on the Greek side of the border for two main reasons, i) a long metal fence running across the Greek customs site (located close to the inter-PLMN HO point) and ii) long queues of trucks which were occasionally formed along the test route between the two countries, waiting to pass customs inspection (depending e.g., on time of day). These two conditions create an unstable and unpredictable propagation environment (blocking / reflections caused by the fence and/or trucks) which affects the measurements, especially on the GR side. *Operators should be aware of the significant impact of the surrounding conditions and dynamic variables (such as vehicle density) on the delivered network performance* and should ensure optimum performance via HO parameter optimization sessions in order to avoid the ping-pong effect due to e.g., reflections and to find a single stable HO point (also dependent on receiver sensitivity). Several optimization sessions were carried out at the GR-TR CBC, in order to optimize network performance along the trial route, before commencing the trials. Without such targeted optimization, i.e., with the use of the standard network settings), the performance observed from a CAM user perspective was universally worse (multiple disconnections and ping pongs, increased service interruption and latency).

4.1.1.2 GR-TR CBC Core Network Architecture

The GR-TR CBC network architecture was defined taking into account the criticality of service continuity and low latency communications for CAM applications. To that end, the core network solutions are deployed at the edge Data Centers (DCs), located close to the border sides. The application servers are connected to the edge DCs, where the complete virtual Evolved Packet Core (vEPC) functionalities are deployed, while the 5G UE – application servers' connectivity is provided over the packet Gateway (PGW) SGi interface. Besides the vEPC, User Data Consolidation (UDC) functionalities are deployed, as well as the supporting Operations Support Systems (OSS) infrastructure. Figure 26 depicts the end-to-end architecture of the GR-TR CBC, including the interconnection interfaces.

To provide service continuity when crossing a country border for CAM applications with stringent high speed, low latency network requirements, the S10 interface is implemented between the Mobile Management Entities (MME) in the two mobile networks operated by the different MNOs to enable cross-border radio handover in seamless operation. Interface S6a (authentication) and S8 (home routed user plane and control plane) are used in all tests as basic roaming interfaces.

The two networks (PLMNs) are interconnected either via a best effort public internet line, making use of the standard GRX/IPX (GPRS Roaming Exchange /IP exchange) interface and/or an IPsec tunnel [3] which is not optimized for delay stringent applications or with a 1 Gbps direct fibre leased line which significantly improves latency between them. During trials, both types of connectivity were used, to evaluate the performance provided by each solution. The fundamental HO procedure as defined by 3GPP in [3] for 5G NSA networks was used during the trials. Release with Redirect was also considered during the trial set-up, however it was abandoned as an option, as it led to connectivity interruptions of several minutes, making it unsuitable for seamless service continuity and CAM services.

The vEPCs are located in the nearest DCs on each side of the border, namely Alexandroupoli in Greece and Kartal in Turkey, and host all the necessary key functions such as the Serving and Packet Gateways (SGW/PGW), MME, the Home Subscriber Server (HSS) and more, as well as the CAM application edge servers supporting the CAM use cases.

The roaming configuration between the two networks during the trials discussed in this thesis was set to Home Routing (HR), meaning that UEs always obtain service from the Home Packet Data Network (PDN) gateway (H-PGW) and through their Home PLMN (H-PLMN). As the service is always managed through the H-PGW, service continuity while roaming can be ensured, but nevertheless with increased latency due to the user plane traffic being routed via the best effort public Internet line to the H-PLMN.

It must be noted that since an NSA variant of 5G was used, there was no slicing support in the core, while in the RAN, the entire channel BW was dedicated to the CAM traffic (without background traffic), essentially emulating a single slice for CAM services (only 1 CAM application tested at a time).

A full overview of all the deployed components in the GR-TR CBC is provided in ***Appendix 1***, offering insights on both network configurations & selected settings, details on the configuration of the roaming schemes and special features used in the RAN.

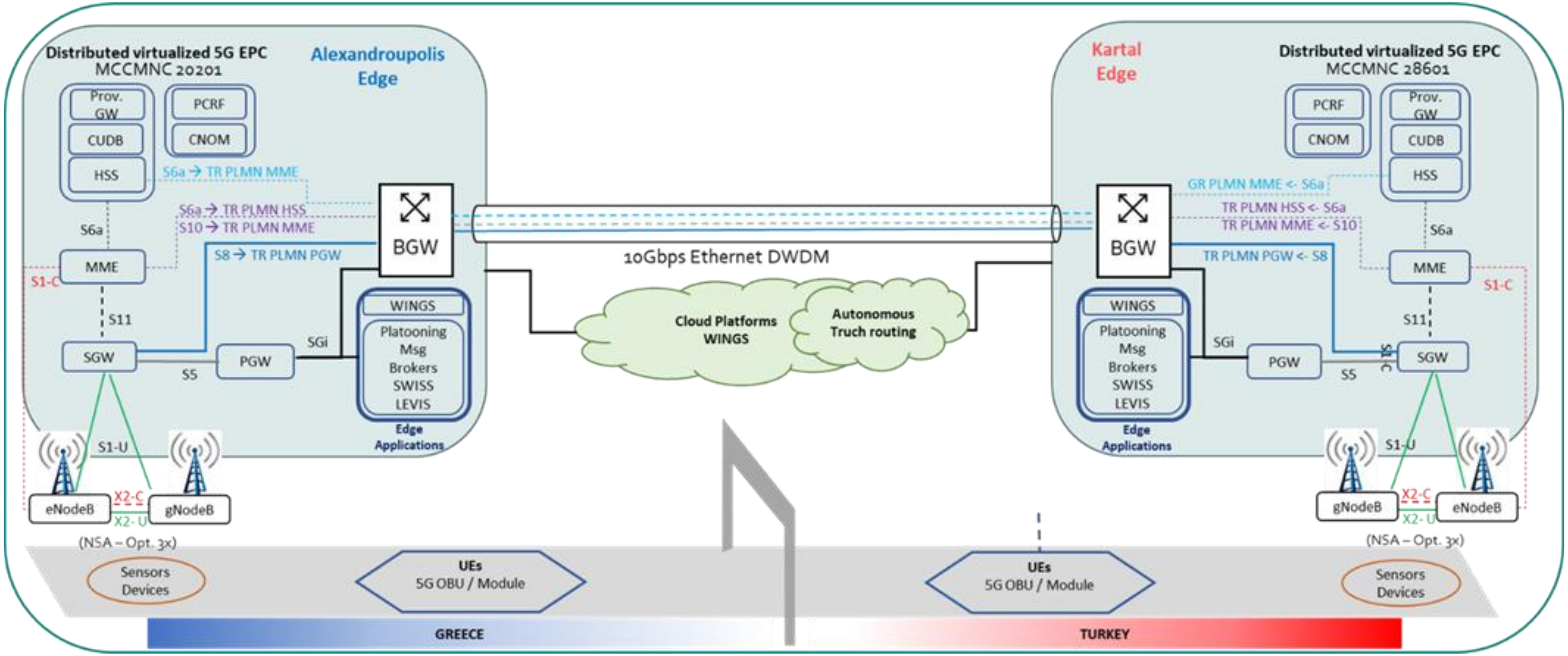


Figure 26: The GR-TR CBC Architecture including inter-PLMN interconnection.

4.1.2 Network operational frequencies & TDD optimization

COSMOTE commercially operates 5G in the awarded frequency bands, including the 3400-3800 MHz band. Given that incumbent legacy systems operate in the 3.5GHz range, the Greek NRA [83] provided some guidelines in terms of synchronised and non-synchronised / semi-synchronised operation that are in alignment with GSMA Recommendation [84]. Specifically, for synchronised operation, it has been decided to utilise the 4+2+4 TDD pattern. In Turkey, no auction had taken place yet as of summer of 2022 for the commercial allocation of the 5G bands, but Turkcell has reserved a test license for the 3.5 GHz band, for the purpose of the 5G-MOBIX trials, where different TDD patterns may be applied.

Generally, in neighbouring TDD deployments, base stations are in a close proximity and even if they are phase synchronized, they can interfere with each other. To avoid interference at least 25 MHz of guard band between operators is recommended [85]. Following, such insights from previous research and based on the GSMA recommendations, a guard band of 50 MHz has been selected for the GR-TR deployment, as depicted in Figure 27. This selection guarantees minimal to zero interference, between the two networks, irrespective of the TDD pattern (to be confirmed by the measurements).

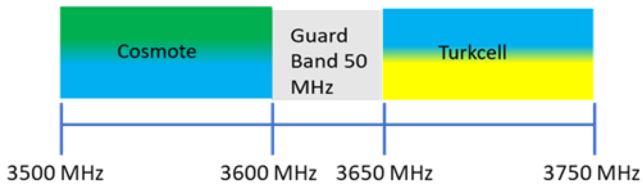


Figure 27: Spectrum Allocation at the GR-TR CBC

As part of the final verification and integration tests performed in the 5G networks of the GR-TR corridor, and before the official CAM trials begin, extensive measurements were taken on both sides of the border to verify the proper functionality of the two networks and to investigate the impact of the usage of different TDD patterns under varying conditions. The measurements focused on the experienced DL and UL throughput using TCP and UDP protocols i) with the neighbouring network activated and deactivated, ii) for different TDD patterns, and iii) with Carrier Aggregation (CA) ON and OFF. All measurements took place from static locations close to the actual border (one location for the GR side measurements and one for the TR side), which translates to an approximate distance of 2.5 km from the COSMOTE gNB for the GR side measurements and 250 m from the Turkcell gNB for the TR side measurements. The measurements results are presented in the rest of this section.

4.1.2.1 Best Practices & SDO Recommendations

It is noteworthy that TDD is not a 5G prerogative; in the 3.5 GHz range, incumbent systems, such as LTE TDD or WiMAX may already be present. Extensive analysis for the unhindered Mobile/Fixed Communications Networks (MFCN) TDD operations addressing all operation modes and conditions is performed by the Electronic Communications Committee of the European Conference of Postal and Telecommunications Administrations (ECC/CEPT) through several published reports that form a detailed handbook to guide policymakers and mobile operators. The Global System for Mobile Communications Association (GSMA) goes a step further by publishing a set of 10 concrete recommendations, including specific proposals for the preferred frame structures.

As a common ground, they both promote the deployment of synchronized neighbouring networks, meaning that all MFCNs in the same band should use (i) a common phase clock reference and (ii) a compatible frame structure to avoid simultaneous UL/DL transmission. Nevertheless, synchronized operations may not always be possible, either because of the existence of incumbent TDD systems or due to the lack of alignment, such as international or cross-border deployments. In the following paragraphs, a selective summary of the prevailing directives guiding the 5G SEAGUL empirical approach is presented, with special focus on the unsynchronized operation modes where interference remedies need to be considered.

ECC on National and Cross Border Synchronization

The ECC Report 296 [86] denotes that synchronised operation of MFCN TDD networks in the 3400-3800 MHz frequency band ensures a higher degree of efficient spectrum utilisation especially for outdoor network deployments in adjacent geographic areas. The unsynchronised operation, if unavoidable, implies the need for large separation distances between unsynchronised macro-cellular base stations/networks with minimum required inter-site distances (ISD) to be 60 Km for co-channel operation and 14 Km for adjacent channel operation without guard bands. Guard bands are intentionally unused frequency bands placed between adjacent frequency bands; while they minimize interference, they incur a performance cost by limiting the effective usage of the full available spectrum.

Unsynchronized operations can be managed with operator-specific filters and inter-operator guard bands, but the most known mechanism for interference avoidance is defined in EC Report 331 [87] to be the Downlink Symbol Blanking (DSB) feature. When DSB is implemented in the 5G NR system, the base stations' schedulers switch off transmissions ("blanking") of those downlink symbols ("blanked DL symbols") that correspond to simultaneous uplink reception, or gap symbols for other networks, to avoid downlink to uplink interference.

To facilitate cross-border coordination in the frequency band 3400-3800 MHz the ECC Recommendation 20(03) [88] proposes the preferred frame structures for MFCNs to be Frame A (DDDSU) and Frame B (DDDSUUDDDD).

GSMA Recommendations

GSMA provides the industry approach for the 3.5 GHz range TDD synchronisation and has published a set of concrete recommendations [84] for alignment among the MNOs. The most relevant recommendations for cross border operation are:

- Recommendation 4 [Synchronization at International Level]: Networks should be synchronized at an international level; nevertheless, priority is given to achieve synchronization at the national level. International alignment is difficult, due to the number of countries involved, the different migration and implementation timescales and the difficulty of negotiating per operator and neighbouring country. It is anticipated that the preferred frame structures are:
  - DDDSU with 30 kHz SCS.
  - DDDDDDDSUU (with a 3ms shift) or DDDSUUDDDD - if LTE is present at the band.
- Recommendation 5 [Cross-border Coordination]: In the border areas where neighbouring countries have not selected the same frame structure, although field strength limits at the borderlines could also apply, it is expected that operators will need to engage in additional coordination efforts.
- Recommendation 6 [Co-existence of non-synchronized networks]: Where no agreements on the frame structure can be reached, the recommendation considers various practical solutions for the coexistence of unsynchronized networks, shortlisting the applicable for this work to be:
  - Network optimization (such as base station location, antenna, direction, and power limits).
  - Downlink blanking where operators, on both sides of the border, agree to stop the use of some of their downlink slots when the other operators are using an uplink slot - although, this will impact performance and may not be supported.
  - A step-by-step migration based on the regional timings of 5G deployments and 4G migrations; 4G networks to be migrated to a different band or to 5G technology.
  - Reduce capacity near the borders, i.e., by only using a part of allocated spectrum.
  - Avoid co-channel use and aim to use adjacent channels.

Besides the above, the GSMA suggests that countries also agree on acceptable signal strength levels at borders (on a bilateral, multilateral, or regional level). It is worth mentioning that while GSMA endorses various mitigation techniques as in Recommendation #6, the use of guard bands and filters between two networks using adjacent channels is considered neither spectrally efficient nor commercially viable and thus not recommended.

4.1.2.2 Performance with neighbouring PLMN ON/OFF

In order to assess the impact of potential TDD interference from the neighbouring network, the throughput at the Turkcell network was measured with COSMOTE network activated and deactivated, while both networks use the same TDD pattern, i.e., the 4+2+4. The UL throughput was selected as the most suitable metric, as most networks are UL limited.

Figure 28 depicts the measured throughput at the TR side measurement point under the Turkcell network which was steadily measured around 140 Mbps with UL CA activated. As this measurement verifies, the operation of the neighbouring (COSMOTE) network has practically no effect on the measured performance, which was expected due to the large guard band used between the two MNOs (50 MHz).

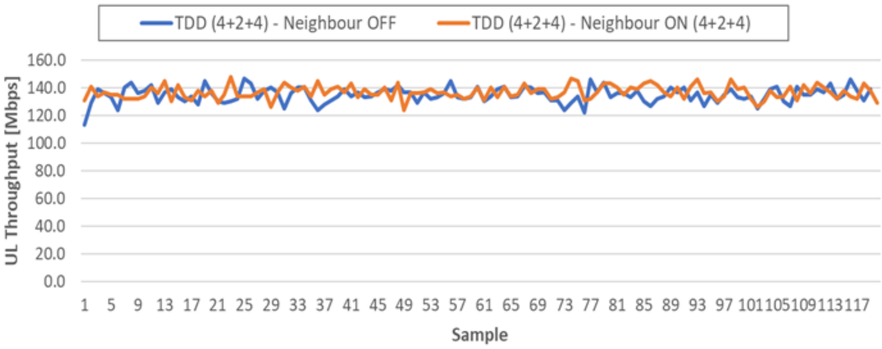


Figure 28: UL Throughput @ Turkcell network with COSMOTE network ON and OFF (same TDD pattern).

4.1.2.3 Performance under different TDD patterns

To investigate the potential impact on performance of the different TDD patterns for TCP and UDP traffic, a series of measurements were performed using the two most common TDD patterns described in GSMA recommendations, namely the 4+2+4 and the 4+1+3+2. Figure 29 depicts the UL throughput measured at the GR side measuring point under the COSMOTE 5G network. It can immediately be observed that the 4+1+3+2 clearly outperforms the 4+2+4 pattern by up to ~60% (avg. 40 Mbps vs 64 Mbps). This observation is in line with the used frame structure as the 4+1+3+2 pattern allocates 30% of the frame to UL slots, while the 4+2+4 pattern only allocates 20% of the frame to UL slots. The use of TCP or UDP traffic does not seem to affect the experienced data rate at all (almost identical performance), while a comparison with the Turkcell network measurements for the 4+2+4 with UL CA deactivated (Figure 28) indicates that the average UL throughput is lower at the GR side. This is due to the much larger distance of the GR measurement point from the serving gNB (see beginning of Section 4).

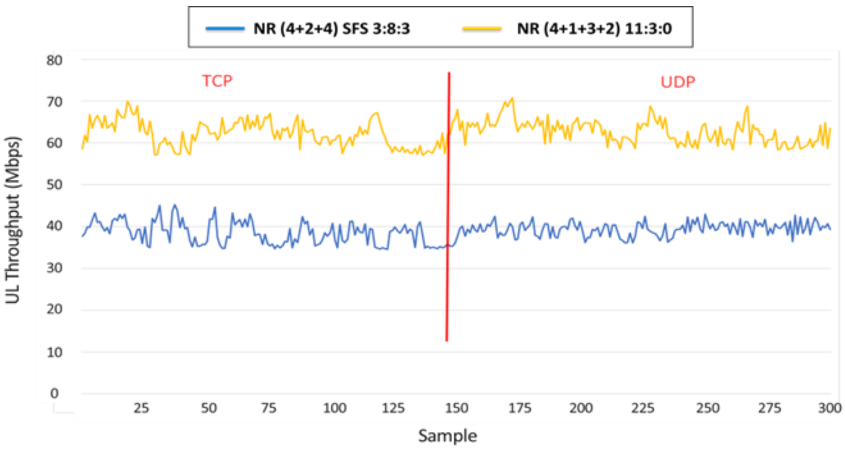


Figure 29: UL Throughput @ COSMOTE with two TDD patterns for TCP and UDP traffic.

Regarding the DL throughput measurements (Figure 30), the average DL throughput at the GR measuring point (2.5 km from the serving gNB) was found to be around 560 Mbps, while the used TDD pattern did not seem to have any significant impact on the experienced DL data rate, despite the different DL slot allocation. This is especially true for UDP traffic where the data rate showcased less variations.

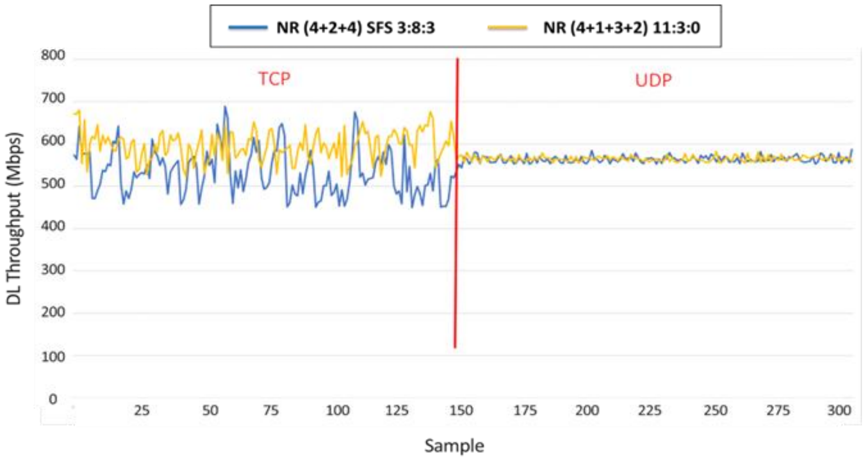


Figure 30: DL Throughput @ COSMOTE with two TDD patterns for TCP and UDP traffiψ.

4.1.2.4 Performance with Carrier Aggregation (CA) ON/OFF

The effect of UL LTE and NR Carrier Aggregation (CA), i.e., the combined use of different spectral resources from LTE and NR to increase the user data rate, was also tested at the TR side and the Turkcell network by taking different measurements with the CA activated and deactivated. Figure 31 depicts the UL experienced TCP throughput for the two different TDD patterns and with CA ON and OFF. In both cases a significant increase of the experienced UL throughput is observed when CA is activated, from an average data rate of about 80 Mbps to an average of 136 Mbps. The use of different TDD patterns did not seem to have any effect on the received CA performance boost.

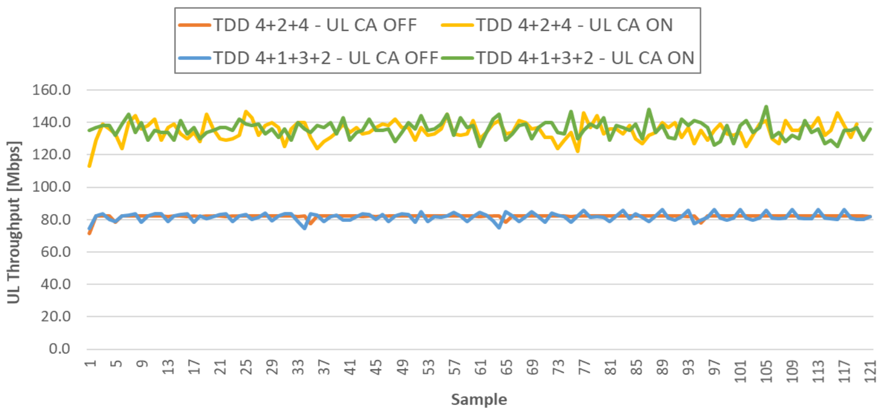


Figure 31: UL Throughput @ Turkcell for two TDD patterns and CA ON/OFF.

The above field measurements on the effect of TDD network synchronization were performed, to investigate the impact of neighbouring 5G networks operating in adjacent bands and the effect of the different TDD patterns. The presented results indicate that the use of *significant guard bands* (as also recommended by GSMA) *protects neighbouring networks from interference*, while *some significant variation in UL performance can be expected* by the use of *different TDD patterns*, according to their slot allocation. *NR and LTE carrier aggregation was also shown to significantly improve UL performance*.

4.2 OBU/Vehicle aspects

4.2.1 OBU Specifications

The On-Board Unit (OBU) is designed to collect and send real time vehicle information. As a computation platform, the raspberry pi 3 is used with a SIM7600 modem attached, providing 2G (GPRS)/3G/4G connectivity. An additional 5G Quectel RM500Q chipset is integrated into the OBU to enable 5G connectivity. The OBU may also work over Wi-Fi connectivity that is build-in the raspberry pi. Power supply is provided from the connected vehicle's battery, through the On-Board Diagnostics (OBD) port connection. There is a capability for secondary power supply from AC voltage (220 V). Once powered up, the OBU starts transmitting data with a refresh rate starting from 1 second.

There is a multitude of onboarded sensors with a wired connection to the OBU, that provide CO_2 , GPS, proximity, acceleration and ECU data. A mini buzzer is used as an alarm indication to inform the vehicle's driver that an obstacle has been detected. The NFC scanner attached, is used for cargo monitoring. The exact specifications of the onboarded sensors are provided below. Figure 32 below depicts the design of the WINGS OBU and its external connectivity to sensors, while Figure 33 shows a picture of the actual implemented WINGS OBU and its connected sensors.

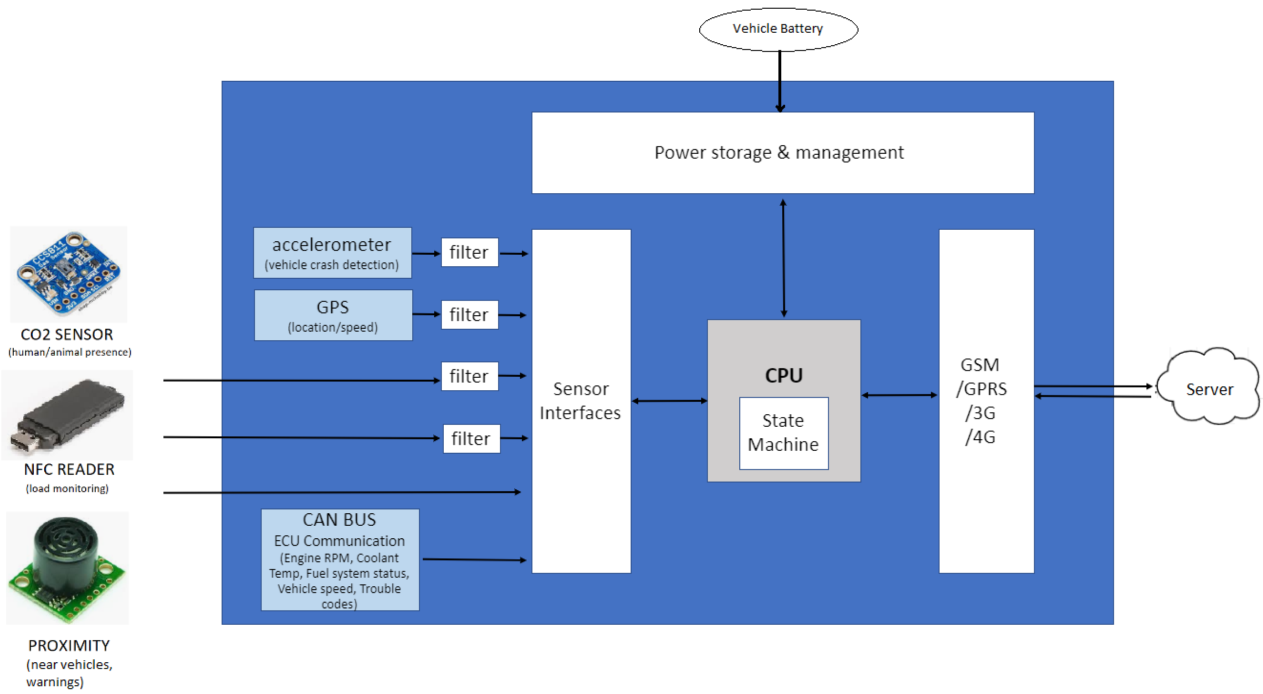


Figure 32: WINGS OBU - Architectural Diagram

Figure 33: WINGS OBU (with integrated 5G chipset) & connected on-board sensors

The sensors integrated into the OBU, which are used for the implementation of the WINGS CAM user story are described below, along with their detailed specifications.

CO2 sensor specs

For CO_2 level measurements, the CCS811 sensor from Adafruit is used. The sensor's output range is [400 – 8192] ppm. A connection to the OBU is established through the I2c protocol.

Lidar specs

The Lidar lite v3HP may be attached at the middle of the front bumper of the vehicle and it measures the distance from the front of the vehicle to a detected obstacle. The sensor has a range of [0.05m – 40m], operates at 5V DC power supply, it can sample at rates as fast as 1kHz, and for this reason, it bypasses the OBU and directly transmits to the WINGS server (in order to not limit the Lidar messages to the 1 Hz transmission rate of the OBU). Essentially, the Lidar messages are the benchmark based on which the latency between the OBU and the server is measured. ill possesses. The sensor is housed in a durable, IPX7-rated housing that makes it water resistant, and it is able to detect obstacles with an accuracy of +/- 2.5cm at >2m.

NFC (reader & tags) specs

The ACR122U NFC Reader is a PC-linked contactless smart card reader/writer based on 13.56 MHz Contactless (RFID) Technology. Compliant with the ISO/IEC18092 standard for Near Field Communication (NFC), it supports both MIFARE and ISO 14443 A and B cards and tags. Every time that a cargo NFC tag is scanned, it's ID is added onto a list of ID's of contained cargo. Each ID is removed from the list when the corresponding cargo is exported. A connection to the OBU is established via a USB port.

GNSS module specs

Global Navigation Satellite System (GNSS) services are provided by the SIM7600 with the following specifications:

- Receiver type: 16-channel, C/A code
- Sensitivity: Tracking: -159 dBm (GPS) / -158 dBm (GLONASS) / TBD (BD), Cold starts: -148 dBm
- Time-To-First-Fix (open air): Cold starts: <35s, Hot starts: <1s
- Accuracy: Position: <2.5 m CEP

4.2.2 RSU specs

The Road Side Unit (RSU) is designed to capture and send real time image frames for the licence plate recognition and control the border bar and the traffic light. As a computation platform, the raspberry pi 3 is used, with build-in Wi-Fi connectivity. Power supply is provided form AC voltage. Once powered up, the RSU should start transmitting image frames to enable the license plate recognition, while continuous data exchange with the server is used to adjust the traffic light and border-bar status.

Border bar

The MX-106 servo motor by dynamixel is used to control the border bar. The need for high torque cancelled the use of simple 5v servo motors, so the option is a 12 v high torque dynamixel servo, with serial communication with the raspberry, and specifications depicted in Table 11.

Table 11: Servo motor specifications

Weight	165 [g]
Dimensions (W x H x D)	40.2 x 65.1 x 46 [mm]
Gear Ratio	225 : 1
Stall Torque	8.0 [Nm] (at 11.1 [V], 4.8 [A]) 8.4 [Nm] (at 12[V], 5.2 [A]) 10.0 [Nm] (at 14.8 [V], 6.3 [A])
No Load Speed	41 [rev/min] (at 11.1 [V]) 45 [rev/min] (at 12 [V]) 55 [rev/min] (at 14.8 [V])

Camera

A Pi camera module V2 has been selected. The board size is around 25mm x 23mm x 9mm and weighing in at over 3g. The sensor has a native resolution of 8 megapixel and has a fixed focus lens on board. In terms of still images, the camera is capable of 3280 x 2464 pixel static images, and also supports 1080p30, 720p60 and 640x480p90 video.

4.3 CAM Application aspects

4.3.1 CAM Application Overview

By utilizing the detailed data provided by the CAM enabled truck's sensors (Lidar, radar, GPS, etc.) as well as the data from surrounding heterogeneous information sources such as traffic cameras, road-side sensors, smart phones, wearables and more, increased intelligence can be created based on a cooperative awareness of the borders' environment. The transmission of these data over reliable, ultra-fast and ultra-low latency 5G network connection combined with modern AI and predictive analytics techniques (at the edge) allows for the creation of a virtual environment of the driver enabling various added-value functionalities. As part of this use case the functionalities that will be showcased at the Greek / Turkish borders are:

- Border inspection preparation based on predictive CAM truck routing
- Secure CAM truck border crossing with increased inspection confidence
- Increased border cooperative environment awareness for incoming vehicles
- Increased border personnel safety (Vulnerable Road Users - VRU)

The above functionalities will showcase a significant minimization of inspection times at all European "hard" borders through the collaboration feasible of different 5G network operators which could even offer "zero touch" inspection (no human intervention needed) in optimal cases. The same solution offers increased cooperative awareness for passing vehicles at the chaotic border-crossing environment and taking advantage of the CAM functionalities of vehicles, such as automated braking, to prevent accidents involving border personnel (customs agents, police officers).

This intelligent border control functionality may be realized through the following trial set-up. Data originating from the truck sensors in areas around the borders are transmitted over 5G networks and analysed in a cloud-based AI platform after fusion. Once a trajectory towards the border crossing is predicted, special measures may be taken to facilitate further exchange of information and immediate response to predicted events (e.g. the assisted driving application may be downloaded from the Cloud to the edge server to minimize latency, a slice may be provisioned towards a cloud server on the neighbouring county's PLMN, etc.). An exchange of available information is commencing towards the border authorities via 5G network (mMTC type of communication from the truck OBU itself or even from the cargo which may be equipped with relevant sensors / transmitters (e.g. NB-IoT)) which will facilitate the border inspection and prepare the customs agents for the appropriate checks. All relevant information is transmitted to the edge / MEC servers available at the trial site where they are processed by the downloaded AI/ML platform instantiating this functionality.

Additional information can be exchanged over the 5G networks of the neighbouring countries facilitating the acquisition of relevant information about the specific truck (e.g. driver's information, travel history, cargo inventory, etc.) which could speed-up the control process. Extra security and control measures can be deployed which are controlled and managed through 5G networks such as drones, street cameras, thermal or x-ray cameras, etc. and which can feed large amounts of data (eMBB functionality) in a very short amount of time. In the case that all the acquired data from on-board as well as surrounding sensors / devices agree with the information that is fetched by national archives regarding this truck (and potentially its driver) and provided material (video, thermal imaging, x-ray imaging) clears the truck of any suspicion, then a case of "zero touch" inspection may be realized in which case the truck may be allowed to cross-the border without any manual inspection performed on it.

Additionally, the data originating from other vehicles, road side infrastructure, smart phones and wearables may also be fused and analysed at the edge generating a "live" cooperative update of the surrounding environment which can be fed on to the vehicles navigation system, thus increasing the environmental awareness of the vehicle (covering blind spots, pedestrian locations and trajectories, assigned inspection lane by the authorities, etc.) and actively contributing to the safety of the border ground personnel (i.e. automated trajectory alignment or braking upon detection of a potential incident).

In all cases, the same services continue being provided as the truck passes the border from the neighbouring country's network, based on exchanged information in such inter-PLMN scenarios. Service continuity during the inter-PLMN HO is of utmost importance in such cases, and the existence of such intelligence deployed at the edge close to the border greatly facilitates continuous service by identifying imminent HO's and helping the MNOs prepare for it based on the available information. This could lead to the provisioning of a roaming slice before the

HO even takes place. Figure 34 provides an overview of the Extended sensors for assisted border-crossing with VRU protection use case.

To implement this use case a laptop onboard the truck will be acting as the UE/gateway that will connect truck and/or cargo devices/systems (e.g. additional sensors deployed in the cargo hold of the truck) to the rest of the system via 5G connectivity (and 4G / NB-IoT during testing & development). These additional sensors are crucial in this case since they have the capability of raising alarms by cross-checking their data with nominal values. For instance, a thermal camera (or even CO_2 sensor) installed in the cargo hold of the truck may provide indications of a human presence in the cargo hold (smuggling / human trafficking attempt) which will enable alerted reaction by the border officers upon the arrival of the truck at the border.

Additional measures may take place in case contradicting information is gathered regarding a truck, in which case drones equipped with cameras for live feed may be deployed or thermal or x-ray imaging may be requested to rule out the possibility of smuggling goods and people. The AI based inspection functionality residing in the edge platform will fuse all available information from these heterogeneous sources (potentially originating from different 5G networks in the case of a cross-border scenario) and will locate potential inconsistencies, assigning a certain risk factor to each truck which will affect the degree (and thoroughness) to which border agents will perform a manual inspection. For the realization of this trial a single autonomous truck is needed equipped with additional sensors. ***Appendix 3*** provides an overview of the entire use case and the specific steps taken to test various aspects of its functionality.

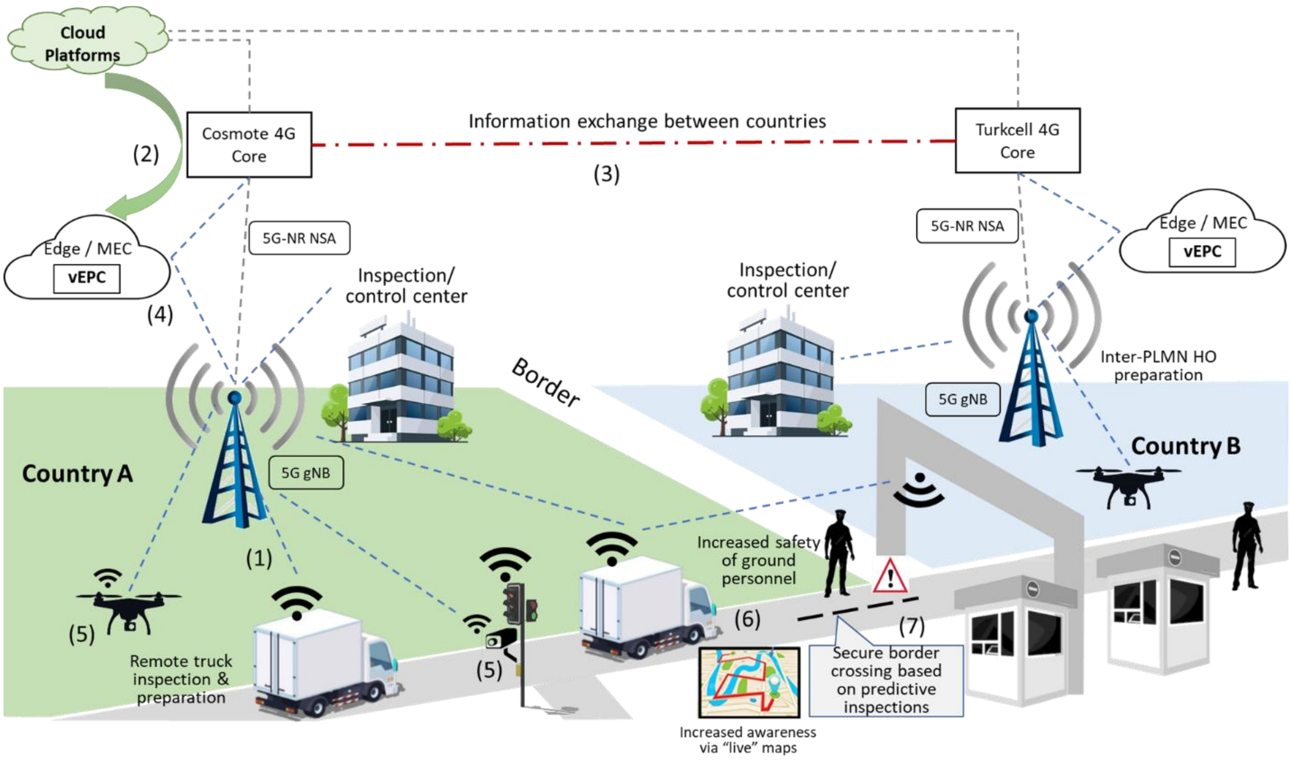


Figure 34: Detailed depiction of "Extended sensors for assisted border-crossing" architecture

4.3.2 Architecture

The "**Zero-touch border-crossing**" user story (US) driven by WINGS will be deployed at the GR-TR CBC and will be realized using the Cosmote & Turkcell networks (deployed by Ericsson GR & TR) for 5G connectivity and an autonomous Ford truck capable of SAE Level 4, which is enriched with the ad-hoc OBU and sensors developed by WINGS. Besides the 5G network infrastructure and the FORD truck, the following entities are required for the realization of this US:

- The WINGS analytics platform running either on the Cloud or in the MEC server
- The WINGS OBU and its integrated sensors transmitting information to the WINGS platform
- The WINGS RSU and the integrated sensors, installed at the customs site, transmitting information to the WINGS platform
- A server / laptop / database where customs manifests / documents can be retrieved from the neighbouring country (may also be co-located with the customs GUI laptop)
- Three laptops/tablets to act as clients and to display the WINGS developed GUIs, one customs agency / officer and one in the truck addressing the driver. All three laptops are receiving information from the WINGS platform.

The end-to-end high-level architecture of the "Zero-touch border-crossing" user story led by WINGS is depicted in Figure 35.

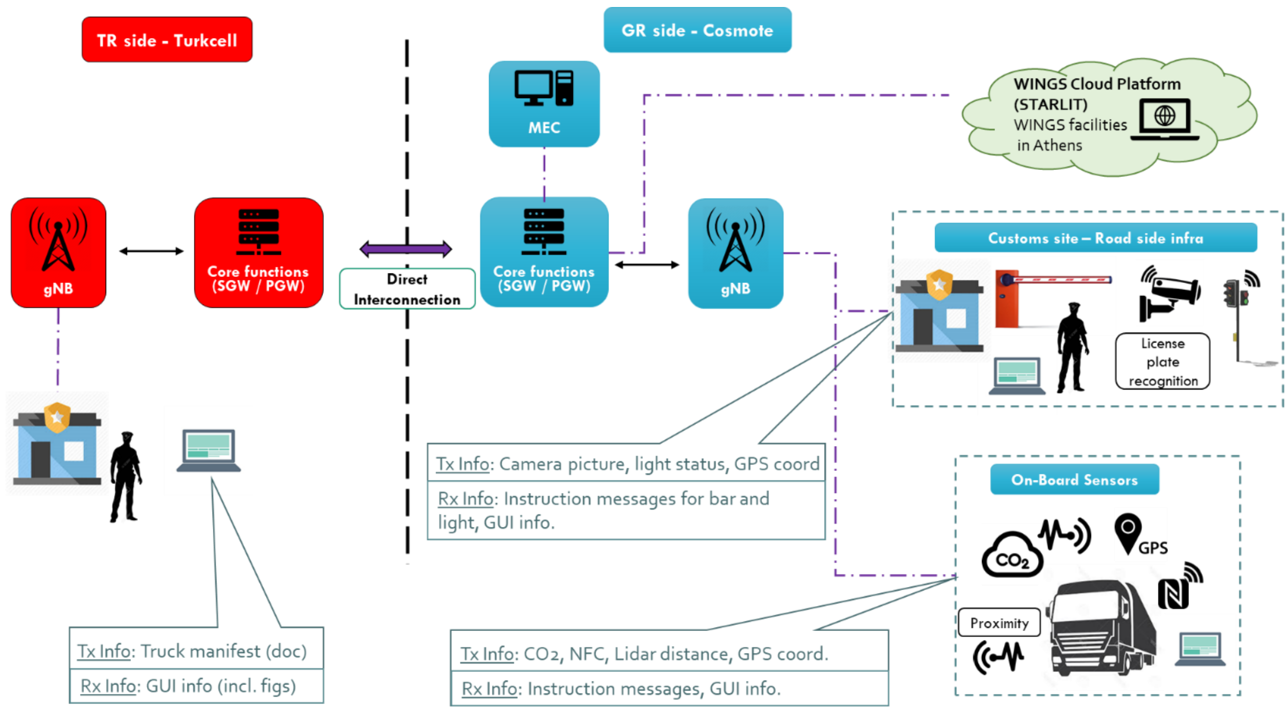


Figure 35: WINGS "zero touch border crossing" architecture

4.3.3 Platform and GUI functionality

4.3.3.1 Platform Location

Three distinct scenarios were tested during trials with respect to the hosting location of the WINGS platform, namely on the Cloud (WINGS office in Athens), the Greek Edge (GR Edge) and the Turkish Edge (TR Edge). The following WINGS platform was accessible at each of these locations via the following addresses:

- WINGS Cloud IP (Athens office): 62.74.232.210
- GR Edge IP: 94.67.143.226
- TR Edge IP: 86.108.223.197

For the case of the edge deployments, the following Architecture and set-up is used. Figure 36 depicts the connectivity of the WINGS platform when hosted at the GR Edge (similar for the TR edge) and the interconnection with the rest of the system components.

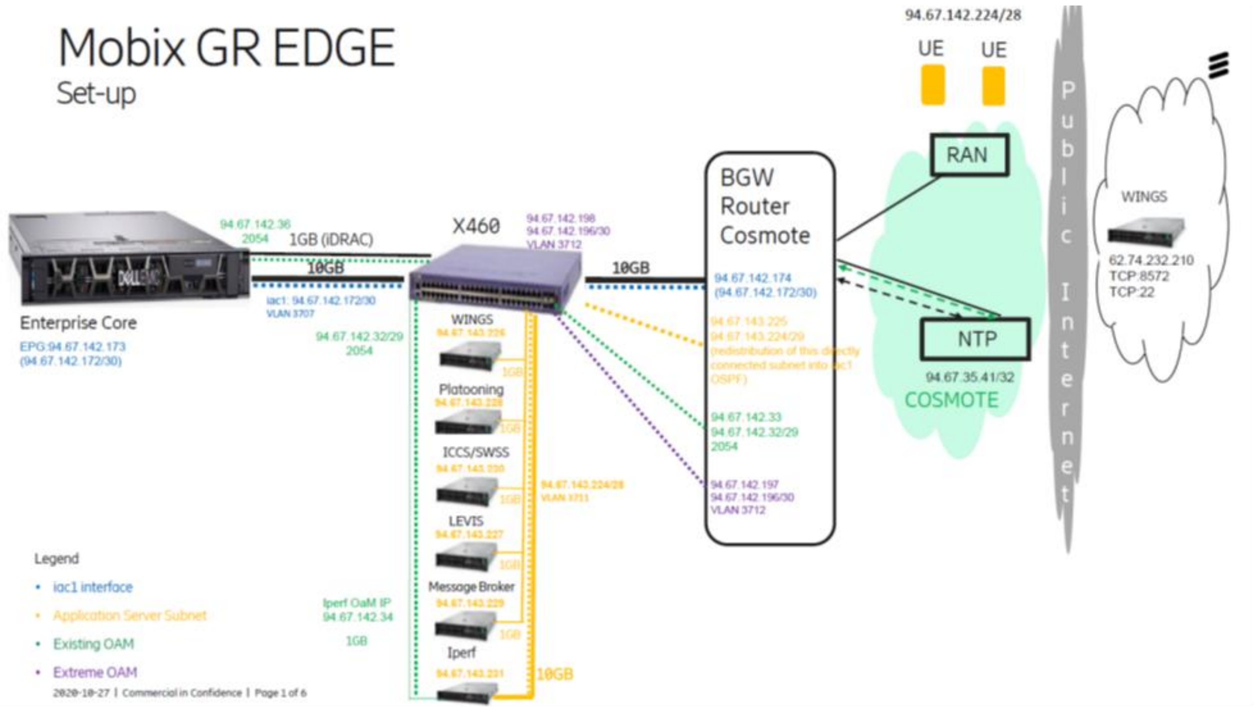


Figure 36: GR Edge setup & Architecture

4.3.3.2 Platform functionality

The WINGS platform running the "Assisted zero-touch border crossing" functionality can be deployed at a laptop, a server or the Cloud. Independent of location, the following system specifications are required to guarantee the SW smooth functionality:

- Processor: Intel Core i5-7300HQ - 2.50 GHz
- Hard Disk: 256 GB SSD
- RAM: 16GB
- Wireless Type: 802.11ac
- USB 3.0 Ports
- Operating System: Windows 10 (additionally Linux Ubuntu 18.04)

In order to collect sensors data, the WINGS platform exposes the following endpoints:

- Truck endpoint: In this endpoint sensors data and ECU values are posted
  - Type: Post
  - Input: Input is a Json object consists of the followings:
    - HUMAN (binary): Indicates human detection on the cargo
    - CO2 (float): Value of CO2 sensor
    - LAT (float): Latitude coordinate of the truck
    - LON (float): Longitude coordinate of the truck
    - ECU (array): Values from the ECU (speed, RPM, temperature etc.)
    - IP (string): IP of the truck (to be used when changing the country network provider)

- NFC endpoint
  - Type: Post
  - Input: Input is a Json object with the NFC data
    - NFC (array): Values from NFC checkpoint

- Lidar endpoint: Input is a Json object having the proximity value
  - Type: Post
  - Input:
    - DISTANSE (float): Value in cm from the nearest object

- Wearable endpoint: In this endpoint the agent's wearable data are posted
  - Type: Post
  - Input:
    - LAT (float): Latitude coordinate of the agent
    - LON (float): Longitude coordinate of the agent

- GUIs endpoint:
  - Type: Get
  - Input:
    - HUMAN (binary): Indicates human detection on the cargo
    - CO2 (float): Value of CO2 sensor
    - LAT (float): Latitude coordinate of the truck
    - LON (float): Longitude coordinate of the truck
    - ECU (array): Values from the ECU (speed, RPM, temperature etc.)
    - NFC (array): Values from NFC checkpoint
    - DISTANSE (float): Value in cm from the nearest object

4.3.3.3 Message format & Encryption – DENM / CAM support

The WINGS platform and OBU have the capability to exchange messages both in proprietary format, facilitating specific functions of the applications, as well as the ETSI standardized Decentralized Environmental Notification Message (DENM) and Cooperative Awareness Message (CAM) message formatting.

The fact that the WINGS platform is compatible with ETSI DENM and CAM messaging means that they can support any COTS OBU and vehicle and to be seamlessly integrated into any autonomous vehicle in production. The functionalities offered by the WINGS OBU and platform may work in parallel with other OBUs and ITS services. All messages between the WINGS platform, the OBU, the UEs and the RSI are further encrypted with a

IS-128 bit Encryption, offering very high levels of security and privacy, and securing that no unauthorized access to any data will be allowed.

4.3.3.4 User Authentication

A login and a registration form are included as shown in Figure 37 below. According to the user's input the appropriate dashboard is shown. If wrong credentials have been entered, a message pops up and prompts the user to re-enter them. There is also a link to a registration form in case the user hasn't created an account yet. In the registration form the user has the option to choose his role to either "Driver" or "Custom". Access is granted to the platform only after verification of the new user's credentials from the platform administrators.

This mechanism introduces an additional layer of security to the WINGS platform, as only authorized users are allowed to use the platform and will hence have access to the information provided therein.

Figure 37: WINGS Platform – User authentication

4.3.3.5 Driver GUI

The driver's GUI displays useful information and sensors metrics for the driver (see Figure 38). An HTTP GET request is being performed to the GUIs endpoint that has been described before in order to get all information regarding the incoming trucks.

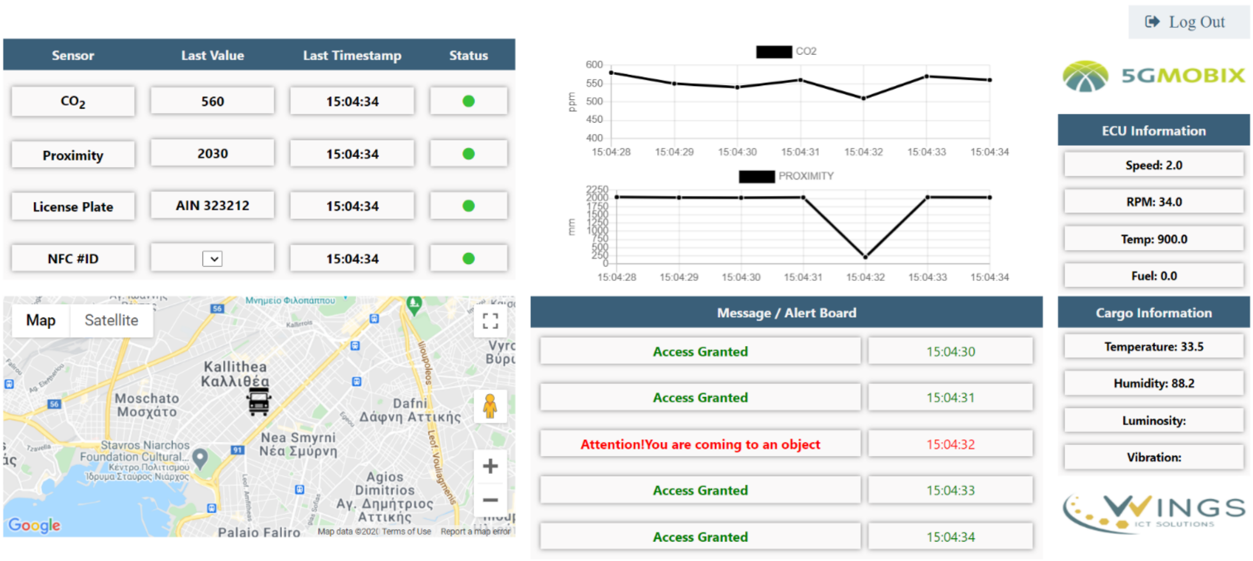


Figure 38: WINGS platform Driver Graphic User Interface (GUI)

The driver's GUI displays useful information and sensors metrics for the driver, in more details it is consisted of:

- A logout button.
- A table of sensors data: CO_2, Proximity, NFCs
- Charts with sensors values: CO_2 and proximity values are represented on charts
- A table of ECU information: Speed, RPM, Temperature and fuel
- A table of Cargo Information: Temperature, Humidity, Luminosity and Vibration.
- An interactive map with truck live coordinates
- Message board: Messages and warnings based on decision algorithms are displayed

4.3.3.6 Customs GUI

The custom's GUI displays useful information and sensors metrics for the customs agents. An HTTP GET request is being performed to the GUIs endpoint that has been described before in order to get all information regarding the incoming trucks. A logout button is also displayed.

On the first screen a table (see Figure 39) of the trucks that are approaching the borders is displayed. In a second screen (see Figure 40), a customs agent may drill down to a specific truck in order to see detailed information such as:

- A table of sensors data: CO_2, Proximity, NFCs
- Charts with sensors values: CO_2 and proximity values are represented on charts
- A video streaming.
- An interactive map with truck live coordinates
- Message board: Messages and warnings based on decision algorithms are displayed
- A manifest panel
- A dropdown list with all the scanned NFCs

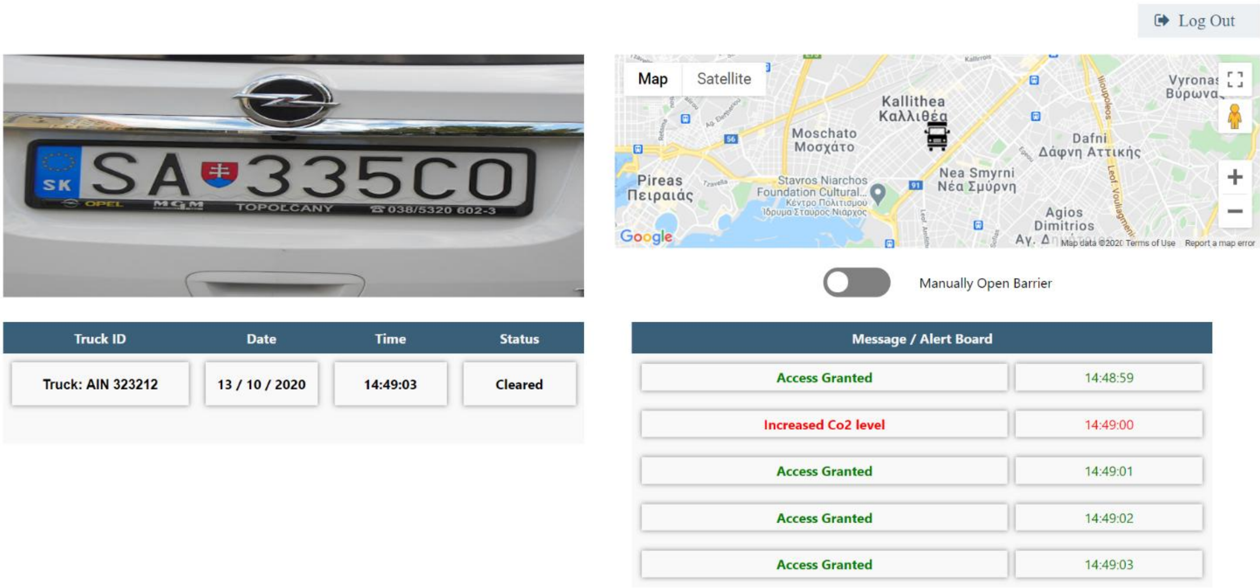


Figure 39: WINGS platform Customs Graphic User Interface (GUI) – View 1

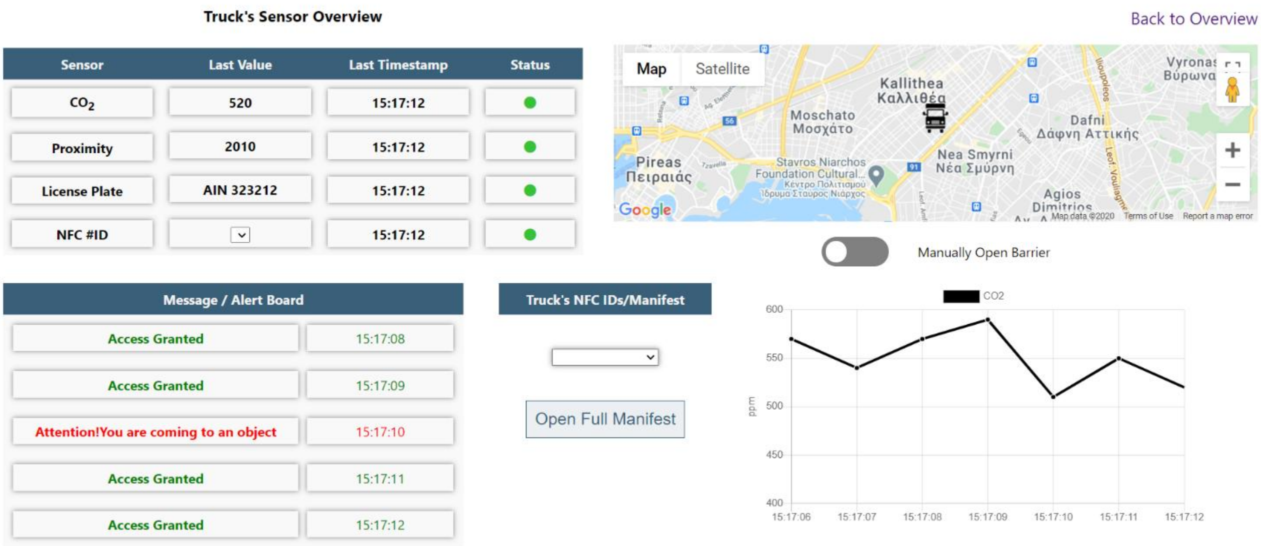


Figure 40: WINGS platform Customs Graphic User Interface (GUI) – View 2

4.3.4 Information flow

Depending on whether the WINGS platforms functionality resides in the remote Cloud located far away from the trial location (i.e. WINGS premises in Athens) or in the MEC close to the trial location, the different information flows to and from the truck / road-side sensors and the WINGS platform need to be established over the 5G network. For the proper functionality of the "Assisted zero touch border crossing" the following flows are necessary:

- CO_2 measurements from OBU to WINGS platform (mMTC service)
- NFC readings from OBU to WINGS platform (mMTC service)
- GPS readings from OBU to WINGS platform (mMTC service)
- Proximity measurements from Lidar / OBU to WINGS platform (uRLLC service)

  - Need for quick reaction to the detection of a person in front of the moving truck
- Still-frames (pictures) from road-side camera to WINGS platform
- Instructions from WINGS platform to smart border bar and smart traffic light (mMTC service)
- GUI information (including maps & license plate picture) from WINGS platform to the two customs agencies GUIs (eMBB service)
- GUI information (including maps & ECU info) from WINGS platform to the driver GUI (eMBB service)

Based on the above identified transmitted and received information from each entity of the user story, information flows can be identified depending on the location of the truck at each side of the borders and the location of the WINGS platform functionality (Cloud or MEC).

4.3.4.1 Cloud Based functionality (Scenario A)

Figure 41 depicts the required (double-sided) information flows for the case that the WINGS platform functionality resides in the Cloud and the truck (with the OBU) is transmitting from the Home-PLMN (H-PLMN). In this case the WINGS platform should be accessible via a public IP, hence internet access is required via the Home-PGW.

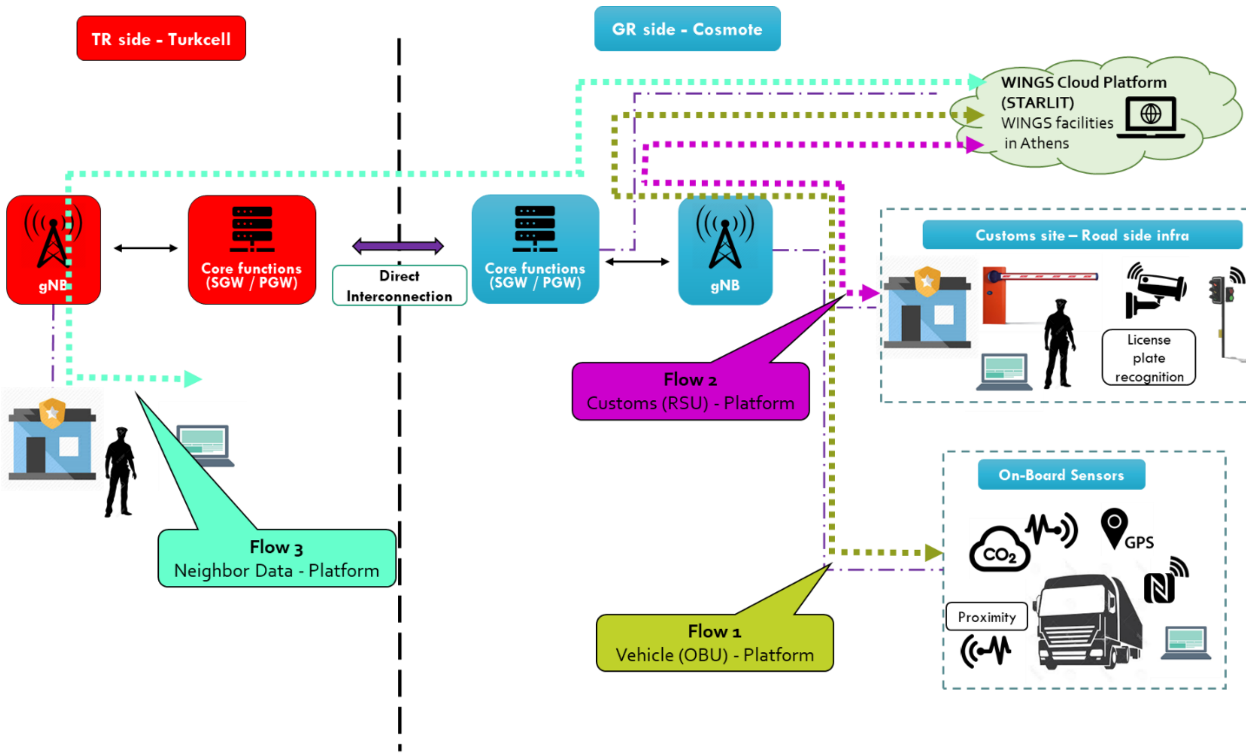


Figure 41: Information flows - Cloud based functionality with the truck on the home network

Figure 42 depicts the required information flows for the case that the WINGS platform functionality still resides in a publicly accessible cloud, but the truck is now transmitting from the Visiting-PLMN (V-PLMN). The direct interconnection between the Cosmote and Turkcell 5G-NSA networks should be utilized to get the data to the WINGS platform residing in the H-PLMN, with a minimal latency.

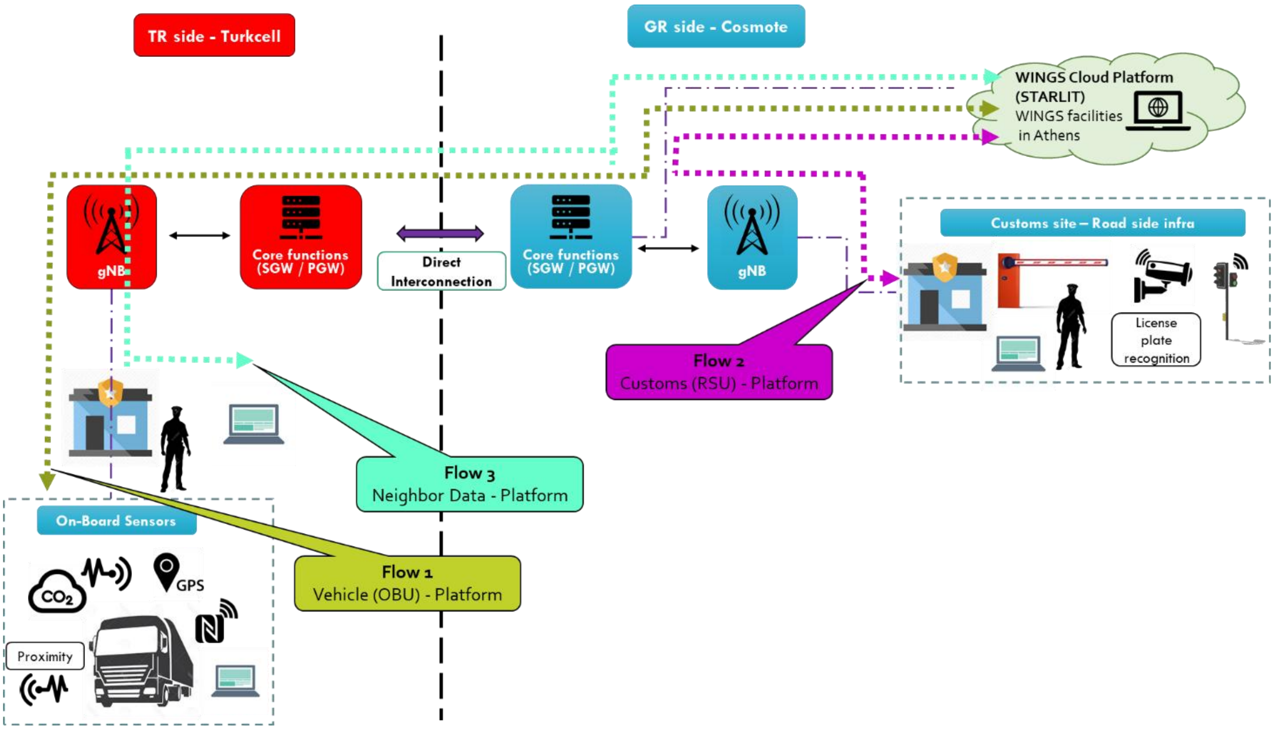


Figure 42: Information flows - Cloud based functionality with the truck on the visiting network

4.3.4.2 MEC / Edge Based functionality (Scenario B)

Figure 43 depicts the required (double-sided) information flows for the case that the WINGS platform functionality resides in the MEC/Edge and the truck (with the OBU) is transmitting from the H-PLMN. In this case the data can be directly forwarded to the co-located MEC, and all generated instructions can use the same way back.

Figure 44 depicts the required information flows for the case that the WINGS platform functionality still resides in the co-located MEC / Edge, but the truck is now transmitting from the Visiting-PLMN (V-PLMN). The direct interconnection between the Cosmote and Turkcell 5G-NSA networks should be utilized to get the data directly to the WINGS platform residing in the H-PLMN MEC, hence significantly reducing latency. Public internet access is not required in this case either.

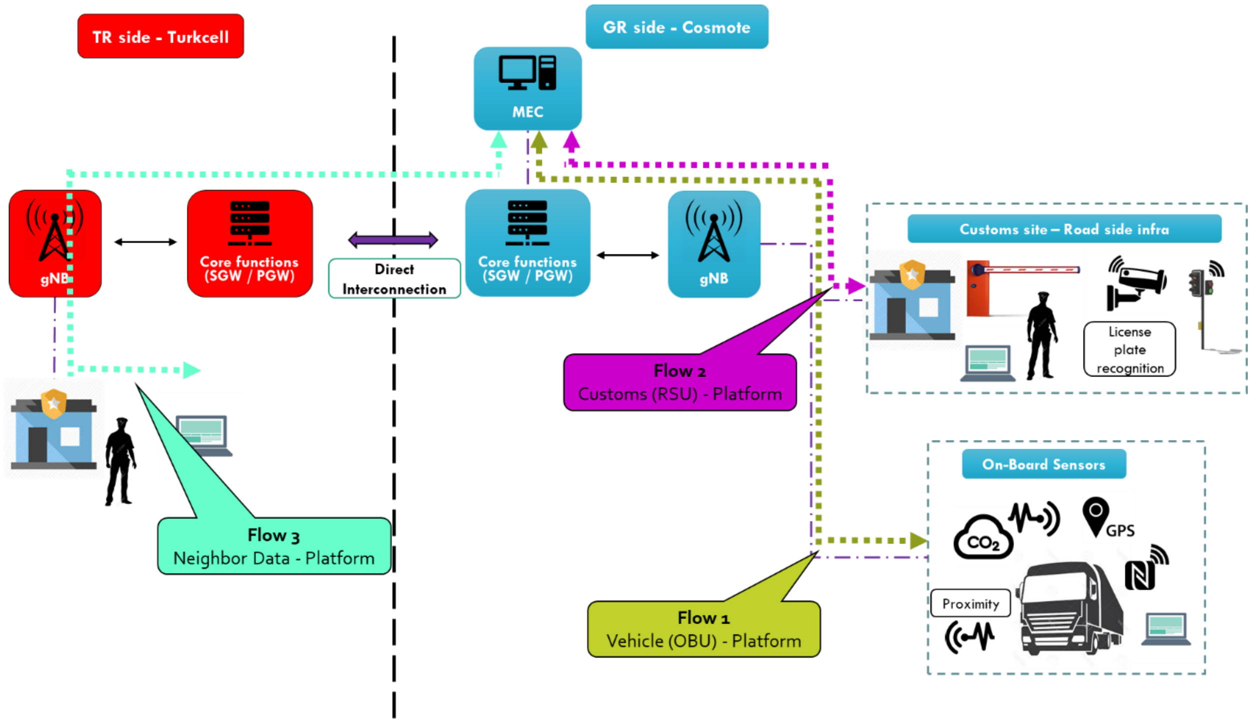


Figure 43: Information flows - MEC/Edge functionality with the truck on the home network.

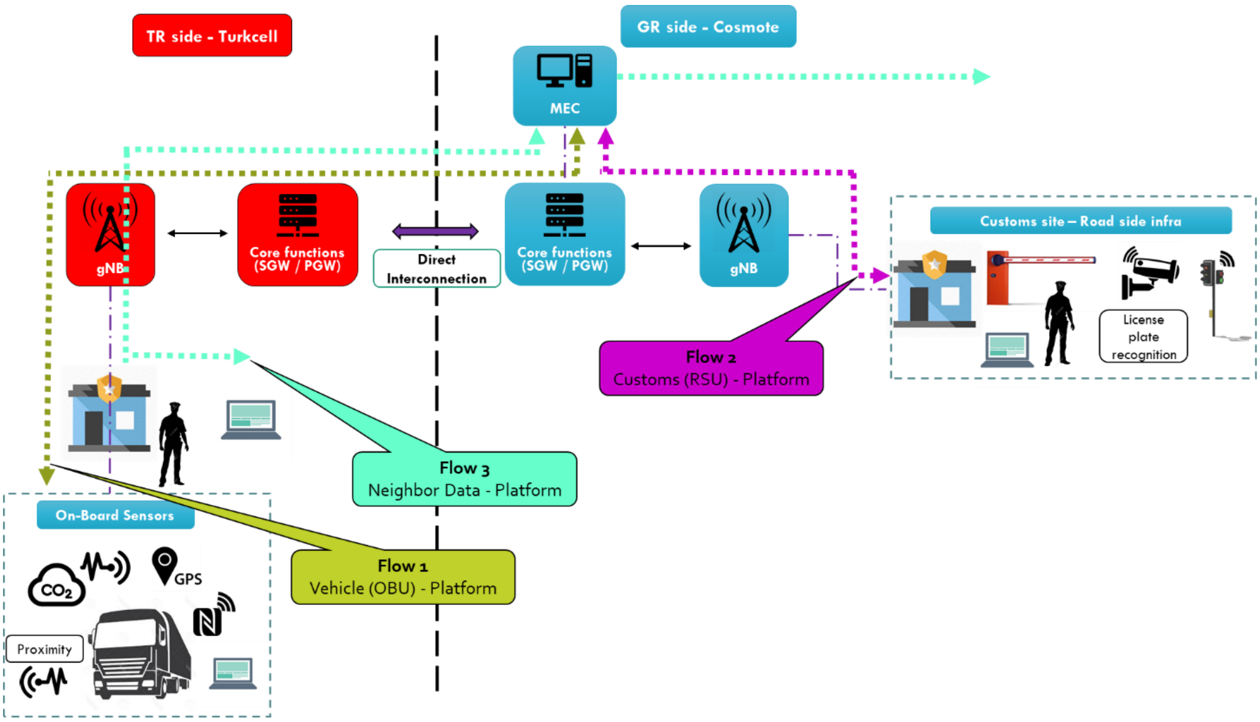


Figure 44: Information flows - MEC/Edge functionality with the truck on the visiting network

4.4 Inter-PLMN HO Algorithm design

As discussed early on, one of the main contributions of this thesis is the design of a specific mechanism (algorithm), to facilitate the inter-PLMN HO of CAM applications, when operating in LBO mode, in order to improve the experienced user performance and to provide fail-safe operations during the service interruption time. Several requirements for such a mechanism were identified based on the SotA analysis presented in Section 2, the current MM challenges and cross border issues presented in Section 3, as well as the specificities of the GR-TR CBC. This section presents the design of the applied algorithm, including flow and UML diagrams to improve understanding. This algorithm was applied by default in all CAM operations in the GR-TR CBC.

During the Local Break-Out (LBO) scenario a service interruption is expected to take place during the execution of an inter-PLMN HO, i.e. when the Ford truck is crossing the border, the truck's OBU will lose its connectivity to the original 5G network and will attach to the visiting network after some time. This scenario causes the following main effects:

[1] Connectivity among the OBU and the application platform will be interrupted for a certain period of time. During that period the OBU will not be able to upload information to the server or receive information and driving instructions from the server.

[2] Once connectivity is established with the V-PLMN the OBU will obtain a new IP address

[3] Once connectivity is established with the V-PLMN, the data routing between the OBU and the server will have changed, as the truck will now be served by the instance of the server residing in the V-PLMN's edge. This also means that there will be a change in the IP of the serving server instance (from the perspective of the OBU)

[4] Once the truck is attached to the V-PLMN, necessary information (status transfer, measurement history, etc.) from the server instance residing at the H-PLMN edge will have to be transferred to the V-PLMN instance of the application server.

In order to deal with the above effects and to avoid the shut-down or malfunction of the CAM application, the below mechanism (algorithm) was developed as part of this thesis, comprising the following main functionalities:

1. Detect an imminent inter-PLMN HO and prepare the OBU and other application instances accordingly.
2. Communicate the new expected IP address of the application instance residing in the V-PLMN's edge.
3. Inform the application instance residing at the V-PLMN that a specific vehicle is about to communicate with it and transfer all available data for that vehicle.
4. Inform the vehicle about the imminent HO and prepare it to take actions in case of loss of connectivity (e.g., degradation of autonomous functionality).
5. Instruct the OBU to also store measurements locally to deal with a potential loss of connectivity.

The specific steps and measures of this mechanism/algorithm, which was solely developed for the purposes of this thesis, are depicted in

Table *12*. This mechanism has been implemented in the WINGS application server and the Ford truck OBU. It has to be noted, ***that without this mechanism a successful inter-PLMN HO on the application layer would not have been possible***, as the vehicle/OBU would not be able to re-establish communication with the V-PLMN server after the network HO was successfully performed. In practice, this mechanism allowed for the full evaluation of the inter-PLMN HO effects on the application level and the analysis of the perceived CAM user experience.

Table 12: CAM application mechanisms to cope with LBO HO

Mechanism / Algorithm to cope with LBO HO		Deals with Effect
CAM Platform / Server	Imminent HO detection mechanism added, based on i) truck GPS signal and ii) mean distance between the GPS coordinates of the incoming truck and customs' agent.	[1], [2], [3], [4]
	Upon the detection of an imminent HO the CAM application notifies the OBU that after loss of connectivity, the OBU will obtain a new IP address from the IP address pool X.	[2]
	Upon the detection of an imminent HO & Edge server location, the platform notifies the OBU that once it obtains a new IP address the new server instance will be accessible via the new IP address Y.	[3]
	Upon loss of connectivity with the OBU & after an imminent HO detection, the H-PLMN initiates transfer of the necessary information to the V-PLMN instances using the OBU SIM IMEI, to identify the truck irrespective of its IP.	[4]
	Once the OBU has registered to the V-PLMN instance using its Unique OBU ID, the V-PLMN instance of the platform will re-associate this Unique OBU ID with the new V-PLMN IP address of the truck.	[4]
	As real-time information on the custom's agents location will not be available for the time of connectivity interruption (HO), the H-PLMN server instance notifies the OBU to: a) Slow down the truck to no more than 20 km/h for the period of no connectivity b) Trigger autonomous braking, if necessary, only based on the on-board Lidar/proximity sensor readings, in order to maintain a minimum level of VRU protection. Upon connection establishment with the V-PLMN, normal operation resumes.	[1]
OBU	Once the OBU has obtained a new IP address at the V-PLMN, it will contact the new server instance at the V-PLMN and will register using the IMEI.	[2], [4]
	Upon an imminent HO detection and a loss of connectivity (during HO) the OBU starts storing all measurements (buffering) and will transmit all of them to the V-PLMN server instance upon reconnection and registration.	[1], [3]
	The OBU switches to "isolated" mode, for the duration of the connectivity interruption. During "isolated" mode, the OBU itself processes the reading of the Lidar/proximity sensor and issues local commands to the Ford truck (if necessary) to brake, upon detection of an obstacle. This will maintain a minimum level of VRU protection, but with less accuracy.	[1]

To better understand the operational mode of the designed algorithm and the flow of actions and information exchange during an inter-PLMN HO, Figure 45 provides a diagram of the various algorithmic steps in order of execution. As mentioned before, this mechanism enables the execution of an inter-PLMN HO in LBO roaming mode, which allowed for the measurements that are reported in the next section to be collected. Without this mechanism the evaluation of the inter-PLMN HO under LBO, would not be feasible.

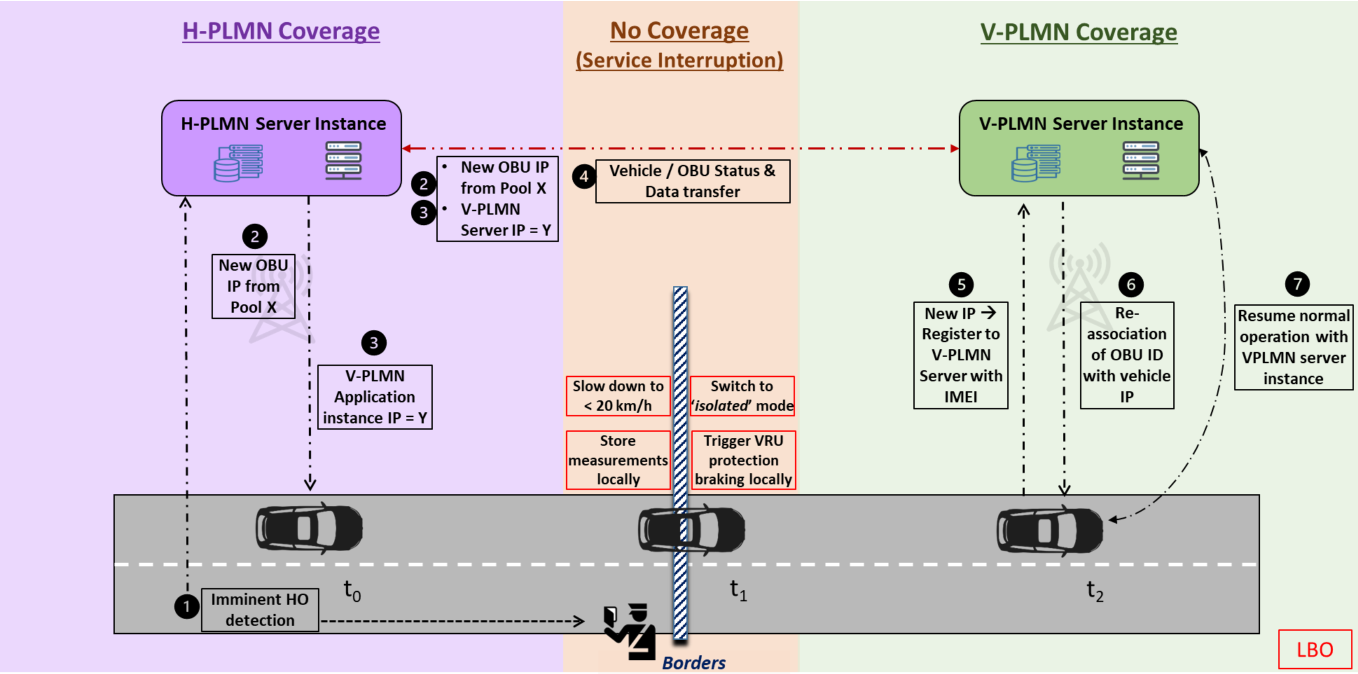


Figure 45: Depiction of algorithmic steps of the designed inter-PLMN HO mechanism

4.4.1 User Story UML Diagrams

To better reflect the information flow among the different nodes participating in this use case, and to clarify the functionality of each of the nodes/equipment in the use case, a few Unified Modelling Language (UML) diagrams have been created from different perspectives. Figure 46 represents the Use case & inter-PLMN oriented UML diagram, Figure 47 represents the Components/sensors oriented UML diagram and Figure 48 represents Integration & security/privacy oriented UML diagram.

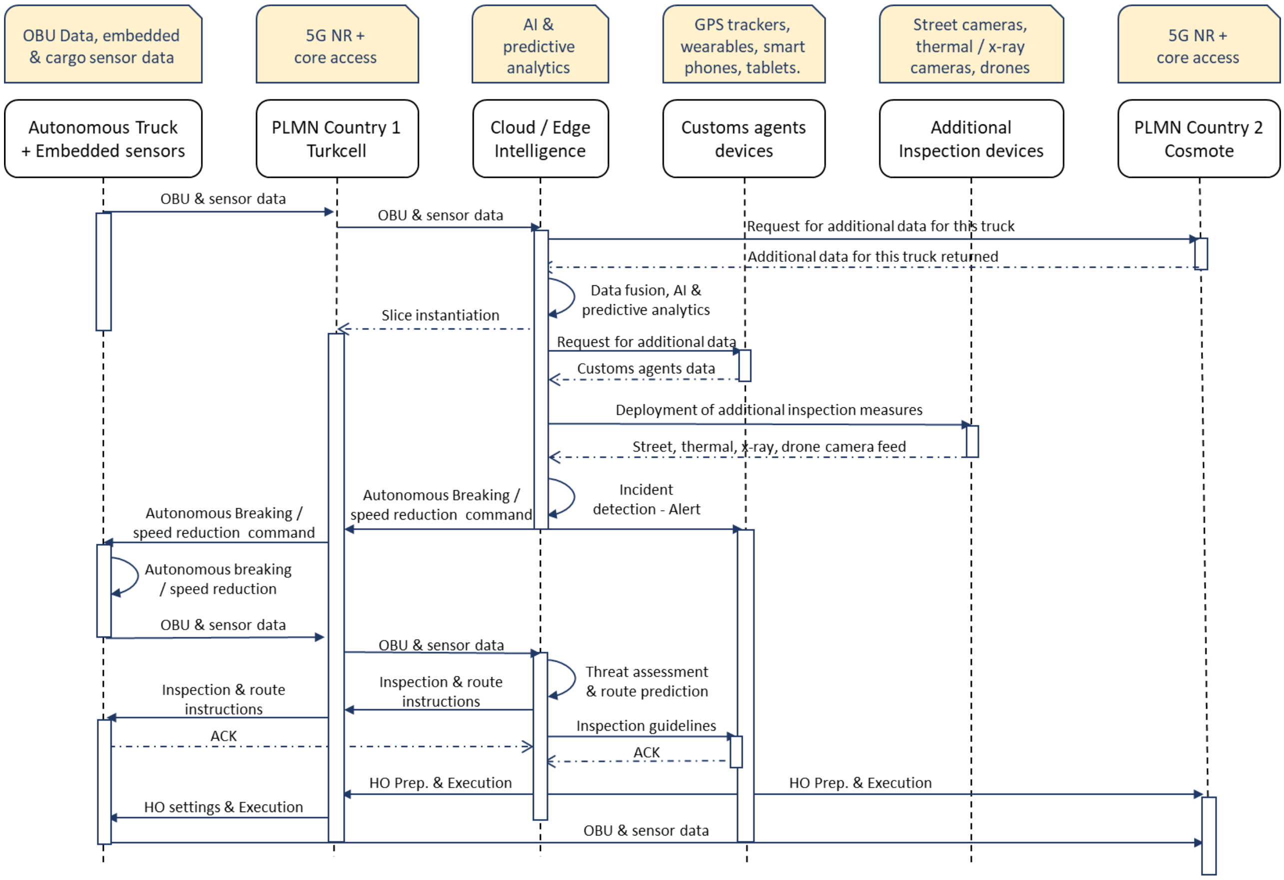


Figure 46: Assisted "zero-touch" border-crossing – UC & inter-PLMN oriented UML Diagram

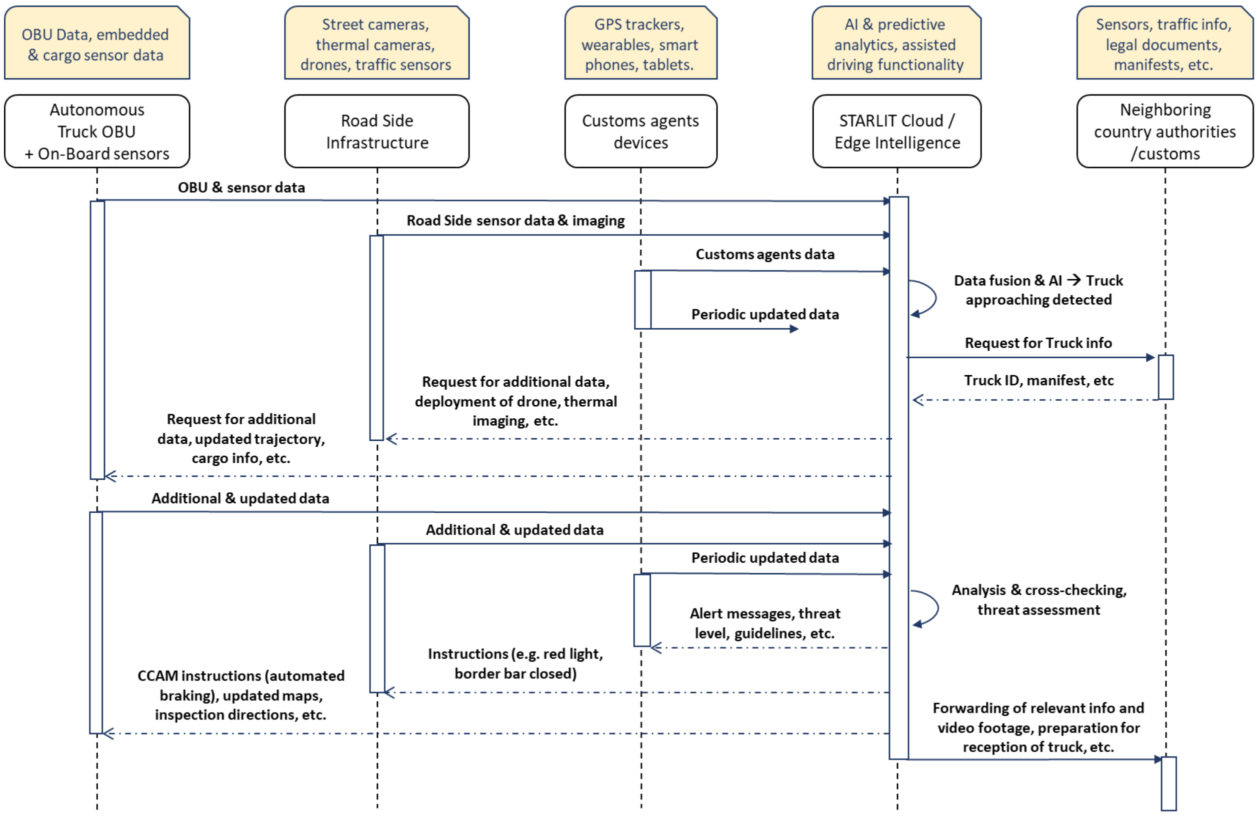


Figure 47: Assisted "zero-touch" border-crossing – Components/sensors-oriented UML diagram

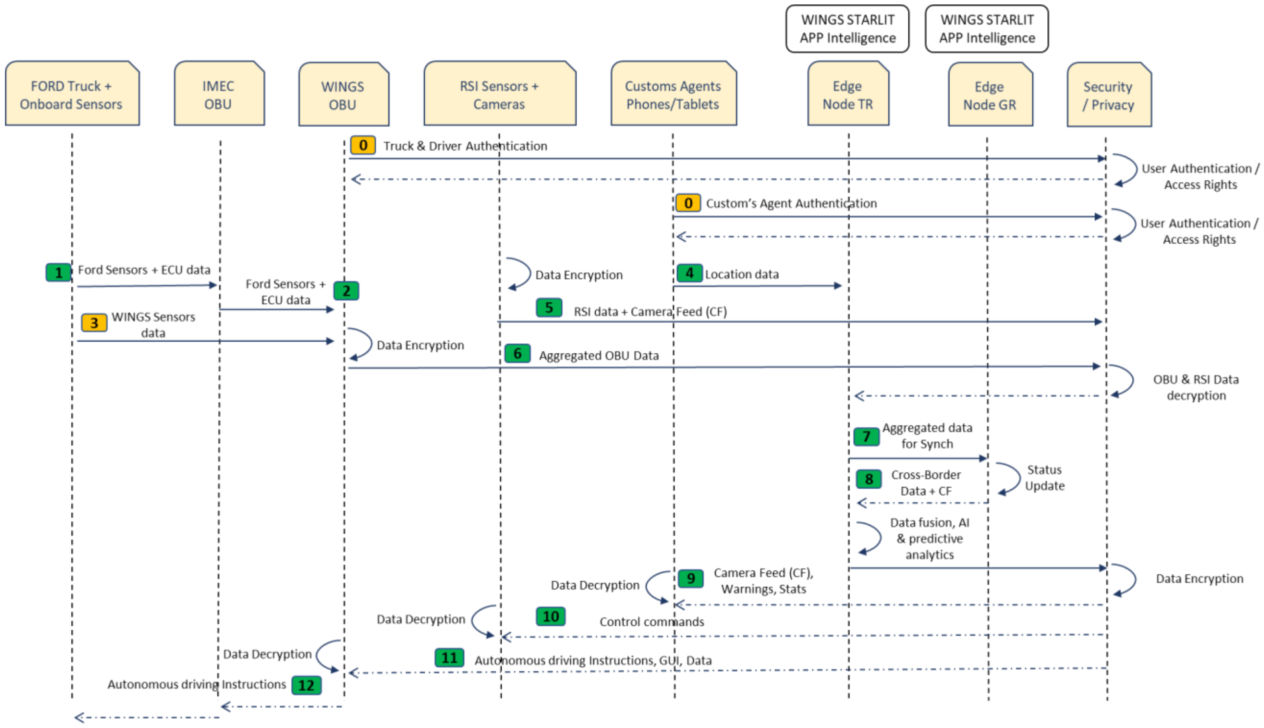


Figure 48: Assisted "zero-touch" border-crossing – Integration & security/privacy-oriented UML diagram

5 5G enabled CAM services evaluation in Cross-Border Conditions

5.1 Trial set-up & Measurement framework

The 5G-MOBIX trials at the GR-TR borders took place in Q2 2022, comprised of several trial runs, testing various network and application configurations. Data collected from the cloud and edge application servers as well as from the OBU and user devices were used to calculate the Key Performance Indicators (KPIs) of the E2E latency and the mobility interruption time, which were used to evaluate the application-level performance of the Extended Sensors use case in cross-border conditions, while the collected measurements from test UEs, network traces and device and server data, where used for the network-level performance evaluation. Several scenario repetitions and successful HO completions per scenario, offer statistical confidence in the obtained results.

During the extensive trials that took place at the GR-TR CBC, both network-level and application-level measurements and evaluation took place (key outcomes reported in [81]). While for the application-level measurements an autonomous truck of autonomy level SAE L4 was used, equipped with 5G enabled On Board Units (OBU) as reported in [62], for the network-level evaluation a specialized UE Huawei P40 (Cat19) and the TEMS Investigation testing tool, were used. Drive tests were performed on both directions, i.e., GR to TR and TR to GR, under varying environmental and situational conditions (i.e., rainy/foggy weather conditions and long queues of trucks seemed to deteriorate the signal quality) and different network and UE settings (e.g., it was observed that the placement of the UE antennae outside of the vehicle offered a gain between 1.5 and 2 dB [89]). Vehicle OEMs should be aware that the placement of internal vehicle antennae for the OBU, may be preferred for aerodynamic and aesthetic reasons, however the impact on communication performance can be significant. Solutions with external OBU antennae should be pursued to maximize performance. Both COSMOTE (GR) network SIM cards and Turkcell (TR) network SIM cards were used for the measurement to detect potential differences in performance.

The road between the GR and TR customs sites, that comprises the GR-TR CBC, and where the drive tests were performed, is a critical piece of infrastructure that could not be closed off for testing. Consequently, all reported measurements took place alongside everyday traffic (passenger vehicles and trucks) between the two countries, which on certain days could be intensive (e.g., weekends, public holidays), resulting in additional signal reflections and channel variation and hence deterioration of the experienced 5G performance. The rest of this section presents the acquired network-level KPIs and the corresponding performance analysis and gained insights.

An elaborate measurement framework that was created by the 5G-MOBIX consortium and adapted for the needs of this thesis, was used for all the measurement at the GR-TR CBC. This measurement framework defined specific Test Cases for the evaluation of each Use Case (User Story) under specific scenarios and conditions and included the Cross-Border Issues (XBI), Considered Solutions (CS) and Traffic Flows (TF) included in each scenario. As such all measurements could be archived, and test cases addressing similar XBIs or using the same CSs could be compared.

Such test cases were also defined for the "*Zero-touch border-crossing*" user story driven by WINGS, which was the primary use case used for the purpose of this dissertation (as described in section 4.3). Five main test cases were defined, offering a mix of configurations, XBIs and considered solutions that were validated with each of them. These test cases focused on collecting measurement for the evaluation of the performance of both the network and the application, based on the use of different settings/configurations and/or considered solutions. The overview of these 5 defined test cases, for the "*Zero-touch border-crossing*" user story, executed at the GR-TR CBC are shown in Table 13. A detailed list of all the Cross-Oder Issues (XBI) and respective Considered Solutions (CS) addressed within the 5G-MOBIX project is provided in ***Appendix 4***, while the full list of Traffic Flows for the Assisted Border Crossing scenario is provided in ***Appendix 5***.

Table 13: Zero-touch border-crossing user story – Test Cases

Test Case	Scenario	Test Case (Group) Purpose	Related X-border Issues	Considered Solutions
GR-TR-4.1 Internet Based Connection (CS_7) HR NSA (CS_17)	All scenarios - Cloud based operation	Run through all the US scenarios when the WINGS platform resides in the Cloud hosted in Athens. Scenarios: Info mismatch (2), VRU (3), human smuggling (2), cargo smuggling (2)	XBI_1 XBI_3 XBI_5 XBI_6	CS_1 CS_7 CS_17
GR-TR-4.2 Direct Interconnection (CS_8) HR NSA (CS_17)	All scenarios - Cloud based operation	Run through all the US scenarios when the WINGS platform resides in the Cloud hosted in Athens. Scenarios: Info mismatch (2), VRU (3), human smuggling (2), cargo smuggling (2)	XBI_1 XBI_3 XBI_5 XBI_6	CS_! CS_8 CS_17
GR-TR-7.1 Internet Based Connection (CS_7) HR NSA (CS_17)	All scenarios - Double Edge based operation	All the US scenarios when the WINGS platform is deployed both at the GR and the TR MECs. Scenarios: Info mismatch (2), VRU (3), human smuggling (2), cargo smuggling (2)	XBI_1 XBI_3 XBI_5 XBI_6	CS_1 CS_7 CS_17
GR-TR-7.2 Direct Interconnection (CS_8) HR NSA (CS_17)	All scenarios - Double Edge based operation	Run through all the US scenarios when the WINGS platform is deployed both at the GR and the TR MECs. Scenarios: Info mismatch (2), VRU (3), human smuggling (2), cargo smuggling (2)	XBI_1 XBI_3 XBI_5 XBI_6	CS_1 CS_8 CS_17
GR-TR-7.4 Direct Interconnection (CS_8) LBO NSA (CS_16)	All scenarios - Double Edge based operation	Run through all the US scenarios when the WINGS platform is deployed both at the GR and the TR MECs. Scenarios: Info mismatch (2), VRU (3), human smuggling (2), cargo smuggling (2)	XBI_1 XBI_3 XBI_5 XBI_6	CS_1 CS_8 CS_16

In the following subsections the measurements obtained during each of these Text Cases scenarios are presented along with the respective analysis, and targeted information regarding the specific functionality tested under each scenario. Different KPIs are calculated, while insights regarding the performance of the various Considered Solutions (CS) for each of the targeted XBIs are offered.

Based on the analysis of all the measurements and for all test scenarios, aggregated results for the most insightful scenarios are offered at the end of the section regarding the overall application-level and network-level performance to be expected under different cross-border conditions. Based on these aggregate results, insightful conclusions are drawn addressing the key research questions asked in this dissertation regarding the expected performance `during inter-PLMN HOs with different inter-PLMN connectivity configurations, routing protocols and cloud/edge placement.

5.2 Performance Evaluation per Test Case scenario

The performed measurements and respective analysis for each of the test cases mentioned in Table 13 are presented in this section. The main TC parameters are highlighted at the beginning of each subsection, mentioning the key configuration settings as well as the relevant XBIs, CSs and TFs. The selected User Story (US) addresses four main XBIs and their respective solutions, which are defined in Table 14. As mentioned before, the definitions of all XBIs, CSs and FLs considered in the 5G-MOBIX project can be found in ***Appendix 4*** and ***Appendix 5***.

Table 14: Main Cross-Border Issues (XBIs) and Considered Solutions (CS) considered for this US

XBI		Associated CS	
ID	**Name**	**ID**	**Name**
XBI_1	NSA Roaming interruption	CS_1	S1 handover with S10 interface using an NSA network
		CS_2	Release and redirect using an NSA network
		CS_3	Release and redirect with S10 interface using an NSA network
XBI_3	Inter-PLMN interconnection latency	CS_7	Internet-based Interconnection
		CS_8	Direct Interconnection
		CS_9	Satellite connectivity
XBI_5	Session & Service Continuity	CS_4	Multi-modem / multi-SIM connectivity - Passive Mode
		CS_5	Multi-modem / multi-SIM connectivity-Link Aggregation
		CS_6	Release and redirect using an SA network
		CS_10	MEC service discovery and migration using enhanced DNS support
		CS_11	Imminent HO detection & Proactive IP change alert
		CS_12	Inter-PLMN HO, AF make-before-break, SA
		CS_13	Double MQTT client
		CS_14	Inter-MEC exchange of data
		CS_15	Inter-server exchange of data
XBI_6	Data routing	CS_16	LBO NSA
		CS_17	HR NSA
		CS_18	LBO SA
		CS_19	HR SA

5.2.1 TC GR-TR-4.1: [Cloud] Internet Connection (CS_7)/HR NSA (CS_17)

Test Case Parameters

→ *PLMN Interconnection*: Public internet connection
→ *Data routing*: Home Routing
→ *Server location* : Cloud (remote)
→ *Relevant XBI*: XBI_1, XBI_3, XBI_5, XBI_6
→ *Relevant CS*: CS_1, CS_8, CS_16
→ *Relevant Traffic Flows* : FL1, FL2, FL5

The results presented in this section reflect the measurements performed on June 15th 2022 at the GR-TR borders, when the WINGS Server located in Athens was used for hosting the application. The results provide an estimation of the UL Throughput, E2E latency and the mobility interruption time experienced by the "Assisted -zero touch- Border crossing" application when performing HOs between the Cosmote and Turkcell networks. These tests were performed using a Cosmote SIM card.

5.2.1.1 User experienced data rate (UL)

These measurements comprise the UL Datarate in Mbps per HTTP request from the OBU to the application server. For each test run the collected samples were in a range of 1 minute before and after the Handover event. The recorded values are low due to the small payload of the CAM and DENM messages transmitted by the OBU. As discussed in earlier sections, the required throughput for this application is relatively low, however it is important to confirm that the UL throughput requirements are met at all times.

Figure 49 indicates per iteration, the mean value, the maximum-minimum, and the confidence interval (CI 95%) of the UL user experienced data rate for each Test run. All measurements were collected from the OBU communication with the Cloud Operation Server. The results show that in the worst-case scenario a value of 118 bps is detected, while the Average value is 19.2 kbps. These values are so small due to the size of the HTTP Packets used by the OBU.

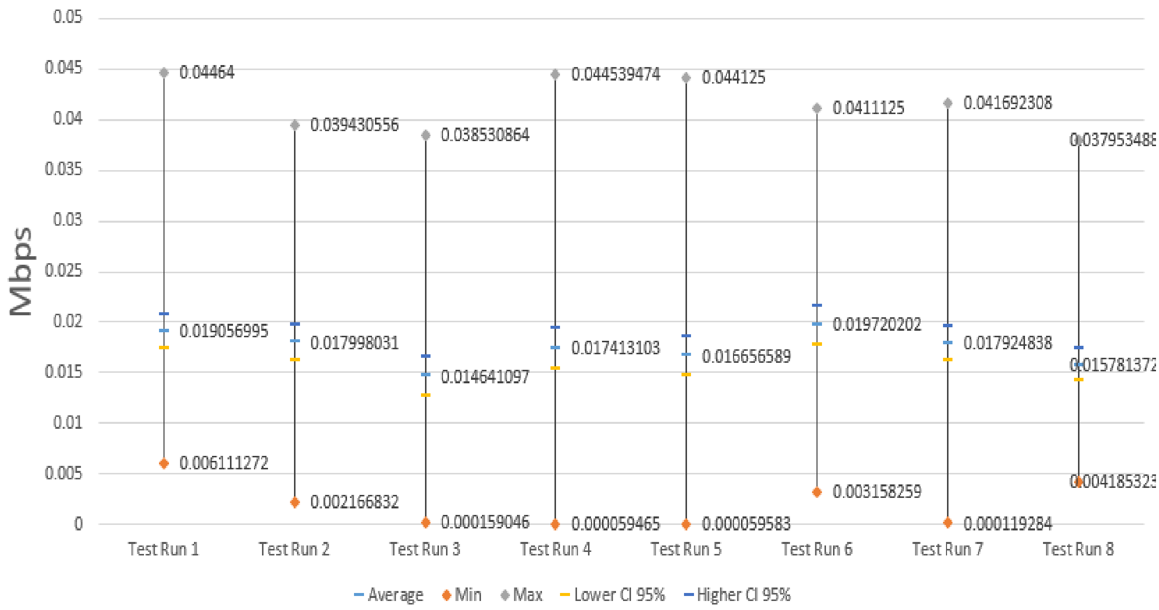


Figure 49: UL User Experienced Data Rate (Mbps) – GR-TR-4.1

Despite the fact that this user story requires very low throughputs, network-based measurements were performed on the site of the test case execution confirming that the throughput delivered by the network is more than satisfactory, namely:

- Avg Data rate (DL/UL) = 374.7 / 21.52 Mbps
- Peak Data rate (DL/UL) = 904 / 68.1 Mbps

The Cosmote network performance in terms of data rate was not stable due to the fact that there is no Line of Sight from the Cosmote gNB to the test case location. For the same reason the experienced data Rates were lower than expected, however more than enough for the execution of the Assisted Border Crossing trials.

Figure 50 depicts the Uplink Data rate measurements 30 seconds before and after the HO events, for each test Run, collected from the OBU logs. Five HO events can be detected (and a similar number of transitions between the H-PLMN and the V-PLMN). The effect of the HO on the UL throughput is visible as the throughput momentarily drops to zero but quickly bounces back (the retransmission protocol ensures the delivery of the packet). The effect of the LoS transmission on the Turkcell network and the NLoS transmission on the Cosmote network is also visible, as it results in steadily higher throughputs on the TR side.

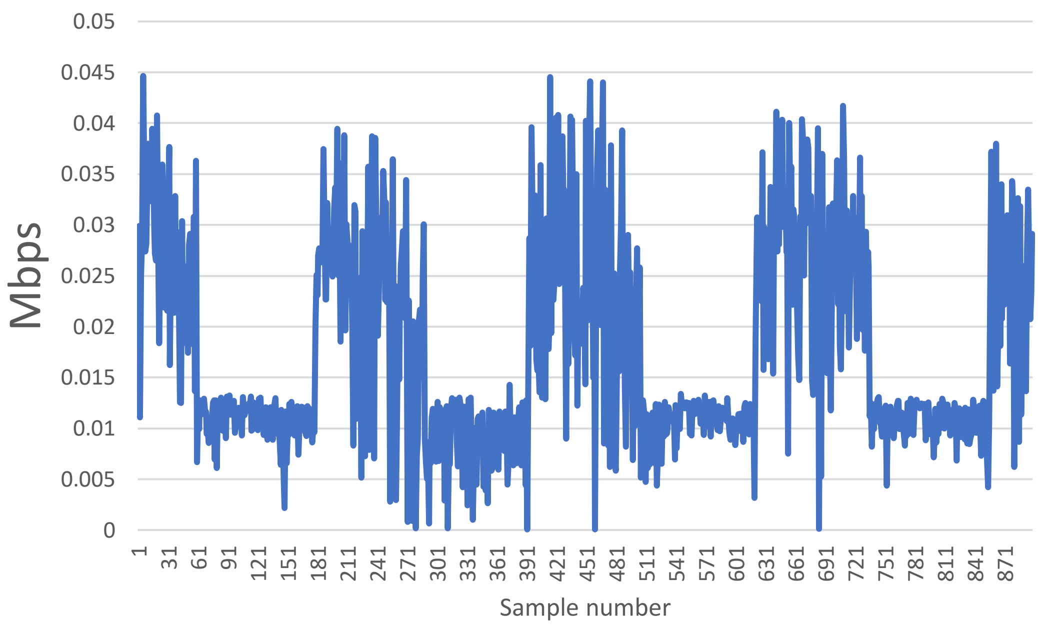


Figure 50: User Experienced data rate per OBU request around the HO events – GR-TR-4.1

5.2.1.2 E2E Latency

The E2E latency is measured from the Lidar requests to the server and vice versa, counting the Round-Trip Time of such requests. The samples collected are in the range of one minute before and after Handover event, thus focusing on the time period around the HO event, which represents cell-edge conditions for both networks.

Figure 51 indicates per iteration, the mean, maximum, minimum value and the confidence interval (CI 95%) of E2E latency for each Test run. The results indicate that in the worst-case scenario a value of 1258 ms was detected (maximum E2E Latency), while the average latency for all test runs was calculated at 212.6 ms. The E2E latency is higher than the targeted latency, however this is the basic configuration. This value is already a huge improvement compared to the latencies experienced without the S10 interface and the optimizations performed for cross-border communications, which were in the order of a couple of seconds.

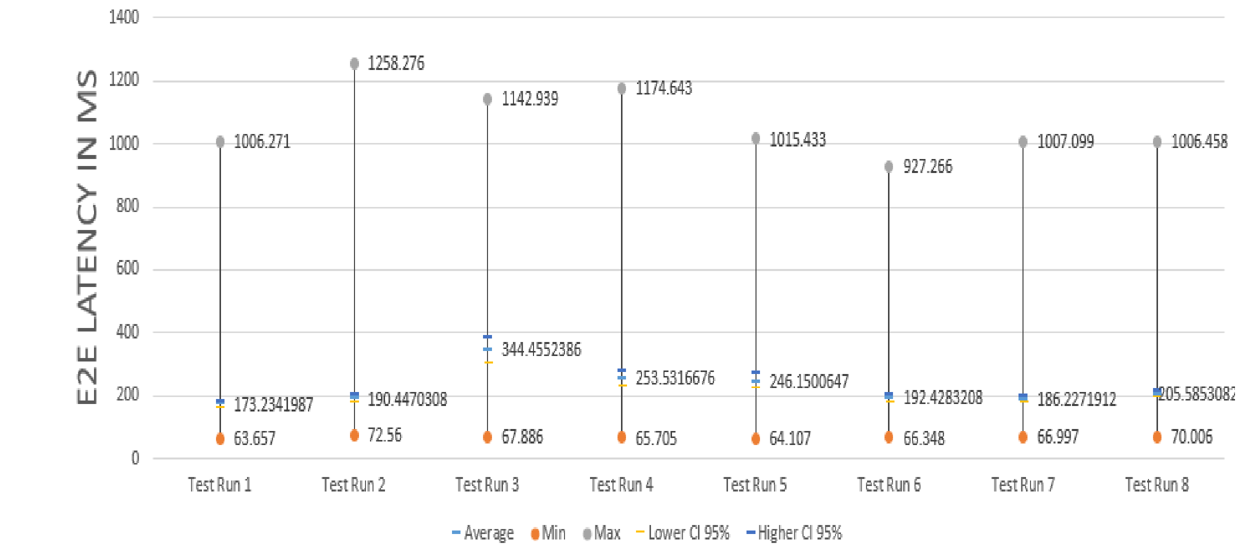


Figure 51: E2E round-trip application latency – GR-TR-4.1

Figure 52 shows the E2E latency per Request-Response from the Lidar (OBU) to the Edge Operation Server. The changes between the Cosmote and Turkcell networks are indicated by the Mobile Country Code (MCC) which is plotted with an Orange line. The transition points depict the detection of a HO event, and it can be observed that a peak of E2E latency is observed at these points.

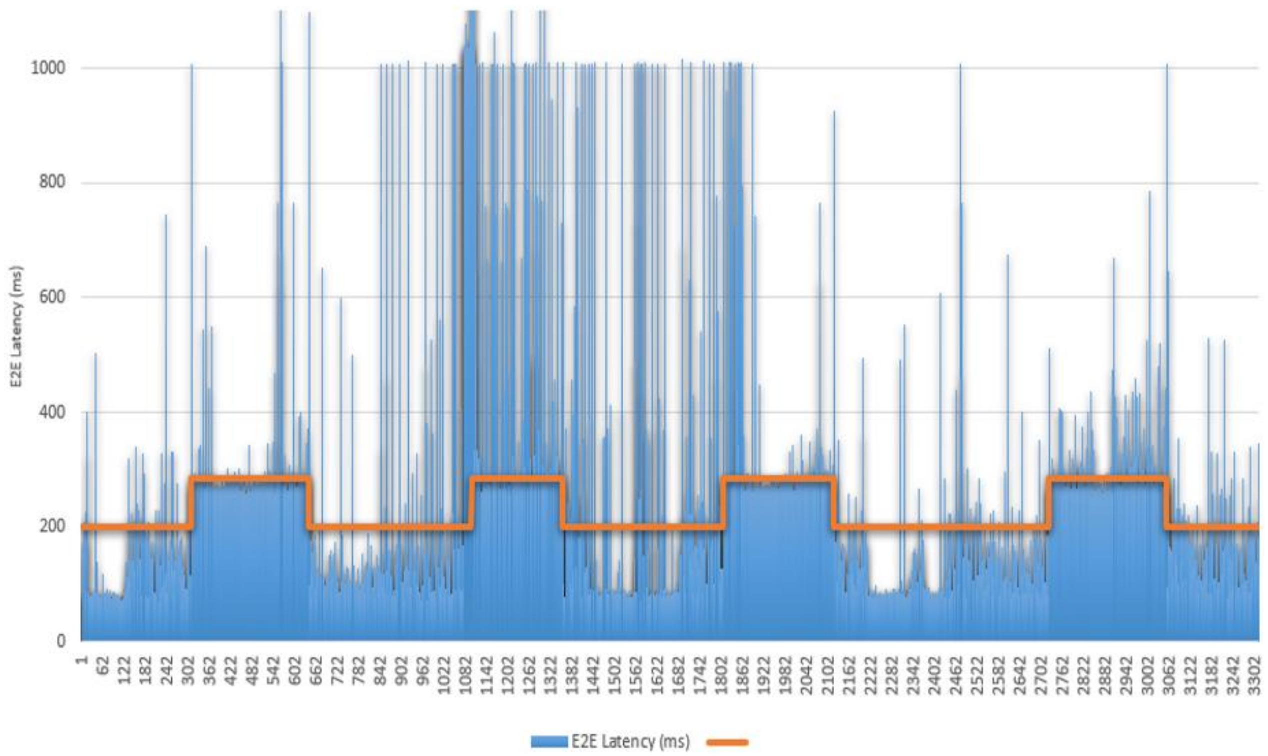


Figure 52: E2E round-trip application latency around the HO events – GR-TR-4.1

Moreover, it can be observed that the experienced latency is unstable, since multiple peaks are detected even when a HO event doesn't take place. Especially between the 2nd and 5th HO events, the latencies observed significantly increased and are much closer to the ones experienced during the HO event. This is probably attributed to environmental / situational and channel conditions (e.g., additional trucks parked between the test site and the gNB, creating additional reflections and blocking points).

Based on the presented measurements it can be deducted that the network seems to be providing relatively unstable performance in terms of E2E latency. The minimum values observed of around 29 ms Round trip time are impressive and more than enough for this CAM scenario to be satisfied, however the maximum values observed (close to 1258 ms) are certainly not satisfactory. The average values (around 212 ms E2E) could support most of the functions of the majority of CAM applications but would jeopardize the performance of some of the most critical functionalities of the User Story.

5.2.1.3 Mobility Interruption Time

This KPI is calculated by the time elapsed between the last received message at the server (at application level) before the HO and the first received message after the HO, hence representing the application-level interruption time. Figure 53 depicts the mobility interruption time as recorded for nine different test runs under this configuration. The mean value of the measurements is 710 ms while a minimum of 307 ms and a maximum of 883 ms have also been recorded. Based on these measurements, it can be deduced that mobility interruption time is also affected by channel variations and environmental condition changes, as it can significantly vary. However, based on the average value the configuration of this test case cannot support this user story, as the experienced interruption time is significantly above the target value.

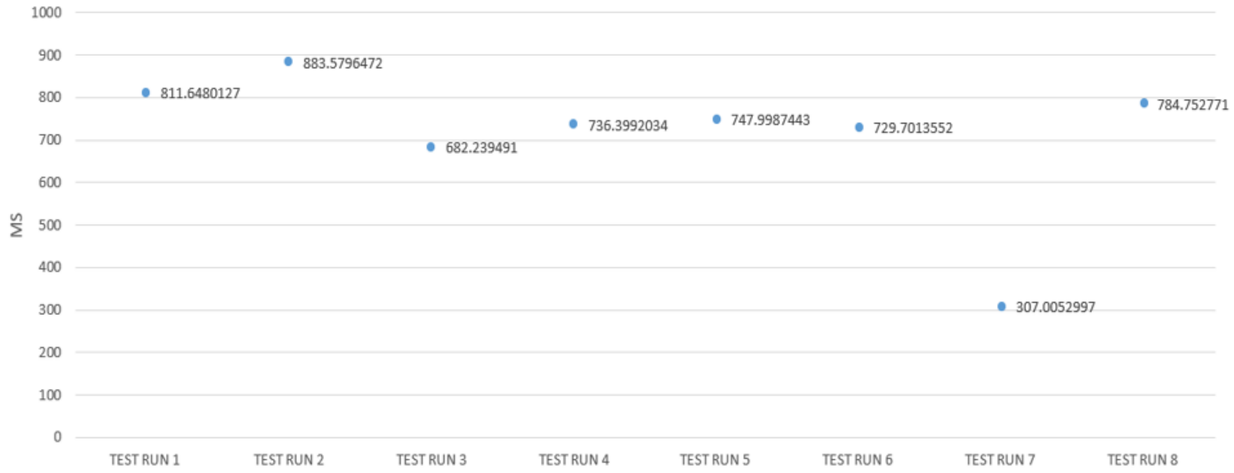


Figure 53: Mobility interruption time per test-run – GR-TR-4.1

5.2.1.4 XBI/CS insights for Test case GR-TR-4.1

Individual conclusions can be drawn for each of the addressed XBIs, using the network settings used for this Test case as well as regarding the effect of the implemented considered solutions.

- **XBI_1**: The average experienced NSA roaming interruption in this case was around 710 ms, which cannot be deemed satisfactory for most aspects of this US. Such an interruption time would jeopardize the performance of the autonomous stopping directive if it occurred right at the moment of the HO, as it would add an additional 10 meters to the stopping distance of any truck driving at 50 km/h.
- **XBI_3**: The average experienced inter-PLMN interconnection latency is around 212 ms, depending on the exact conditions. The experienced round-trip time for communication between the OBU and the server is enough to adequately perform the less time-critical envisioned functions of the US. It is observed that the experienced E2E latency is highly variable. The experienced values close to the minimum are more than enough to satisfy even the most stringent aspects of this US, however it seems very difficult to maintain the network performance at those levels. The higher experienced values are not at all satisfactory. It seems that the networks is capable of providing the necessary latencies, however more effort should be dedicated towards the stabilization of performance even under extreme channel and environmental conditions.

- **XBI_5**: The service interruption experienced on average during inter-PLMN HO was in the order of 710 ms, which is not close to the targeted values, however some of the functionalities of this US could still be performed with this interruption. The same analysis applies as for XBI_1.
- **XBI_6**: The HR data routing leads to higher experienced E2E latencies as the data always needs to be routed back to the H-PLMN of the user. This is indeed observed by the measurements, as the average E2E latency observed (~ 212 ms) is deemed relatively high for CAM applications. The Public internet interconnection used in these tests is also a contributing factor to the increased latency experienced.

5.2.2 TC GR-TR-4.2: [Cloud] Direct Interconnection (CS_8)/HR NSA (CS_17)

Test Case Parameters

→ *PLMN Interconnection*: Direct interconnection
→ *Data routing*: Home Routing
→ *Server location* : Cloud (remote)
→ *Relevant XBI*: XBI_1, XBI_3, XBI_5, XBI_6
→ *Relevant CS*: CS_1, CS_8, CS_17
→ *Relevant Traffic Flows* : FL1, FL2, FL5

The results presented in this section reflect the measurements performed on April 12th 2022 at the GR-TR borders, when the WINGS Server located in Athens was used for hosting the application. The results provide an estimation of the, E2E latency and the mobility interruption time experienced by the “Assisted -zero touch- Border crossing” application when performing HOs between the Cosmote and Turkcell networks. These tests were performed using a Cosmote SIM card.

As the UL Throughput measurements were practically identical with the ones reported for the Test case GR-TR4.1 (section 5.2.1) it was not deemed useful to repeat them again in this sub-section. This section focuses on the E2E latency and mobility interruption time measurements.

5.2.2.1 E2E Latency

The E2E latency once again represents the RTT of the Lidar packets. The samples collected are in the range of one minute before and after Handover event, thus focusing on the time period around the HO event, which represents cell-edge conditions for both networks.

Figure 54 indicates per iteration, the mean value, the maximum-minimum, and the confidence interval (CI 95%) of the measured E2E latency for each Test run. All measurements gathered from the Lidar’s communication log with Cloud Operation Server, i.e., WINGS server located in Athens. The results indicate that in the worst-case scenario a value of 1006.337 ms is detecetd as a maximum E2E Latency, while the average observed value for all test runs is calculated at ~118 ms. This measurement could support most of the functions of the Assisted border crossing User Story, as it is very close to the original target KPI of ~ 100 ms RTT. However strictly speaking the target KPI is not met, under this network configuration and test conditions. The minimum observed values of around 65-70 ms RTT latency, exceed the targeted latency and are deemed very satisfactory, once again indicating that the network (and application) are capable of providing the necessary performance, although not constantly, as performance significantly fluctuates (also indicated by the large confidence interval margins). The encouraging observation is that the average values observed per test run, are much closer to the minimum latency value recorded, and much farther away from the maximum, indicating that the large latencies recorded are usually outliers.

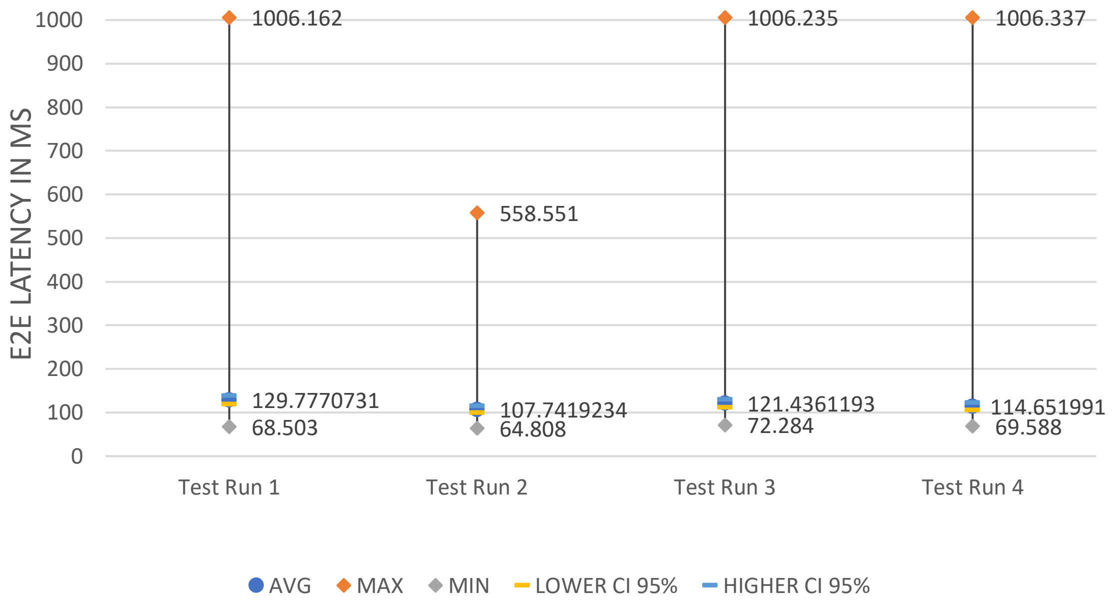


Figure 54: E2E round-trip application latency – GR-TR-4.2

To further investigate the components that make up the recorded RTT latency, per sample measurements were taken from both the Lidar port (communicating with the server with a frequency of approximately ~50-100 ms), as well as from the main OBU port, communicating with the server with a frequency of 1 Hz (due to HW limitations from the GPS sensor). Figure 55 shows the E2E latency per Request-Response from the Lidar and OBU to the Cloud Operation Server, around the HO events. The HO events can be detected via the change in Mobile Country Code (MCC) received by the network, and a peak of E2E latency can be detected from the Lidar's request response. There is no equivalent peak form the OBU measurements, as the OBU communication frequency of 1 Hz, is too low matching the peak detected from the Lidar (1 message every 1000 ms).

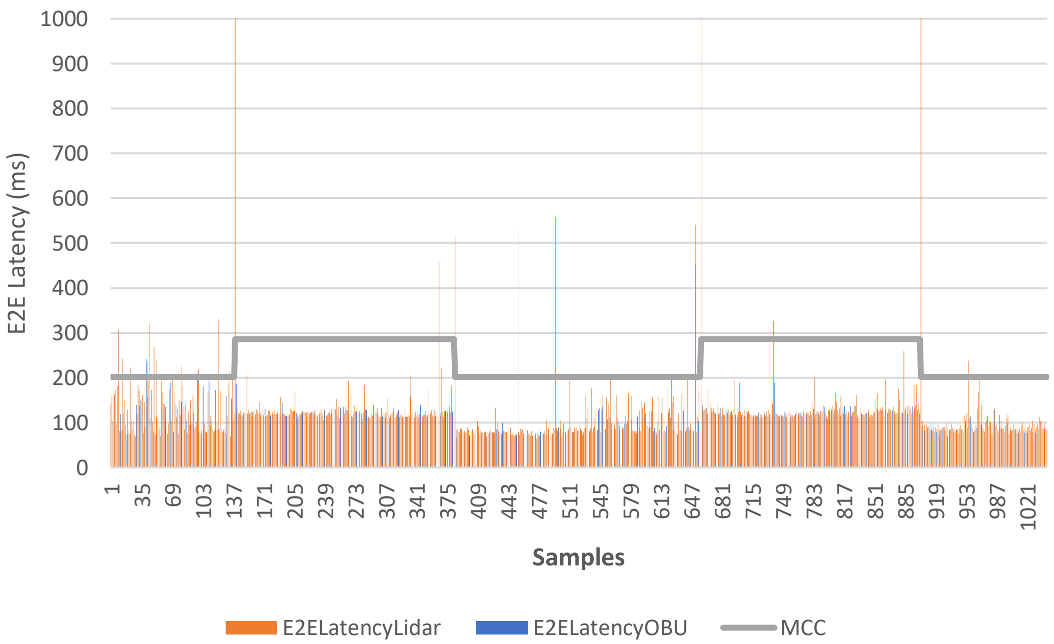


Figure 55: E2E round-trip application latency around the HO events – GR-TR-4.2

It is very interesting to observe that for the most part, the performance remains relatively stable around the average value of 118 ms, while several outliers/peaks can be detected, which are in all likelihood caused by environmental and situational conditions (e.g., blocking, reflections, etc.) which could lead to retransmissions. It is also interesting to note, that the average performance fluctuates depending on which network (MCC) is serving the vehicle, while even within the same network, the performance may vary significantly between different test runs, i.e., the 1st pass from the Cosmote GR networks with MCC 202 (samples 1 to 137) and the 2nd pass from the Cosmote GR network (samples 375 to 647) present very different performance, due to a change in the local environmental conditions.

Overall, the effect of the direct interconnection between the two neighbouring networks can be immediately observed, as the average E2E latency has dropped from 212 ms for test case GR-TR-4.1 to 118 ms for test case GR-TR-4.2, which represents an improvement of ~45%.

5.2.2.2 Mobility Interruption Time

Figure 56 depicts the experienced interruption time from the application perspective, calculated as the time interval elapsed between the timestamp of the last OBU message delivered via H-PLMN and the first OBU message delivered via the V-PLMN. The Results indicate that in the worst-case Scenario a service interruption time of 893.736 ms was detected, while the average interruption time experienced by the application during HOs was 767 ms. This service interruption time is not satisfactory for the most critical service of custom agents protection via autonomous stopping (VRU), as it significantly exceed the KPI target.

Based on the sample of these measurements, the mobility interruption time is once again the main bottleneck when a remote cloud server is used with Home routing configuration, even when a direct interconnection is used between the two neighbouring networks. It can also be observed that mobility interruption time is not affected by the network interconnection time, as no significant difference is observed in the performance with test case GR-TR-4.1.

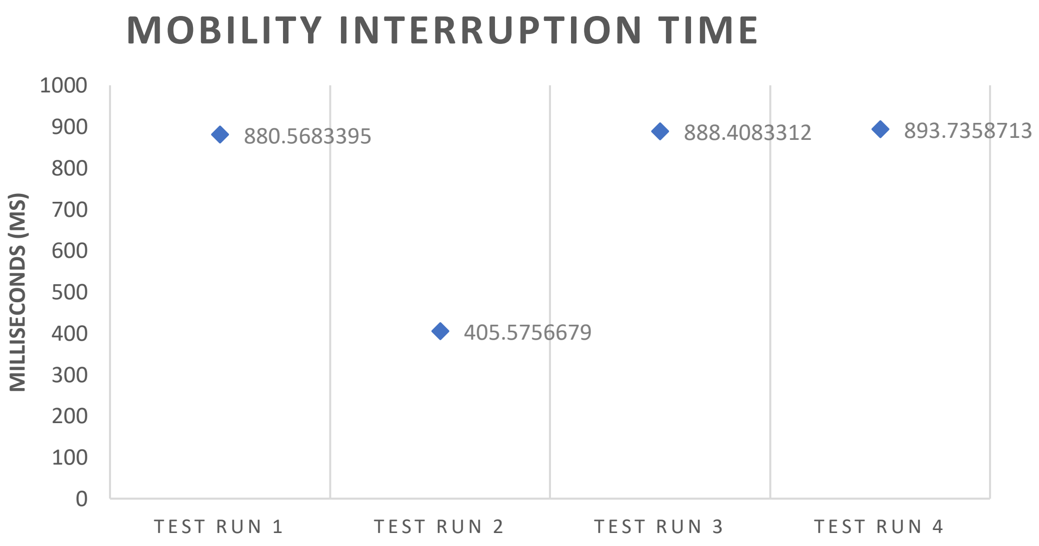


Figure 56: Mobility interruption time per test-run – GR-TR-4.2

5.2.2.3 XBI/CS insights for Test case GR-TR-4.2

Individual conclusions can be drawn for each of the addressed XBIs, using the network settings used for this Test case as well as regarding the effect of the implemented considered solutions.

- **XBI_1**: The experienced NSA roaming interruption on an application level when using CS_8 and CS_17 (HR, Direct interconnection) is deemed satisfactory only for the hard border environments of this US, but not at all satisfactory for soft border conditions, where vehicles do not stop. The most critical aspect of this US, which is the autonomous stopping of the vehicle when detecting a human/customs agent, will suffer a significant degradation of performance which may translate into an additional stopping distance of ~10 meters for vehicles moving at a speed of 50 km/h, due to the service interruption time.
- **XBI_3**: The experienced inter-PLMN interconnection latency is deemed very satisfactory from an application-level perspective. The experienced RTT for communication between the OBU and the server is enough to adequately perform all the envisioned functions of the US. The average performance is quite satisfactory, while peak performance exceeds expectations.
- **XBI_5**: The service interruption experienced during inter-PLMN HO is not excessive, however the most stringent requirements of the US (VRU functionality) cannot be safely met. This should not pose a major issue for hard-border environments; however, it may become an issue for soft-border environments. The service continuity experienced by the application was satisfactory for all other functions of this US.
- **XBI_6**: The HR data routing scheme, ends up in relatively low service interruption times (compared to the LBO routing, as will be seen in the next section) and very acceptable average E2E RTT latencies. As such this routing scheme is deemed satisfactory and adequate for the early deployment of this and similar USs at hard-border environments.

5.2.3 TC GR-TR-7.1: [Edge] Internet Connection (CS_7)/HR NSA (CS_17)

Test Case Parameters

→ *PLMN Interconnection*: Public internet connection
→ *Data routing*: Home Routing
→ *Server location* : Double Edge (GR & TR)
→ *Relevant XBI*: XBI_1, XBI_3, XBI_5, XBI_6
→ *Relevant CS*: CS_7, CS_17
→ *Relevant Traffic Flows* : FL1, FL2, FL5

The results presented in this section reflect the measurements performed on June 15th, 2022, at the GR-TR borders, when the WINGS Server hosting the application was located in both the GR and the TR edge servers and an "application instance HO" was required when the autonomous vehicles changed serving networks (stateful application). The results provide an estimation of the UL Throughput, E2E latency and the mobility interruption time experienced by the "Assisted -zero touch- Border crossing" application when performing HOs between the Cosmote and Turkcell networks. These tests were performed using a Cosmote SIM card.

5.2.3.1 User experienced data rate (UL)

These measurements comprise the UL Datarate in Mbps per HTTP request from the OBU to the application server, residing at the edge server. For each test run the collected samples were in a range of 1 minute before and after the Handover event. Once a HO is performed and the vehicle is served from the V-PLMN (instead of the H-PLMN) there is a change in the edge server as well (and the application instance) and the application instance at the edge server residing at the V-PLMN is used after the HO.

Figure 57 depicts the recorded UL throughput values based on the OBU packets for eight different test runs. The recorded values are low due to the small payload of the CAM and DENM messages transmitted by the OBU. As discussed in earlier sections, the required throughput for this application is relatively low, however it is important to confirm that the UL throughput requirements are always met. The average value recorded is 23.1 kbps which is very similar to the average throughput value recorded for the testcase with the use of the cloud server (see Figure 49), while multiple variations are also recorded (wide CI intervals and significant min/max value differentiation) which shows the variability of the packet size as well (based on sensor measurements transmitted by the OBU).

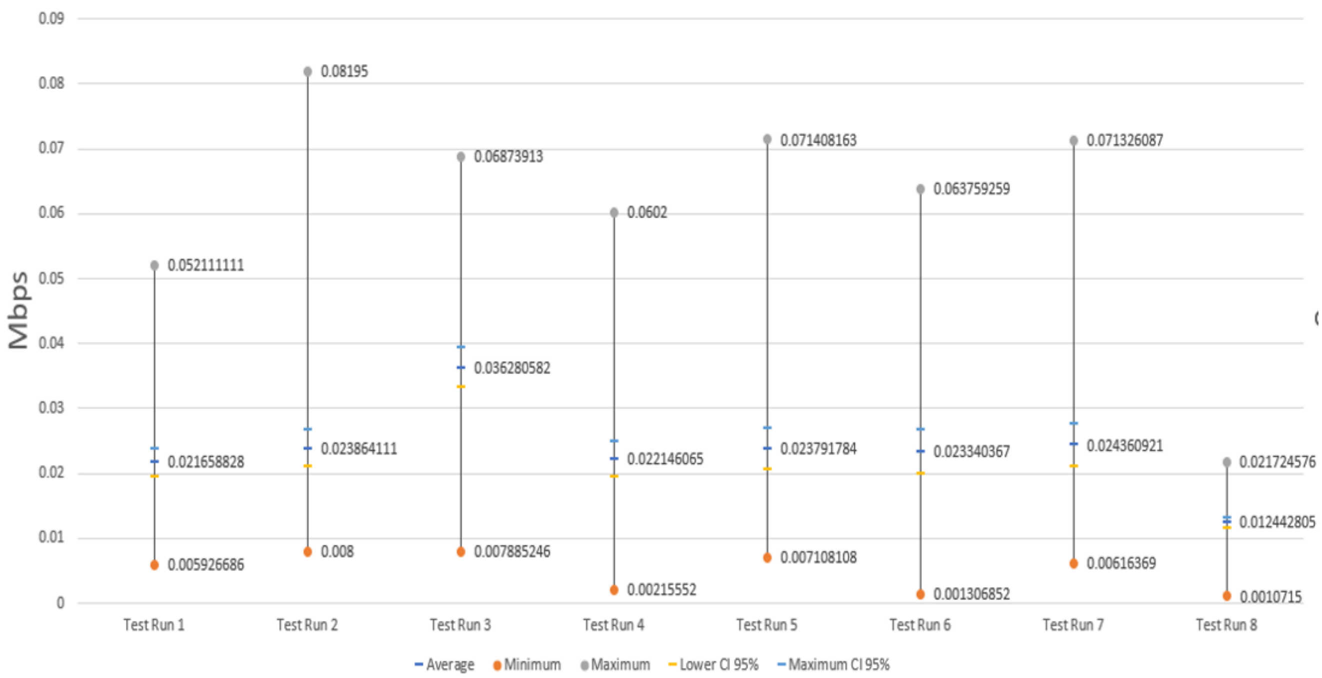


Figure 57: UL User Experienced Data Rate (Mbps) – GR-TR-7.1

In order to get a better understanding of the UL throughput experienced during the drive and the inter-PLMN HO, the continuous throughput values experienced by the CAM user are depicted in Figure 58, including the HO events (indicated by the red highlights). Similarly to the observations made in section 5.2.1 (for test case GR-TR-4.1), the difference in the UL throughput experienced in the two networks is a result of the LoS conditions experienced in the TR networks and the NLoS conditions in the GR networks. The measured throughput presents similar values and characteristics around the HO points, indicating that throughput (at these levels) is not affected by the placement of the application server in the cloud or the edge server, and both set-ups can provide satisfactory throughput for this US, even under bad channel conditions.

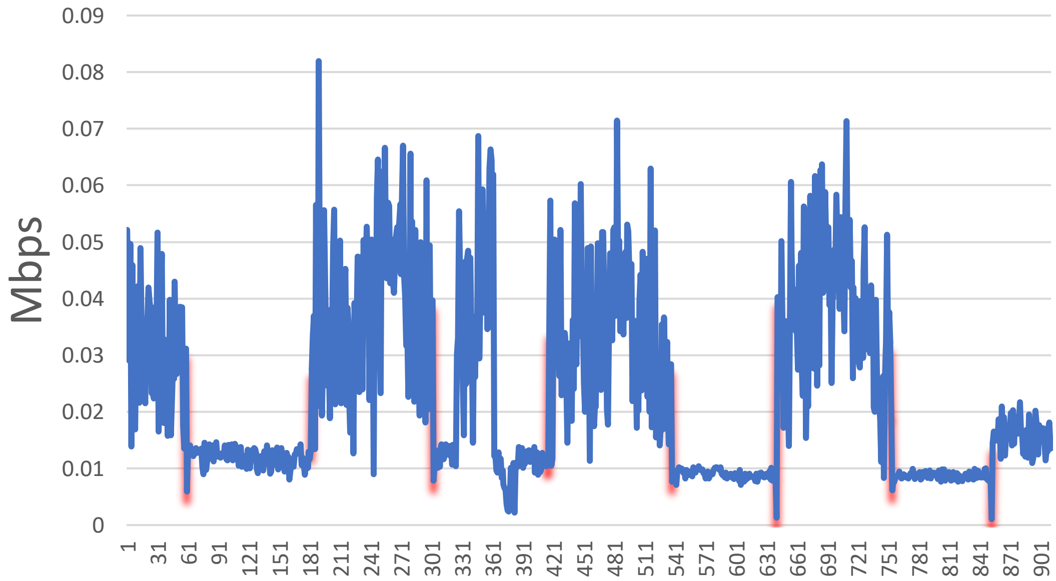


Figure 58: User Experienced data rate per OBU request around the HO events – GR-TR-7.1

5.2.3.2 E2E Latency

The E2E latency once again represents the RTT measured from the Lidar requests to the server and back. The samples collected are in the range of one minute before and after Handover event.

Figure 59 indicates per iteration, the mean, maximum, minimum value and the confidence interval (CI 95%) of E2E latency for each Test run. The mean value of 137 ms round trip time does not meet the initial requirement but can be considered somewhat satisfactory as it is close to the original target of 100 ms. The overall performance is significantly improved compared to the cloud based operation (average E2E latency of 212 ms vs 137 ms for edge – see section 5.2.1) while values as low as 35 ms RTT can be observed, which is approximately 100% improvement in the min latency observed compared to the cloud server implementation. Once again, the average values per run are much closer to the minimum values recorded rather than the maximum values, indicating that the maximum recorded values should be considered outliers.

In order to get a better view of the distribution of the latency along the cross-border route, the per sample experienced E2E latency was also measured. Figure 60 shows the E2E latency per Request-Response from the Lidar to the Edge Operation Server. The changes between the Cosmote and Turkcell networks are indicated by the Mobile Country Code (MCC) which is plotted with an Orange line. The effect of the HO is clearly visible in all HO instances (resulting in a peak of close to 1000 ms), while some instability can also be observed close to the moments of the HOs.

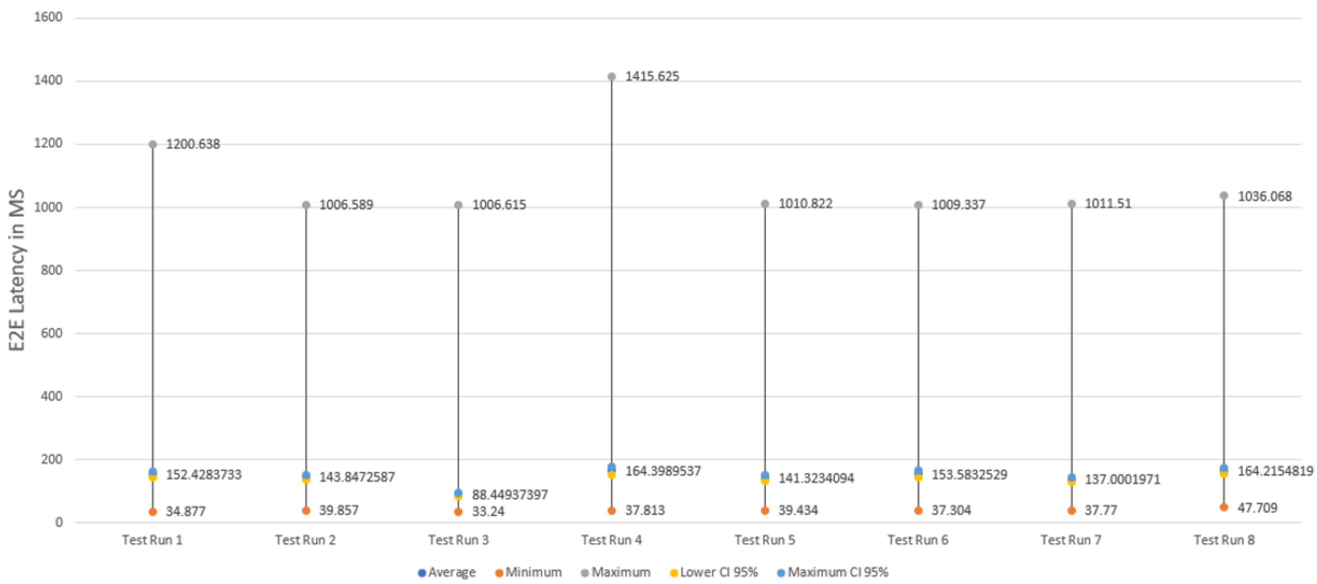


Figure 59: E2E round-trip application latency – GR-TR-7.1

Moreover, a higher delay can be observed when data is transmitting to the TR edge instance (MCC of 286) compared to the GR edge instance (MCC of 202), which prompts additional analysis. Besides the statistics based on the samples focused around the HO events (showcased in Figure 60), more extensive statistics based on the entire sample pool were generated, to create statistical confidence, and to acquire insights regarding the E2E experienced latency throughout the entire operation of the application/trials. These statistics are provided in Table 15 below.

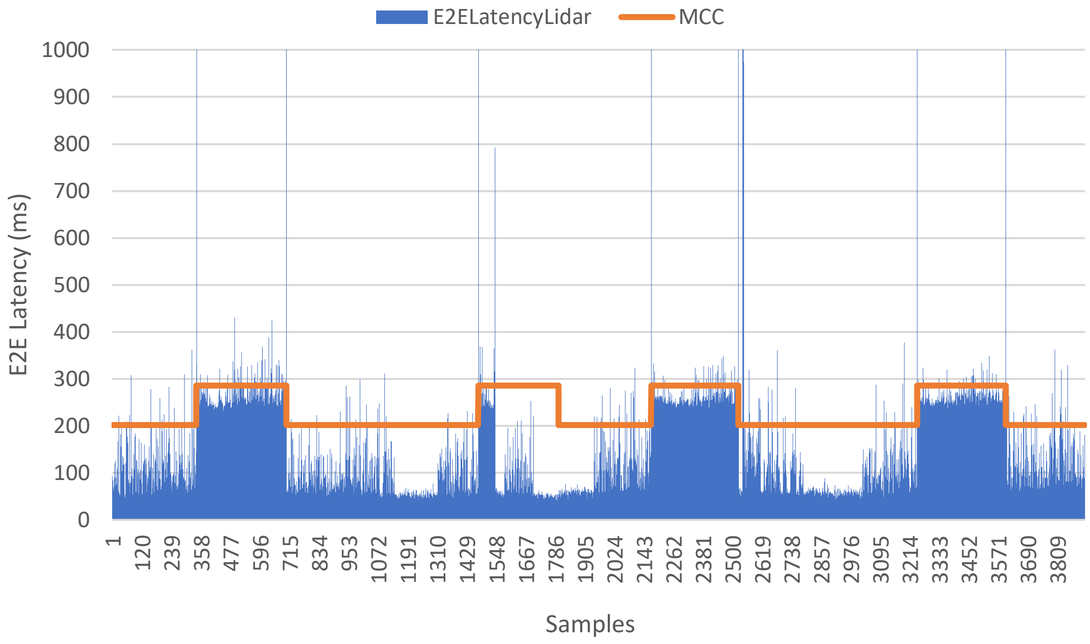


Figure 60: E2E round-trip application latency around the HO events – GR-TR-7.1

Based on the measurements presented in Table 15, the effect of the edge node and the HR data routing can immediately be seen. The E2E latency is significantly improved when going from the Cloud server to the Edge server for the GR edge case, when the trials are performed with the Cosmote SIM card (H-PLMN), while when communicating with the TR edge server, the latency is significantly higher (553 ms on average).

The performance observed with the GR edge server and the GR SIM card is extremely satisfactory as under the proper conditions it is shown that E2E latencies down to 12 ms can be achieved from the application perspective, which is much more than the original application requirements. When crossing the borders however, communication with the TR edge server with a GR SIM card and with a HR network configuration (all data traffic needs to travel back to the GR PLMN), increases the experienced E2E latency to extremely high levels, unsuitable for CAM applications.

Table 15: E2E latency measurements – ALL samples (GR & TR Edge)

ALL Samples – GR Edge			
# Total Samples	***Mean***	***Median***	***Std. Deviation***
28774	117.6 ms	74.7 ms	133.77 ms
Max value	***Min value***	***CI 95%***	***95th Percentile***
1415 ms	12.02 ms	Lower = 116.05 ms Higher = 119.15 ms	260.96
ALL Samples – TR Edge			
# Total Samples	***Mean***	***Median***	***Std. Deviation***
5175	553 ms	294.77 ms	133.77 ms
Max value	***Min value***	***CI 95%***	***95th Percentile***
1359 ms	26.97	Lower= 542.49 ms Higher= 564.732 ms	1115 ms

5.2.3.3 Mobility Interruption Time

This KPI is once again measured in a similar fashion measuring the elapsed time between the last message received at the edge server before the HO and the first message after the HO. Figure 61 depicts the recorded values of mobility interruption time per test run. The average value of all measurements is 867 ms with a minimum of 798 ms and a maximum of 1026 ms.

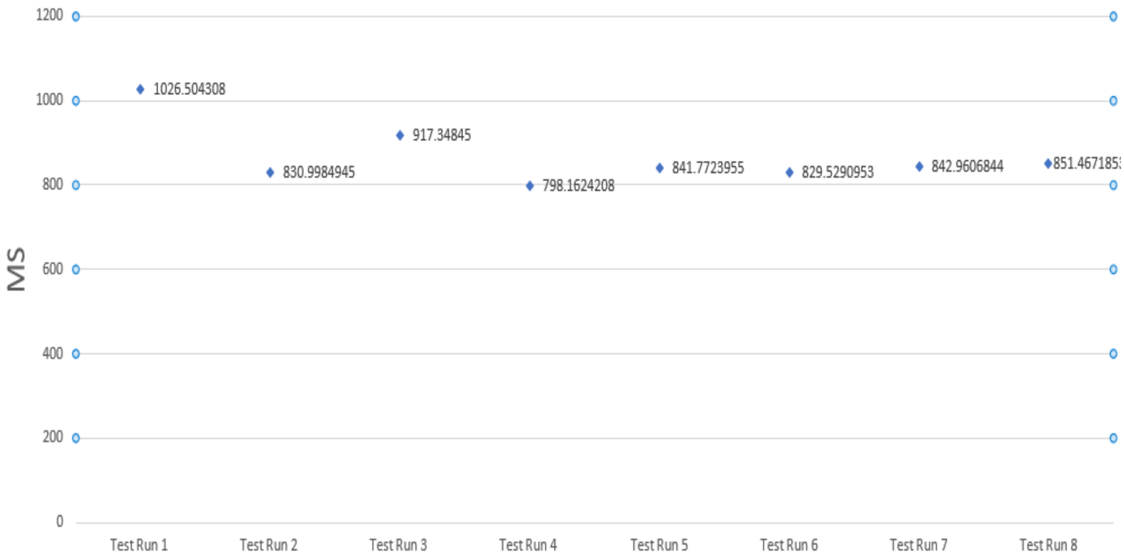


Figure 61: Mobility interruption time per test-run – GR-TR-7.1

Based on these measurements it can be concluded that the using edge servers instead of a cloud server doesn't play a significant role in the experienced interruption time, 710 ms when the server is located in a remote cloud (see section 5.2.1) vs 867 ms when the server is located at the edge (difference of 18%). This is due to the fact that HR data routing scheme is being used, meaning that even after the change to the V-PLMN, the OBU data are transmitted back to the H-PLMN edge server, which means that there is no need for an application instance HO to the V-PLMN edge server (and application instance) and no need for an application state transfer between edge servers.

5.2.3.4 XBI/CS insights for Test case GR-TR-7.1

Individual conclusions can be drawn for each of the addressed XBIs, using the network settings used for this Test case as well as regarding the effect of the implemented considered solutions.

- **XBI_1**: The average experienced NSA roaming interruption in this case was around 867 ms. Such an interruption time would jeopardize the performance of the autonomous stopping directive if it occurred right at the moment of the HO, as it would add an additional 10 meters to the stopping distance of any truck driving at 50 km/h. No significant difference is observed when switching from a cloud application server (Test case GR-TR-4.1 in section 5.2.1) to an edge application server.
- **XBI_3**: The average experienced inter-PLMN interconnection latency significantly varies when using the H-PLMN with H-edge server and when using the V-PLMN with the V-edge server, as the HR data routing scheme will always force the data via the H-PLMN. In this case extremely satisfactory values of E2E latency are offered from the H-edge server which are significantly improved compared to the cloud implementation (from 261 ms to 117 ms). Moreover, a more stable performance with less variations is observed. On the other hand, the E2E latency with the V-PLMN and the V-edge server is extremely high and completely unacceptable for CAM applications.
- **XBI_5**: The service interruption experienced on average during inter-PLMN HO was in the order of 867 ms, which is not close to the targeted values. The same analysis applies as for XBI_1. No significant difference is observed between the cloud and the edge implementations.

- **XBI_6**: The HR data routing leads to higher experienced E2E latencies as the data always needs to be routed back to the H-PLMN of the user. Same conclusions as for XBI_3 apply here as well.

5.2.4 TC GR-TR-7.2: [Edge] Direct Interconnection (CS_8)/HR NSA (CS_17)

Test Case Parameters

→ *PLMN Interconnection*: Direct interconnection
→ *Data routing*: Home Routing
→ *Server location* : Double Edge (GR & TR)
→ *Relevant XBI*: XBI_1, XBI_3, XBI_5, XBI_6
→ *Relevant CS*: CS_1, CS_8, CS_17
→ *Relevant Traffic Flows* : FL1, FL2, FL5

The results presented in this section reflect the measurements performed on April 13th and May 9th 2022 at the GR-TR borders, when the WINGS Server hosting the application was located in both the GR and the TR edge servers and an "application instance HO" was required when the autonomous vehicles changed serving networks (stateful application). The results provide an estimation of the E2E latency and the mobility interruption time experienced by the "Assisted -zero touch- Border crossing" application when performing HOs between the Cosmote and Turkcell networks. These tests were performed using a Cosmote SIM card.

As the UL Throughput measurements were practically identical with the ones reported for the Test case GR-TR7.1 (section 5.2.3) it was not deemed useful to repeat them again in this sub-section. This this section focuses on the E2E latency and mobility interruption time measurements.

5.2.4.1 E2E Latency

The E2E latency once again represents the RTT measured from the Lidar requests to the server and back. The samples collected are in the range of one minute before and after Handover event.

Figure 62 indicates per iteration, the mean, maximum, minimum value and the confidence interval (CI 95%) of E2E latency for each Test run, while Figure 63 depicts the experienced latency per sample around the HO events. The results indicate that the mean sample value is around 160 ms, which is higher than expected. Figure 63 clearly shows that in the 4th Test run the E2E latency is close to 236 ms, which is causing the increased mean value, especially when compared to the latency from the Cloud Operation Server scenario (Testcase GR-TR-4.2). This also indicates that the network performance is not always steady, as outliers and channel condition may significantly affect the experienced performance.

Besides the outlier of Test Run 4, it can be observed that all other test runs experience much lower latencies, usually even below 100 ms, and only around the HO points some samples experience higher latencies. Overall, the direct interconnections seems to be effective, offering low RTTs but stability remains an issue. To further investigate the difference effects at play here, additional processing is carried out based on the entire sample pool (not just around the HO points), and separately for the GR and TR edge servers. These statistics are provided in Table 16.

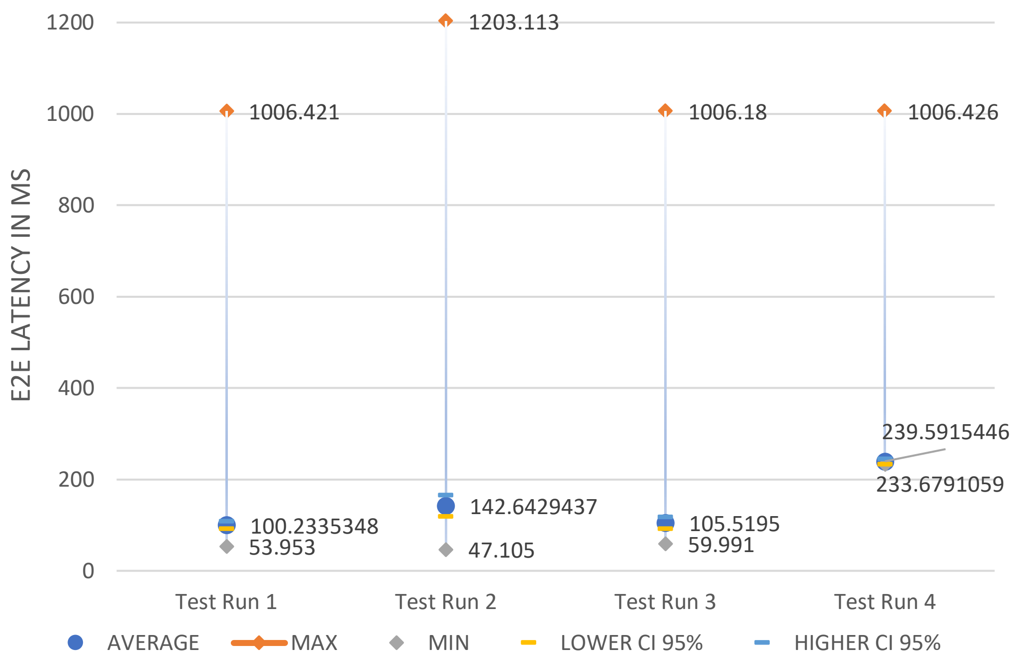


Figure 62: E2E round-trip application latency – GR-TR-7.2

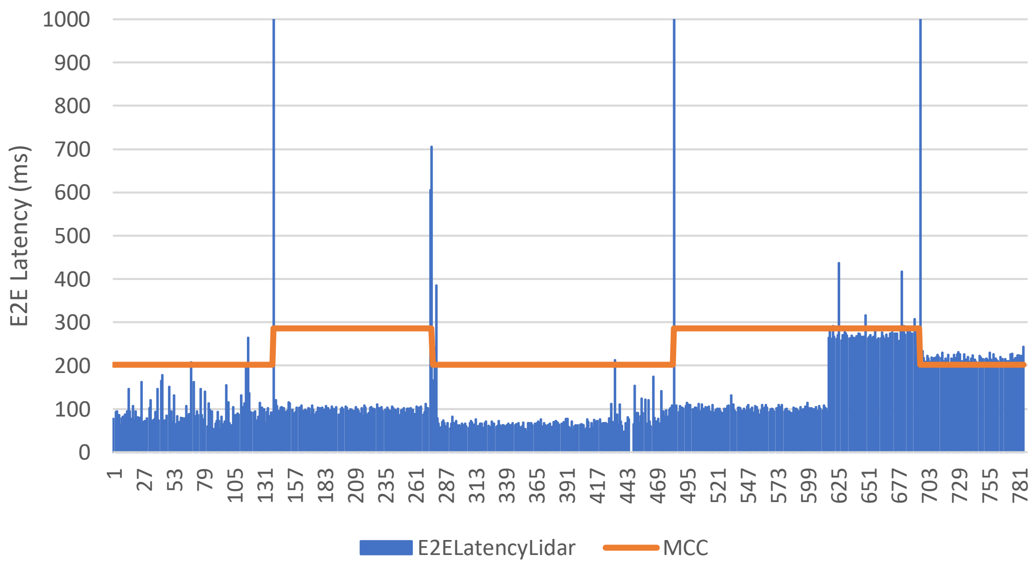


Figure 63: E2E round-trip application latency around the HO events – GR-TR-7.2

Table 16: E2E latency measurements – ALL samples (GR & TR Edge for TS GR-TR-7.2)

ALL Samples – GR Edge			
# Total Samples	***Mean***	***Median***	***Std. Deviation***
34068	82.62 ms	74.37 ms	42.63 ms
Max value	***Min value***	***CI 95%***	***95th Percentile***
1203 ms	12.22 ms	Lower = 82.13 ms Higher = 83.12 ms	131.74
ALL Samples – TR Edge			
# Total Samples	***Mean***	***Median***	***Std. Deviation***
3094	268.69 ms	263.5 ms	46.69 ms
Max value	***Min value***	***CI 95%***	***95th Percentile***
1006 ms	80.19	Lower= 167.04 ms Higher= 270.33 ms	335.48 ms

When analysing the experienced E2E latency based on the different edge servers (Table 16), the effect of the HR configuration is once again immediately clear. When using a Cosmote SIM card, the E2E latency using the GR edge server (H-PLMN) is extremely low and even the most stringent CAM application requirements can be met. The experienced average E2E latency of 82 ms (roughly ~40 ms one way delay) is an improvement of approximately 38% compared to deploying the application at the remote cloud section 5.2.2, hence proving the usefulness of the edge server deployment.

The effect of the V-PLMN HR routing is once again visible, as the experienced E2E latency when using the TR edge server (V-PLMN) is very high and not acceptable for CAM applications. Even so, some acceptable values can also be obtained under the proper circumstances, as can be observed by the minimum value of 80 ms.

The positive effect of the direct interconnection is also visible by comparing the results of Testcases GR-TR 7.1 (section 5.2.3) with GR-TR7.2. The average E2E latency for the GR edge server (H-PLMN) has improved by about 30% (decreased to 82 ms from 117 ms for public internet connection), while the TR edge server implementation has decreased to 268 ms from 553 ms for public internet connection).

5.2.4.2 Mobility Interruption Time

This KPI is once again measured in a similar fashion measuring the elapsed time between the last message received at the edge server before the HO and the first message after the HO. Figure 64 depicts the experienced interruption time from the application perspective. The Results indicate that in the worst case scenario a service interruption of ~910 ms is experienced, while the average service interruption time due to HOs was calculated at ~774 ms.

This performance is very similar to the Testcase of HR/Direct with cloud based operation (GR-TR-4.2 in section 5.2.2) as there is a difference of only 0.9% in average service interruption time. Under these network settings the service seems to be quite stable, and the service interruption time is tolerable for most functions of the US. In general, the mobility interruption time does not seem to be affected much by the use of cloud or edge servers and/or by the use of a public internet or direct interconnection among the networks.

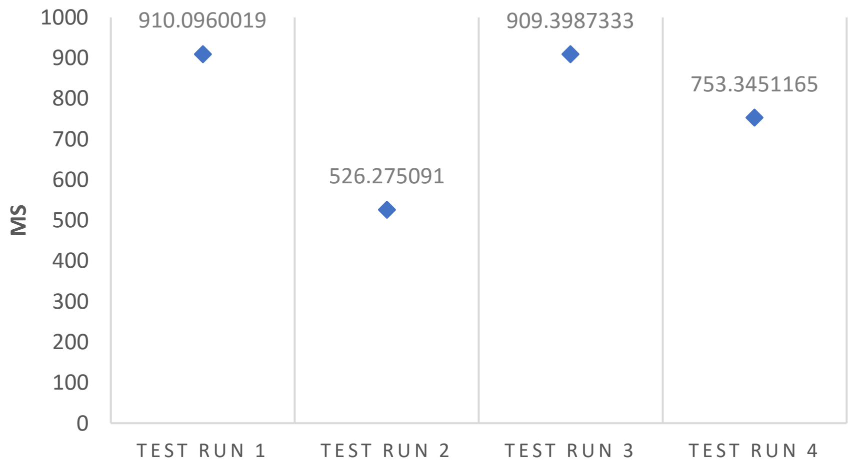


Figure 64: Mobility interruption time per test-run – GR-TR-7.2

5.2.4.3 XBI/CS insights for Test case GR-TR-7.2

Individual conclusions can be drawn for each of the addressed XBIs, using the network settings used for this Test case as well as regarding the effect of the implemented considered solutions.

- **XBI_1**: The experienced NSA roaming interruption on an application level when using CS_8 and CS_17 (HR, Direct interconnection) is deemed satisfactory for the hard border environments of this User Story. The most critical aspect of this US, which is the autonomous stopping of the vehicle when detecting a human/custom's agent, will suffer a significant degradation of performance which may translate into an additional stopping distance of ~10 meters for vehicles moving at a speed of 40 km/h, due to the service interruption time. However, the experienced interruption time is satisfactory for all other functionalities of this US. The positioning of the application in a cloud or edge server, doesn't seem to impact the experienced service interruption time, as in both cases the experienced time is similar (see testcase GR-TR-4.2)
- **XBI_3**: The experienced inter-PLMN interconnection latency is deemed very satisfactory from an application-level perspective when using the H-edge server, especially in non-cell-edge conditions, i.e., far away from the HO points. The experienced RT time for communication between the OBU and the edge server via the H-PLMN is enough to adequately perform all the envisioned functions of the US. The average performance is quite satisfactory, while peak performance exceeds expectations. The use of edge servers for the deployment of the CAM application, seems to significantly improve the experienced E2E RT latency as an improvement of 30% and above can be observed when using edge servers. However, the experienced latency when using the V-PLMN to communicate with the edge server, remains unacceptable for CAM applications, as the HR data routing scheme introduces significant latencies which can only partially be mitigated by the direct interconnection between the PLMNs.
- **XBI_5**: The service interruption experienced during inter-PLMN HO is not excessive, however the most stringent requirements of the US (VRU functionality) cannot be safely met. This should not pose a major issue for hard-border environments, however it may become an issue for open-border environments. The service continuity experienced by the application was satisfactory for all other functions of this US. Almost no difference can be observed in service level continuity when utilizing edge application servers instead of cloud application server.
- **XBI_6**: The HR data routing scheme, ends up in relatively low service interruption times (compared to the LBO routing – see section 5.2.5) and acceptable E2E RT latencies when the H-PLMN is used. As such this routing scheme is deemed somewhat satisfactory and may be adequate for the early deployment of this and similar USs at hard-border environments (without the support of the critical VRU service). The use of this routing scheme in combination with edge server CAM application deployment, seems to offer the best combination of service interruption and experienced latency, from the application perspective.

5.2.5 TC GR-TR-7.4: [Edge] Direct Interconnection (CS_8)/LBO NSA (CS_16)

Test Case Parameters

→ *PLMN Interconnection*: Direct interconnection
→ *Data routing*: Local break-Out
→ *Server location* : Double Edge (GR & TR)
→ *Relevant XBI*: XBI_1, XBI_3, XBI_5, XBI_6
→ *Relevant CS*: CS_1, CS_8, CS_16
→ *Relevant Traffic Flows* : FL1, FL2, FL5

The results presented in this section reflect the measurements performed on June 2nd 2022 at the GR-TR borders, when the WINGS Server hosting the application was located in both the GR and the TR edge servers and an "application instance HO" was required when the autonomous vehicles changed serving networks (stateful application). The results provide an estimation of the E2E latency and the mobility interruption time experienced by the "Assisted -zero touch- Border crossing" application when performing HOs between the Cosmote and Turkcell networks. These tests were performed using a Cosmote SIM card.

As the UL Throughput measurements were practically identical with the ones reported for the Test case GR-TR7.1 (section 5.2.3) it was not deemed useful to repeat them again in this sub-section. This this section focuses on the E2E latency and mobility interruption time measurements.

5.2.5.1 E2E Latency

The E2E latency once again represents the RTT measured from the Lidar requests to the server and back. The samples collected are in the range of one minute before and after Handover event. Figure 65 indicates per iteration, the mean, maximum, minimum value and the confidence interval (CI 95%) of E2E latency for each Test run. All measurements gathered from the Lidar in communication with the Edge Operation Server. The mean value of 104 ms round trip time is very satisfactory from the application perspective and right on the target set for this KPI by this US (50 ms one way latency). The overall performance is greatly improved compared to the cloud-based operation as values as low as 35 ms RT delay can be observed (100% improvement in the min latency observed compared to the cloud server implementation in section 5.2.2). Moreover, thanks to the LBO data routing, an improvement of the E2E latency is also observed compared to the HR network setting (Testcase GR-TR-7.2) which is around 35% (from an average of 160 ms down to 104 ms).

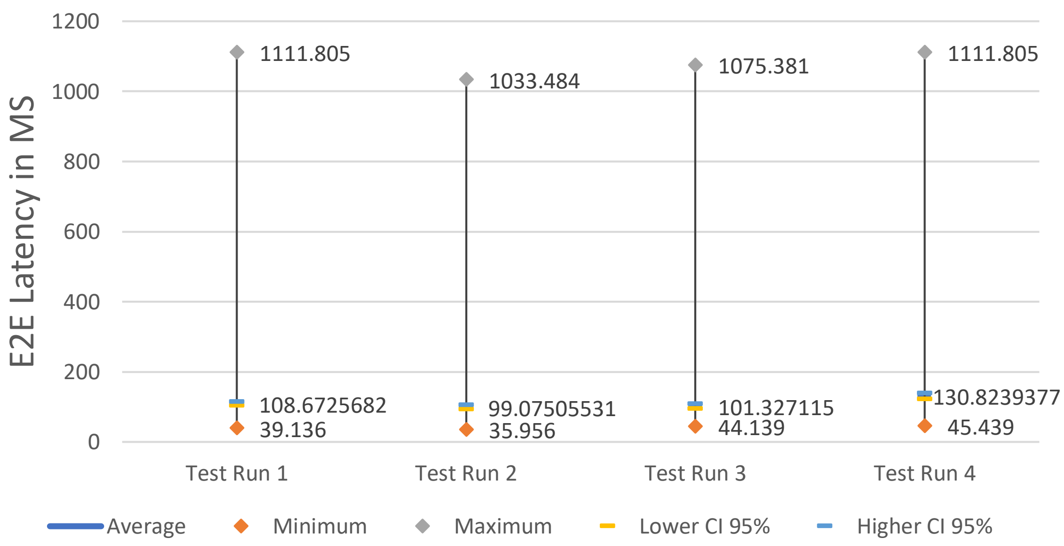


Figure 65: E2E round-trip application latency – GR-TR-7.4

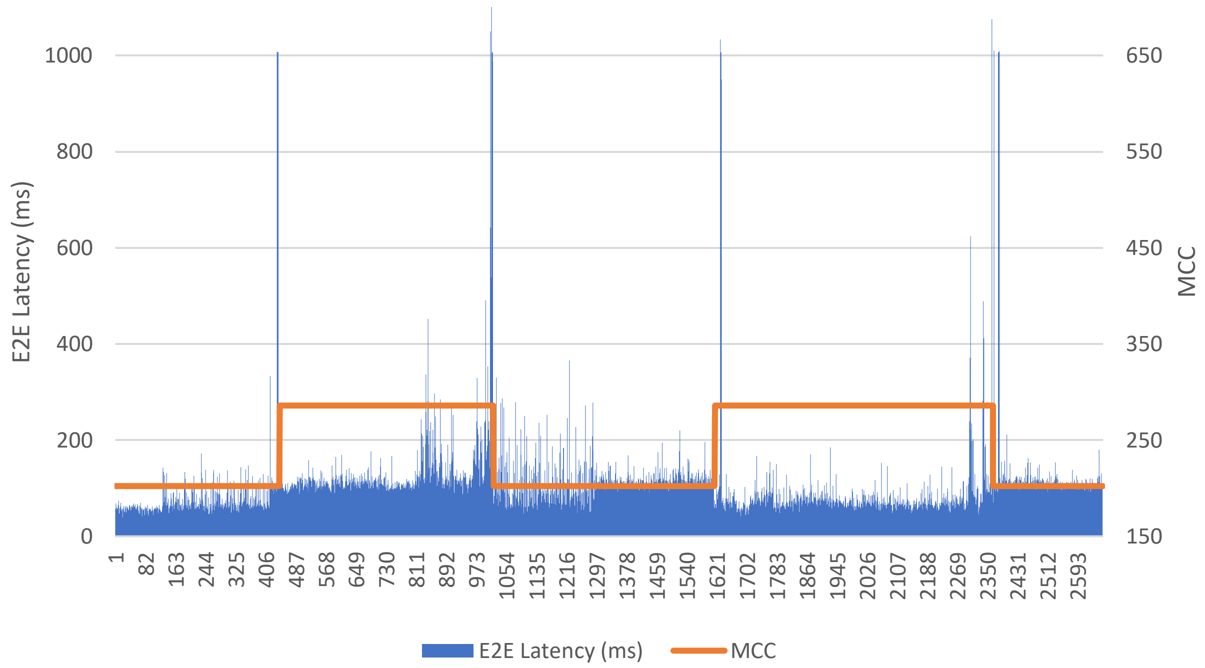


Figure 66: E2E round-trip application latency around the HO events – GR-TR-7.4

Figure 66 shows the E2E latency per Request-Response from the Lidar to the Edge Operation Server. Similarly to previous graphs the HO events are depicted by the change in the MCC, where a peak of E2E latency from the Lidar's request/response can be detected. The effect of the HO is clearly visible in all HO instances, while some instability can also be observed close to the moments of the HOs. Besides these HOs points, the experienced latency seems to be quite stable and very close to the target of 100 ms.

Once again, more extensive statistics based on the entire sample pool were generated, to create statistical confidence, and to acquire insights regarding the E2E experienced latency throughout the entire operation of the application/trials. These statistics are provided in Table 17.

Table 17: E2E latency measurements – ALL samples (GR & TR Edge for TS GR-TR-7.4)

ALL Samples – GR Edge			
# Total Samples	***Mean***	***Median***	***Std. Deviation***
2848	78.45 ms	67.11 ms	42.75 ms
Max value	***Min value***	***CI 95%***	***95th Percentile***
1050 ms	35.96 ms	Lower= 77.90 ms Higher= 79.12 ms	140.75
ALL Samples – TR Edge			
# Total Samples	***Mean***	***Median***	***Std. Deviation***
2522	119.62 ms	109.64 ms	49.98 ms
Max value	***Min value***	***CI 95%***	***95th Percentile***
1316 ms	69.75	Lower= 116.65 ms Higher= 132.47 ms	177.74 ms

When analysing the experienced E2E latency based on the different edge servers, the effect of the LBO configuration becomes clear, when comparing these measurements with the measurements using an HR configuration with Direct interconnection (GR-TR-7.2), i.e. Table 16.

- For the GR edge server the mean E2E latency drops to 78.45 ms with LBO from 82.62 ms with HR (~5% improvement). Even more impressively the median drops to 67.11 ms with LBO (~10% improvement). The performance with the HR configuration was already impressive in this case, and thanks to the improved latency with the LBO configuration it became even better.
- For the TR edge server the mean E2E latency drops to 119.6 ms with LBO from 268.69 ms with HR (~55% improvement), while the median drops to 109.64 ms with LBO (~58% improvement). This is where the biggest difference with LBO is observed, i.e., when using a different SIM card to roam to a V-PLMN and to transmit data to a local (V-PLMN) edge server. The LBO configuration guarantees a direct connection of the OBU to the V-PLMN edge server, while with the HR configuration the data had to go through the H-PLMN gateway.

The combination of LBO with edge servers and direct interconnection of the PLMN's seems to provide the best performance in terms of E2E latency. However, the large interruption time, as will be addressed in the next sub-section, is a significant drawback.

5.2.5.2 Mobility Interruption Time

Figure 67 depicts the experienced interruption time from the application perspective. The results indicate that the impact of the LBO configuration on the experienced service interruption time is significant as the average experienced interruption time is 4540 ms. This huge interruption time is mostly caused by the triggering of the P-GW change by the OBU once the RAN HO is completed. A new session has to be established in the V-PLMN, through the reset of the OBU's connection management layer. This artefact indicates that such OBU triggered P-GW change will always lead to significant interruption times.

This performance is much worst compared to the service interruption time experienced with the HR network configuration (GR-TR-7.2 in section 5.2.4), which was expected and now confirmed via the experimental results.

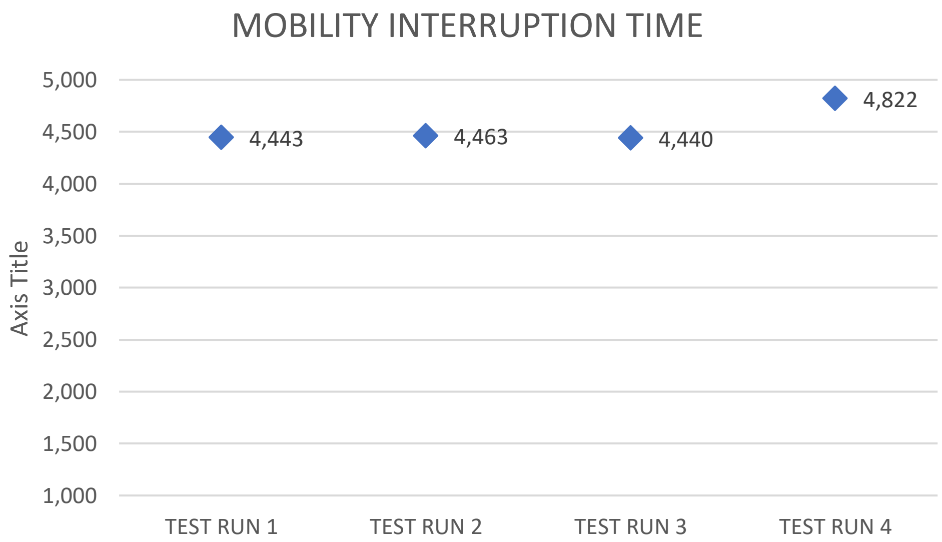


Figure 67: Mobility interruption time per test-run – GR-TR-7.4

5.2.5.3 XBI/CS insights for Test case GR-TR-7.4

Individual conclusions can be drawn for each of the addressed XBIs, using the network settings used for this Test case as well as regarding the effect of the implemented considered solutions.

- **XBI_1**: The experienced NSA roaming interruption on an application level when using CS_8 and CS_16 (LBO, Direct interconnection) is by far the worst, due to the necessary change of the P-GW by triggering a reset in the OBU connection manager. Such significant service interruption does not allow for the successful CAM service provisioning at cross-border conditions. A network-initiated P-GW change could significantly reduce the interruption time here, but such a mechanism does not exist in 3GPP Rel.15 NSA networks.
- **XBI_3**: The experienced E2E latency when using CS_8 and CS_16 (LBO, Direct interconnection) with edge servers implementation is the best experienced among all other network configurations. The performance measured with this network configuration, easily achieves the initial KPI target of ~50 ms one way latency and in most cases, it exceeds it. Thanks to the LBO data routing, an improvement of the average E2E latency by approximately 10% is observed for the H-PLMN/H-Edge server compared to the HR network setting (Testcase GR-TR-7.2), while an improvement of approximately 55% is observed for the V-PLMN/V-Edge server setup.
- **XBI_5**: The service interruption experienced during inter-PLMN HO is excessive and does not allow for the successful implementation of the US. The experienced interruption time of around 4,5 seconds is mostly caused by the OBU-triggered P-GW change, which requires the reset of the OBU's connection manager. At this stage this cannot be considered as a realistic solution.
- **XBI_6**: The LBO network configuration seems to impose a significant penalty in terms of service interruption time, while the benefits gained in terms of E2E latency are not that significant to make the use of LBO an attractive option for deployment over 5G NSA networks.

Based on the analysis of the tested scenarios (HR vs LBO and Public Internet vs Direct interconnection), it is clear that the ***LBO/Direct configuration*** in combination with edge servers, is offering the best E2E latency, far exceeding the US requirements, however the huge interruption time during the P-GW change, renders this configuration an unrealistic solution for CAM applications at this stage. The solid performance obtained by the ***HR/Direct configuration***, both in terms of E2E latency (on average achieving the US requirements) and in terms of interruption time (not ideal, but good enough), renders it as the most suitable solution for CAM application support at cross-border conditions with 5G NSA network deployment. Once 5G-SA networks have been widely deployed and the SSC mode 3 feature is readily available, the configurations should be reconsidered.

5.3 Aggregate CAM Application-level performance assessment

Besides the investigation on a per Testcase basis, it is important to extract aggregate insights regarding the performance from a CAM user's perspective under key realistic scenarios. The following sections present the measured KPIs from the application perspective and provide an analysis of the observed performance under varying conditions. The KPIs measured on an application level are the E2E latency (mean and per packet) and the average interruption time during handovers. The results are processed and presented in such a fashion in order to provide insights with regards to the posed cross-border challenges and the considered solutions.

5.3.1 Inter-PLMN Interconnection & Application Placement

The experienced E2E latency is potentially one of the most critical KPIs for CAM applications, to guarantee safe operation. For the Extended Sensors use case, one-way latencies of about 50 ms (or ~100 ms E2E Round Trip Time (RTT)) are usually targeted (as discussed in section 2.3). During the multiple runs of the GR-TR trials the E2E RTT latencies of all the transmitted and successfully delivered OBU packets (i.e., the time between the original transmission of a packet from the OBU, it's reception from the application server, and the reception of the ACK from the OBU) were collected and used to evaluate the experienced E2E latency. As these were application-level measurements, no packet loss was observed due the underlying 5G retransmission protocol (HARQ), which guaranteed retransmission and delivery of initially non-delivered packets. These retransmissions are reflected in the much larger E2E delay of these packets.

Figure 68 depicts the mean E2E latency, and the corresponding 95% Confidence Interval (CI), based on all collected samples, for six different trial scenarios at the GR-TR borders, evaluating different inter-PLMN interconnection schemes and application server placement. The dark blue columns correspond to the Public interconnection measurements (over GRX/IPX). All measurements depicted in Figure 68 took place under the HR data roaming scheme, and for each scenario at least 3-4 HOs took place, guaranteeing that the effect of inter-PLMN HO would be captured by the measurements.

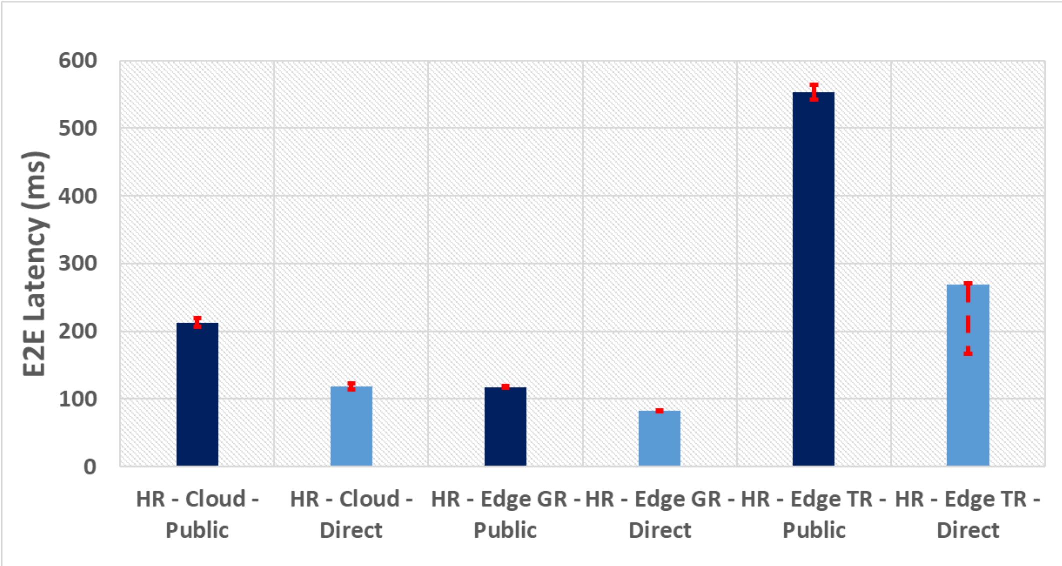


Figure 68: Mean E2E Latency (HR) – Public vs Direct interconnection for Cloud & Edge application server placement.

Firstly, it can be observed that for five out of six scenarios the 95% CI is extremely close to the mean value, indicating stable performance i.e., 95% of samples fall within the CI range. For the HR-Edge TR-Direct, a more unstable performance is detected due to the longer data route and the varying environmental and channel conditions (the GR-TR borders is a harsh, rapidly varying environment due to multiple passing trucks). By comparing the measurements between the public interconnection scenarios with the Direct leased line scenarios, it is obvious that a significant improvement of E2E latency is observed when a direct line is used. The improvement ranges from about 44% for cloud operation to 30% for the GR Edge case and up to 51.4% for the case of the TR Edge. This significant reduction in E2E latency was expected as the GRX/IPX public interface is a best effort interface without any latency guarantees and introduces significant latency in the communication between two PLMNs. The Direct leased line on the other hand, offers very stable and low-latency performance, which is extremely suitable for CAM applications, however its real-world applicability is challenging due to the high cost.

The experienced E2E latency when a cloud application server is used is 212 ms and 118 ms, with a public and a direct interconnection respectively. That shows that a public interconnection is not sufficient to meet the CAM application requirements, but when using a direct interconnection, the target KPI value of 100 ms is almost met. Performance further improves when using an edge server, which significantly reduces the path that data traverse and consequently the E2E latency. For operation in the H-PLMN the performance exceeds the target value as the mean E2E latency drops to 82 ms.

The worst performance is observed during operation in the V-PLMN (TR side in this scenario), which was expected as the data travel back to the H-PLMN and from there to the cloud and/or TR edge server. When the data traverse the GRX/IPX interface and come back to the TR Edge server, the mean latency is recorded at 553 ms which is unacceptable for CAM applications. When using a direct interconnection, the E2E latency is significantly improved (drops to 268 ms), but it is still not good enough for CAM applications. Based on the reported measurements, when the HR data roaming scheme is used, there is a limitation on the experienced latency at the V-PLMN side.

5.3.2 Data Routing / Roaming Scheme

To find out the limitations of the HR roaming scheme and to evaluate the improvement the LBO scheme stands to offer in terms of E2E latency, additional trial scenarios with the LBO scheme were executed. Figure 69 depicts the mean measured E2E RTT latency of the OBU packets for the HR and LBO schemes, as measured at the GR-TR borders. The dark blue columns represent the HR measurements and the light blue the LBO measurements. As the goal was also to investigate the best attainable performance that CAM applications may expect from the 5G network, the direct interconnection with Edge servers configuration was selected for this comparison.

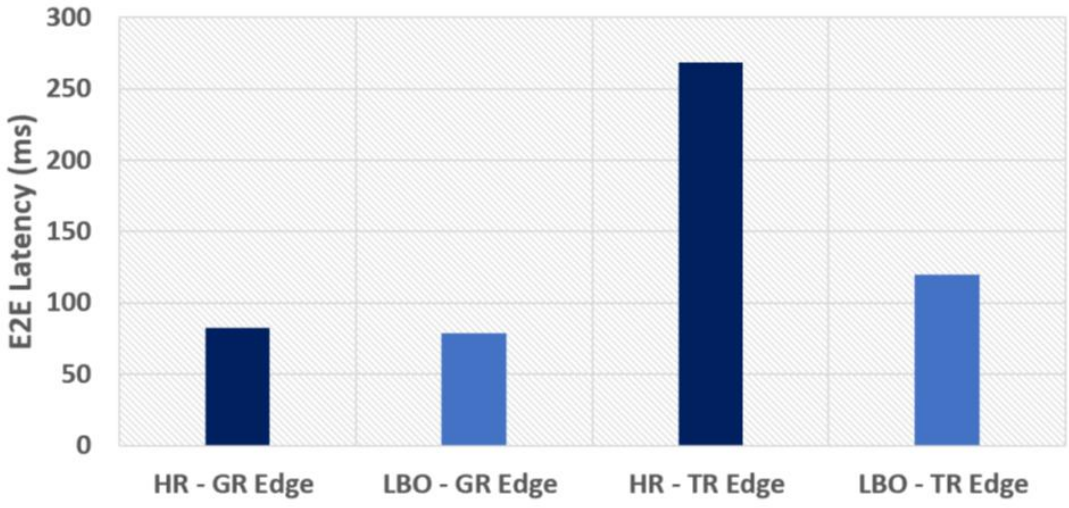


Figure 69: Mean E2E Latency – Direct PLMN interconnection and Edge server utilization- HR vs LBO roaming

Based on the results of Figure 69 it can be observed that for the case of operation on the H-PLMN the LBO doesn't offer any practical improvement (82 ms for HR vs 79 ms for LBO). This was expected as the H-PLMN data route is practically the same (from OBU directly to the GR edge server) irrespective of the routing/roaming scheme. However, a significant improvement can be observed when observing the mean E2E latency of the OBU packets delivered to the TR Edge server at the V-PLMN. In this case the E2E latency drops to 119 ms for LBO from 268 ms for HR. This impressive reduction of E2E latency is due to the much shorter route followed by the OBU packets towards the TR Edge server, when LBO is used (see Figure 22).

Based on the analysis of the above measurements, the LBO data roaming scheme has the potential to significantly reduce the experienced CAM application latency when a vehicle is roaming, while the use of Edge servers also seems to provide quantifiable benefits. A 5G network configuration with edge servers, LBO routing and a direct interconnection between the neighboring PLMNs, can easily meet the CAM application's E2E latency requirements. In order to obtain additional insights into the behavior of the CAM application in cross-border conditions, Figure 70 depicts the raw recorded E2E RTT latency experienced by the successfully delivered packets of the OBU around (and during) four inter-PLMN HO events for both the HR and the LBO network configurations.

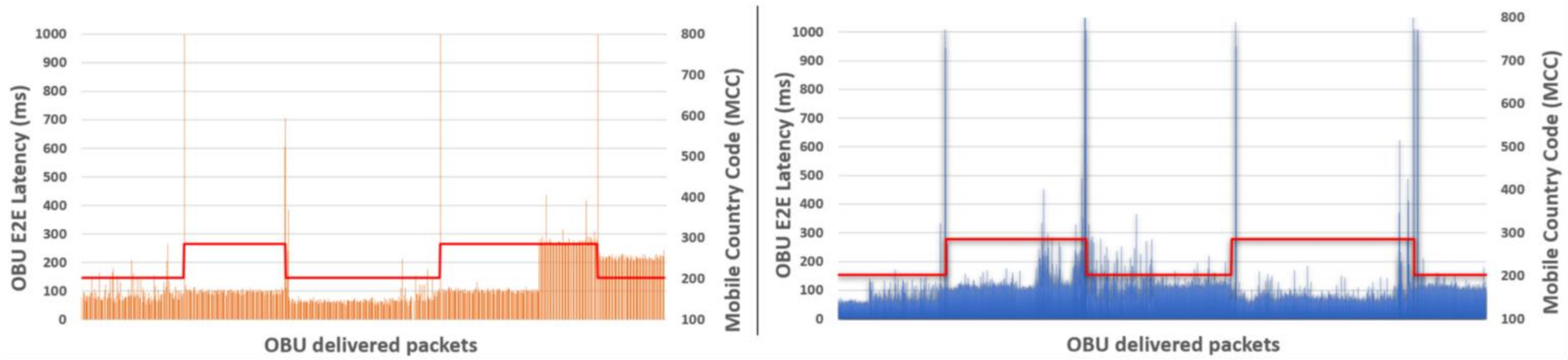


Figure 70: E2E Latency per OBU packet during Edge-based inter-PLMN HOs for a) HR data routing and b) LBO data routing.

The red line on both graphs indicates the MCC (secondary y axis) under which the OBU packet was transmitted and hence the used network (202 for GR PLMN and 286 for TR PLMN). It also highlights the HO points between the two networks. As expected, it can be observed that during the HOs, the experienced latency of the packet attempted to be transmitted was significantly increased (around 1 sec) for both HR and LBO cases. This was caused by the unavailability of service during the HO and the resulting packet retransmissions once service was obtained by the neighboring network. It can also be observed that very quickly after the HO, the E2E latency experienced by the packets returned to values close to the mean. More "spikes" are observed in the case of LBO especially around the HO points, which could indicate a more severe effect of the HO event and in general a larger deviation of measurements from the mean. Environmental conditions during the trials may also play a role in this case (difficult to quantify). The effects of the channel condition are in general obvious in these measurements, as for some HOs performance is very good for the LBO case (values below 100 ms which in general don't appear as often in the HR case), while in other cases the experienced latency is more erratic. It is also interesting to note that the experienced latency during the last HO event with HR is much higher than the mean value, again attributed to channel and environmental conditions during the measurements, as it affects performance on both networks (under both MCCs).

5.3.3 Experienced Mobility Interruption Time

Another important KPI, which significantly affects the performance of CAM applications in cross-border conditions, is the mobility interruption time, i.e., the time interval elapsed between the OBU losing connectivity with the H-PLMN and obtaining service from the V-PLMN (and vice versa). It has been shown that the LBO routing scheme helps reduce the experienced E2E latency, however it is also expected to introduce significant interruption times, due to the fact that the OBU session must be released and re-established with the neighboring network during the HO. Table 18 provides the average measured mobility interruption time during inter-PLMN HOs, under various network configurations (aggregated values from all scenarios presented in section 5.2). The combination of public interconnection with LBO routing was never tested as the other configurations reflect more realistic network set-ups.

Table 18: Average Mobility Interruption Time

Mobility Interruption Time	**Cloud Server Placement**	
	Home Routed	
Public (GRX/IPX) Interconnection	*710 ms*	
Direct Interconnection	*767 ms*	
	Edge Server Placement	
	Home Routed	***Local Break Out***
Public (GRX/IPX) Interconnection	*867 ms*	*n/a*
Direct Interconnection	*774 ms*	*4542 ms*

No major deviations are observed for HR operation. The mobility interruption time does not seem to be affected much by the use of cloud or edge servers and/or by the type of interconnection among the networks. The obtained value of 710 ms – 860 ms seems to be the result of the change of the Radio Access Network (RAN), i.e., detaching from H-PLMN RAN and attaching to V-PLMN RAN, and the session continuity mechanism of 5G which is straightforward when HR is used (same P-GW). This performance is not good enough for CAM applications, however its impact may be considered minimal, as session continuity is guaranteed and only a few OBU packets are affected around the HO event, as shown by Figure 70.

When LBO roaming is used on the other hand, the experienced mobility interruption is much worse, in the order of multiple seconds. This is the result of the lack of a mechanism from the 5G network's side (for 3GPP Rel.15 NSA networks) to trigger the P-GW change, i.e., from the Home P-GW to the Visited P-GW. Instead, the P-GW change needs to be triggered by the OBU once a RAN HO is detected and completed. A new session has to be established in the V-PLMN, through the reset of the OBU's connection management layer. This artefact indicates that such OBU triggered P-GW change will always lead to significant interruption times, making it unsuitable for the support of CAM application in cross-border conditions (for 3GPP Rel.15 NSA networks).

The above presented results indicate that gains up to 45% can be expected when using edge application servers instead of cloud servers, while a 51% reduction in E2E latency can be expected under proper configuration when a direct line is used instead of a public interconnection. Finally, the use of LBO roaming can improve E2E latency by up to 55% compared to HR but suffers from extreme service interruption time.

5.4 Aggregate Network level performance assessment

5.4.1 User Experienced throughput during HO (TCP DL/UL)

We begin our analysis by measuring the Packet Data Convergence Protocol (PDCP) throughput delivered by the two networks along the route of the GR-TR CBC, using Transmission Control Protocol (TCP) traffic, to get an estimate of the experienced network performance both in the Downlink (DL) as well as the Uplink (UL) direction. Even though the throughput KPI doesn't provide particular insights with regards to the artefacts during the HO between the two networks, it is still very useful in terms of evaluating the channel conditions along the test route and it also provides significant insights into the effect of roaming on the expected performance when receiving service from a V-PLMN. Home Routing (HR) is the selected roaming configuration for these tests, which means that traffic is always routed back to the H-PLMN.

Figure 71 depicts the PDCP DL throughput as recorded by the TEMS Investigation tool during a round-trip test drive from TR to GR and back. A Turkish SIM card was used for this measurement making the TR network the Home network and, the GR network the Visited network. The white dotted vertical lines indicate the HO points between the two networks where the serving network changes.

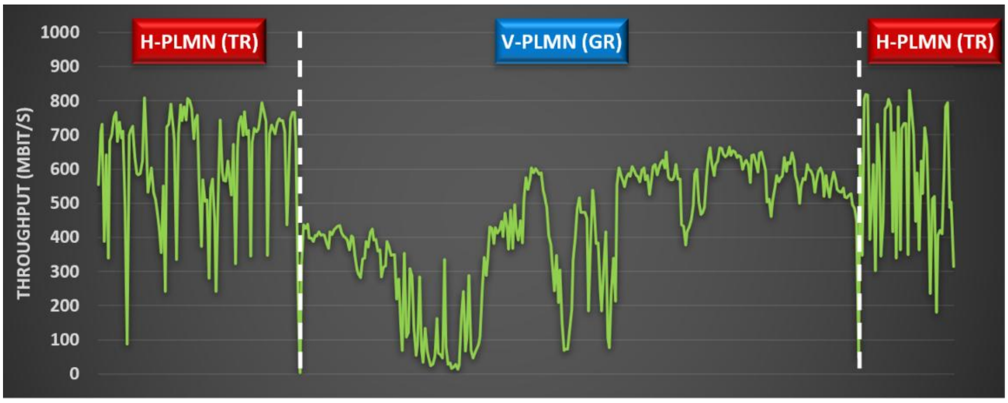


Figure 71: DL PDCP Throughput on the GR-TR CBC (TR SIM).

By examining Figure 71 it can be observed that the performance on the TR network (H-PLMN) in terms of DL throughput is better as it peaks at 831 Mbps with an average of 605 Mbps and a 10th percentile throughput of 163 Mbps. Respectively on the GR network (V-PLMN) the DL throughput peaks at 663 Mbps with an average of 421 Mbps and a 10th percentile of 81 Mbps. This significant difference, which was observed during the entire measurement campaign, is attributed to two factors, i) the clear LoS and closer proximity of the TR serving gNB to the test route, which result in much better propagation/channel conditions on the TR side (see achieved RSRP in Figure 25) and ii) on the better environmental/situational conditions experienced on the route under TR network coverage (open space with no metal obstacles) compared to the route under GR network coverage (tight road, long queues of trucks waiting for inspection, metal fence obstructing LoS).

Another interesting observation is the high variability of experienced throughput along the test route of the GR-TR CBC, on both sides of the borders, which is a clear indication of the high variability of the channel conditions, creating an unstable environment. Such conditions are far from ideal for the deployment of CAM services (partially caused by sparse gNB deployment in rural areas), however the achieved performance should meet the requirements of most CAM applications in terms of DL throughput.

The UL throughput along the GR-TR CBC also demonstrates a highly variable behavior, as depicted in Figure 72. In this case, the COSMOTE (GR) SIM card was used for the measurement UEs, making the COSMOTE network the H-PLMN and the Turkcell network the V-PLMN. The effect of the bad channel conditions experienced on the GR side are even more visible in this figure, as the throughput is significantly lower on the GR side, even though the GR network is the H-PLMN. The achieved peak UL throughput on the GR side is 49.5 Mbps while the average and 10th percentile throughput are 13.7 Mbps and 3 Mbps respectively. The achieved UL performance on the TR network (V-PLMN) on the other hand reaches a peak UL throughput of 116 Mbps with an average and 10th percentile throughput of 60 Mbps and 25 Mbps, respectively. The effect of the metal fence close to the GR customs site is particularly visible on the UL performance, as a plateau of consistently low throughput is observed when the test UE approaches the metal fence area. Another interesting artefact that can be observed in Figure 72 is the ping pong effect experienced right after the first HO from the GR to the TR network, as indicated by the orange vertical lines. As the propagation conditions were bad on both networks at that particular point in the route, the UE briefly reconnected to the GR network before reconnecting to the TR network permanently.

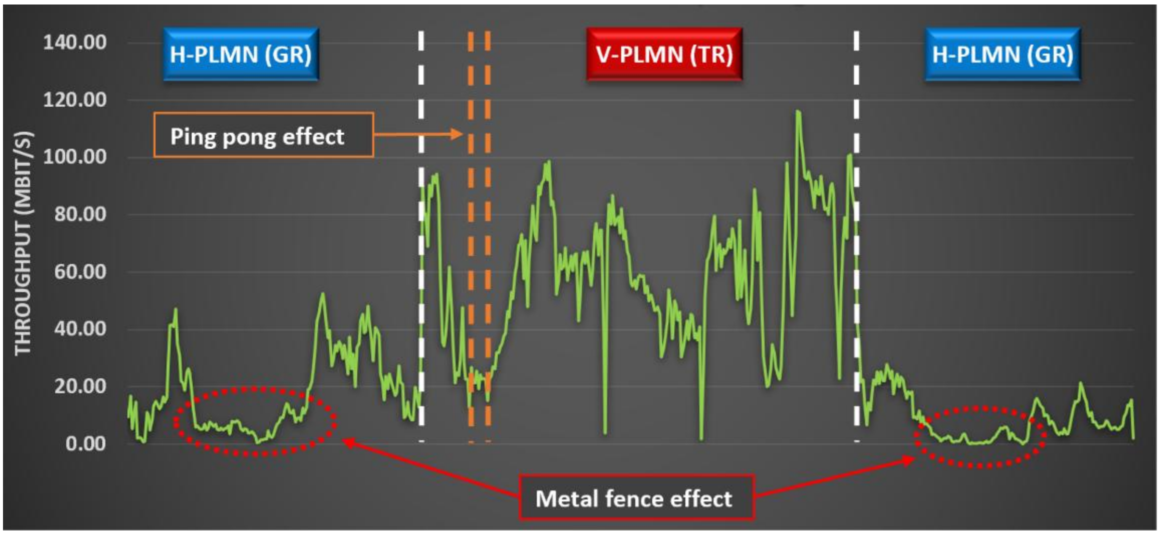


Figure 72: UL PDCP Throughput on the GR-TR CBC (GR SIM).

The observed throughput performance (DL and UL) along the GR-TR CBC nicely depicts the challenges that need to be addressed at rural environments and especially in hard-border conditions, to properly provision CAM services. Sparse or NLoS coverage and physical obstacles due to customs facilities and high vehicular traffic, create a highly challenging and unpredictable propagation environment which significantly affects the throughput delivered by the 5G network.

5.4.2 Service Interruption evaluation.

One of the most critical KPIs to ensure the provision of inter-PLMN CAM services is the service interruption time experienced by the CAM user (UE), which depicts the time that a UE remains without service during the HO from one network to another. The service interruption time can be broken down in two components namely, i) the network interruption time reflecting the time it takes for the UE to detach from one network and attach to the neighboring network and ii) the application-level interruption time which reflects the time required for the application instance hosted at the UE to (re)connect with the application server via the new network. The end-to-end service interruption time (from the perspective of the CAM user, i.e., application level) was presented in section 5.3.3 and in [62], however, no insights are offered as to which part of this interruption time was due to the network processes and which due to the application processes.

During the discussed drive tests, the experienced service interruption was calculated using the network traces from the MMEs of the two networks. As the GR-TR CBC uses 5G-NSA networks with an LTE anchoring layer on both sides, the HO interruption time of both the LTE and the NR layers were measured. The HO process is triggered by the LTE layer and at the same time the NR layer release process also initiates (at the H-PLMN). During this time no data may be received by the user on either layer (LTE or NR). The LTE HO process is completed first (as will be shown) and the user starts receiving data on the LTE layer, but the NR layer is still not available. Once the NR layer addition process is also completed, the user starts receiving data via the NR (5G) layer. Trace outputs were collected by both the GR and TR MMEs after a TCP DL drive test was performed and were processed following the signaling flow described in [90]. Based on the signaling flow, the exact time that user data flow stopped on one network and started on the other after the HO could be identified and the interruption time was calculated. Table 19 provides some examples of the probing tool's recordings of network HO events (for Direct interconnection), along with the exact timestamp of the HO at the LTE and NR layers.

Table 20 depicts the average network interruption times observed after several HOs, under both PLMN interconnection configurations, namely public internet (GRX/IPX) and the direct leased line. The interruption times depicted indicate the elapsed time between a user plane HO start and HO completed (on each layer), as identified by the MME traces. It can be observed that there are no significant differences in the network-based interruption time when using the GRX/IPX interface to interconnect neighboring PLMNs and when using a direct fiber line, or between DL and UL performance, as in all cases average values between 52 and 60 ms are observed for the LTE layer and between 187 and 199 ms for the NR layer. This indicates that control plane signaling which is necessary for the inter-PLMN HO and attachment of the UE to the new network is not significantly affected by the inter-PLMN interconnection type.

Table 19: Timestamped Network HO Events (LTE & NR).

Date - Time	User Plane HO Start	User Plane HO End	Interruption Time (ms)	Direction
LTE Interruption – Direct Interconnection (DL)				
2022-03-29, 12:15:23.681	LTE HoPdcpDIStopTime			TR→GR
2022-03-29, 12:15:23.739		LTE HoPdcpDIContinueTime	58	
2022-03-29, 12:17:01.029	LTE HoPdcpDIStopTime			GR→TR
2022-03-29, 12:17:01.099		LTE HoPdcpDIContinueTime	70	
2022-03-29, 12:19:30.462	LTE HoPdcpDIStopTime			TR→GR
2022-03-29, 12:19:30.514		LTE HoPdcpDIContinueTime	52	
2022-03-29, 12:23:38.818	LTE HoPdcpDIStopTime			GR→TR
2022-03-29, 12:23:38.884		LTE HoPdcpDIContinueTime	66	
NR Interruption – Direct Interconnection (DL)				
2022-03-29, 12:15:23.681	NR User Plane HO Start			TR→GR
2022-03-29, 12:15:23.879		NR User Plane HO End	198	
2022-03-29, 12:17:01.029	NR User Plane HO Start			GR→TR
2022-03-29, 12:17:01.211		NR User Plane HO End	182	
2022-03-29, 12:19:30.462	NR User Plane HO Start			TR→GR
2022-03-29, 12:19:30.654		NR User Plane HO End	192	
2022-03-29, 12:23:38.818	NR User Plane HO Start			GR→TR
2022-03-29, 12:23:38.996		NR User Plane HO End	178	

Table 20: Average Network Based Interruption Time During Handovers.

	Interruption Component	Public Internet Interconnection	Direct Interconnection
Downlink (DL)	LTE HO Interruption	56 ms	61 ms
	NR HO Interruption	199 ms	187 ms
Uplink (UL)	LTE HO Interruption	52 ms	55 ms
	NR HO Interruption	191 ms	199 ms

It must be noted that LTE/NR interruption time measurements collected during all the HOs during drive tests, displayed very small variance and were all very close to the averages reported in Table 20, indicating a very stable performance for that metric. Even though HR allows for service continuity, the experienced service interruption during the inter-PLMN HO as measured in the field with 5G NSA networks (on the NR layer), can be considered satisfactory but not ideal for some stringent CAM services (i.e., services requiring a service interruption below 200 ms).

Based on the results of Table 20 and the end-to-end service interruption reported in section 5.3.3 which was approximately **770 ms** on average, **it can be concluded that the largest component of the end-to-end service interruption is attributed to the application-level interruption time, as the network-based interruption, with a max of 199 ms, only accounts for ~26% of the total experienced service interruption** time by a CAM user. This is a very useful insight, which points to the fact that the expected advances of 5G SA will not be enough to reach the targeted performance, if CAM application developers do not simultaneously improve the application functionality, to take into account inter-PLMN HOs. Parallel improvements on the network side as well as on the application side are necessary to reach the demanding requirements of CAM applications, and novel techniques such as e.g., Network Applications, offering application developers direct access to network functions, may be a promising way forward for the provision of cross-border CAM services.

5.4.3 Network Latency (Round Trip Time)

Potentially one of the most critical metrics for the successful provisioning of CAM services is the experienced end-to-end latency by the CAM users, i.e., the time it takes for a message to be transmitted from a UE to a CAM application server and for the response from the CAM server to reach the UE. As most CAM applications are time-critical due to the high-mobility environment, an end-to-end latency of around 100 ms is considered as a common requirement for safety-critical applications [54][53]. The user observed end-to-end application-level latency as experienced in the GR-TR CBC with HR roaming configuration, was reported in section 5.3 and in [62] to be approximately 212 ms when public internet interconnection is used and ~120 ms when a direct leased line is used, which is further reduced to ~82 ms, if edge application servers are also used. However, no insights were provided with regards to the contribution of the 5G network and the application side to this total experienced latency. By using ping messages in the network during the drive tests the network Round Trip Time (RTT) could be calculated for both types of inter-PLMN interconnection.

Figure 73 depicts the average ping RTT measured along the GR-TR CBC for both types of interconnections among the two PLMNs. The measurements include data from drive tests performed on both directions (GR to TR and TR to GR) and incorporate the delays experienced during several inter-PLMN HOs. The ping interval was set at 100 ms in order to catch potential packet losses. From Figure 73 it can be observed that the baseline RTT for operations in the H-PLMN is around 20 ms, irrespective of the roaming scheme, as traffic never crosses to the V-PLMN when the user operates in their home network (i.e., roaming is not used). These values have been confirmed with both GR and TR SIM cards in their respective home networks. The effect of the selected interconnection scheme though becomes obvious when the UE crosses to the V-PLMN and roaming is activated. The average value of the experienced end-to-end latency from a network perspective reaches 94 ms when the baseline public internet (GRX/IPX interface) interconnection is used. This value is extremely restrictive for CAM applications, as the end-to-end latency requirement 'budget' is already mostly consumed just with the network component and without adding the application latency on top.

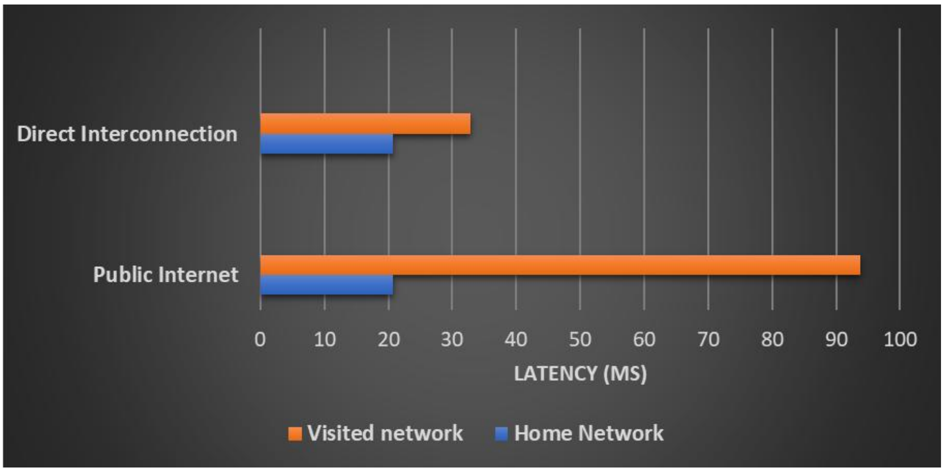


Figure 73: Average Ping RTT for Public & Direct interconnection.

The use of a direct leased fiber line to interconnect the two neighboring PLMNs proves to be highly effective, as the average ping RTT drops to around 32 ms. Such a network latency value is much more suitable for the provision of CAM services, as it is below the requirements threshold, allowing for additional delay from the application layer. This outcome was expected as the GRX/IPX interface routes the UE traffic from the V-PLMN back to the H-PLMN through a third-party network not located in any of the two countries, when HR is used, significantly increasing the experienced latency. The use of a dedicated direct line between the two networks proves to be an efficient technical solution, however its global applicability for CAM service provisioning may be arguable due to the increased cost.

In order to better understand the behaviour of the network and the experienced performance under different scenarios and network settings, it is important to look beyond the average RTT value. Figure 74 depicts the Cumulative Distribution Function (CDF) of multiple RTT measurements under different PLMN interconnection settings and with different SIM cards. As expected, when the UE operates in its home networks (H-PLMN) the experienced RTT is very good irrespective of the network settings and interconnection scheme, as roaming is not used (confirmed by the four first H-PLMN scenarios).

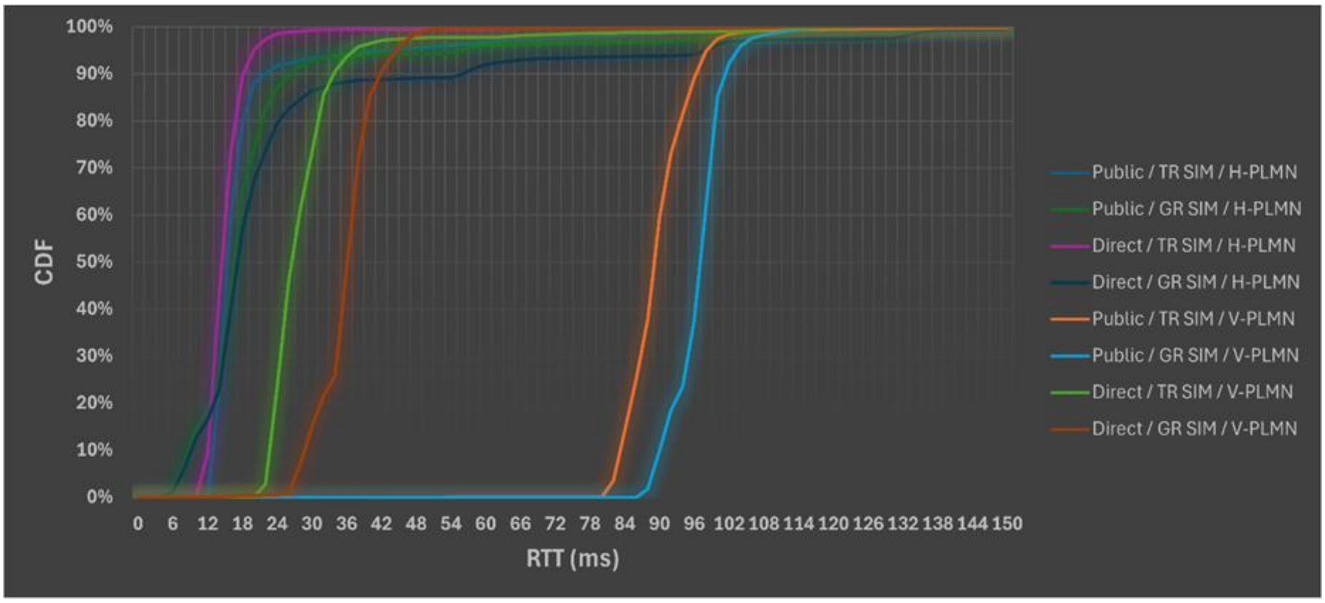


Figure 74: Cumulative Distribution Function of RTT for different test scenarios.

The experienced end-to-end latency in the H-PLMN scenarios is extremely good, as more than 90% of the samples indicate an RTT of below 25-26 ms. Once again, the better propagation conditions on the TR side are confirmed, as the measurements with the TR SIM on the TR side (H-PLMN for TR SIM) are significantly better than with the GR SIM on the GR side. In the GR side, it can be observed that in the scenario Direct/GR SIM/H-PLMN while 80% of the samples experience an RTT below 24 ms, there is a "longer tail" in the CDF as several samples experience longer latencies (90th percentile of the CDF is at 56 ms). This is the effect created by the bad propagation conditions on the GR side (e.g., metal fence reflections, etc.), leading to a more variable performance.

The most interesting insights originate from analyzing the samples when roaming is activated, i.e., the V-PLMN scenarios (when the TR SIM is using the GR networks or the GR SIM is using the TR network). When the public interconnection is used between the two PLMNs the performance significantly deteriorates as it can be observed by the Public/TR SIM/V-PLMN and Public/GR SIM/V-PLMN scenarios in Figure 74. The CDF indicates that in both scenarios the vast majority of samples experience an RTT between 80 and 102 ms, which is significantly worse than the H-PLMN performance. The improvement offered by the Direct interconnection between the PLMNs is immediately visible by comparing these scenarios with the Direct/TR SIM/V-PLMN and Direct/GR SIM/V-PLMN scenarios, where the Direct interconnection is used. The experienced RTT immediately falls under 34 ms for the TR SIM and 42 ms for the GR SIM, for 90% of the samples, practically bringing the experienced performance close to the H-PLMN scenario levels. This is a significant performance improvement showcasing the potential benefits of the direct inter-PLMN interconnection for cross-border CAM applications.

In order to obtain a deeper understanding of the behavior of the channel along the drive-route of the GR-TR CBC and the effect it has on the transmitted packets, the experienced latency per sample (ping packet) is provided in Figure 75 for two drive-tests, one with the Public internet interconnection enabled (a), and one with the direct interconnection enabled (b).

By comparing Figure 75 a) and b) the difference in latency when roaming, caused by the inter-PLMN interconnection type, is immediately visible, as almost all sample values of Figure 75 a) when operating in the V-PLMN are between 90-100 ms, while the respective latency for most samples in V-PLMN (roaming state) when the direct interconnection is used (Figure 75 b), are around the 30 ms mark.

It is also worth noting that the radio conditions can affect the delivery time of a packet as even under H-PLMN operation there are scattered packets that experience very long delays (> 100 ms). However, this phenomenon is relatively rare (outliers) and the latency experienced by most packets can be characterized as stable (small variation from the average). It is also not surprising that packets around the HO points between the two PLMNs also experience longer delays (~100 ms), as the channel conditions around the HO points are not optimal, and the rerouting of traffic from the V-PLMN back to the H-PLMN has an effect on the transmitted packet.

Based on the reported measurements, the end-to-end latency delivered by the 5G NSA networks on the GR-TR CBC should be sufficient for most CAM applications when a direct interconnection between the networks is available. Roaming in a neighboring network with a public internet line on the other hand, creates challenges for CAM services. Even though the recorded latency can be characterized as relatively stable, the ping outliers with latencies above 100 ms indicate that a few messages may be delayed, even on the H-PLMN, which may be an issue for safety critical CAM applications.

An important lesson learned from these measurements is that the use of a public GRX/IPX interface is almost prohibitive when attempting to provision cross-border CAM services. As the cost of a direct fiber line among all national operators may be discouraging for the operators' OPEX, alternative solutions should be explored by the operators (e.g., national roaming in cross-border areas with nominated incumbents per geographic location), while national and EU authorities should also work towards facilitating a collaborative framework that would enable efficient cross-border handovers without an extreme cost increase for operators.

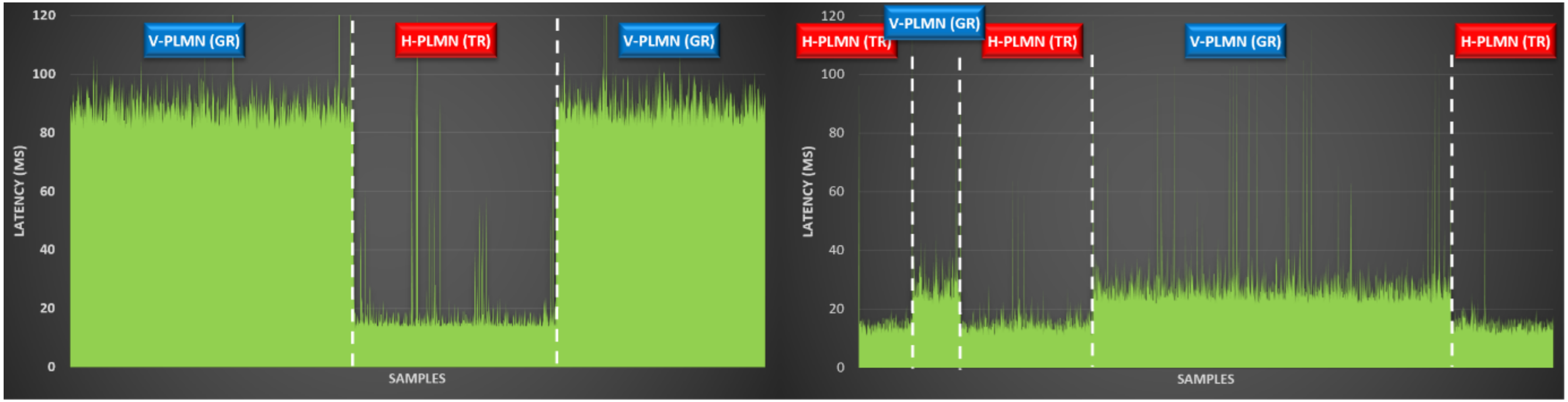


Figure 75: Ping Round-Trip Time (RTT) along the GR-TR CBC for a) GRX/IPX interconnection and b) Direct interconnection

5.5 Discussion & Insights

The results presented in the previous sections comprise some of the first available field measurements from 5G cross-border corridors and contributed to an initial analysis of 5G networks performance when provisioning CAM services in a cross-border environment. The performed analysis focused on three main KPIs, namely throughput (DL and UL), connectivity interruption time due to inter-PLMN HO and end-to-end network latency in an attempt to evaluate the capability of 5G NSA networks to meet the requirements of stringent CAM applications, not only under standard operation in their H-PLMN but also during an inter-PLMN HO and the consequent operation in roaming mode in the V-PLMN. It is worth noting that multiple optimization rounds took place prior to the measurement campaigns in order to avoid coverage gaps, minimize the experienced ping-pong effects and configure the two networks (and used UEs) for optimum performance in high mobility scenarios for cross-border environments, i.e., minimize the user experienced interruption time via HO parameter optimization.

The recorded throughput across the GR-TR CBC indicates that for the most part the CAM application requirements can be met, especially in the downlink, as 700-800 Mbps values could be reached, although significant variations were detected in performance due to the high mobility and varying propagation conditions. This is especially true in the uplink, were performance especially when roaming on the GR side varied significantly, leading to reduced throughput. These significant variations in performance are caused for the most part by the quickly varying hard borders environment of the GR-TR CBC, with intense traffic intervals and surrounding obstacles.

The lesson learned from this analysis is **that current sparse gNB placements in rural environments, resulting in non-Line of Sight conditions and low RSRP values, may hinder or delay the adoption of CAM services** close to cross-border areas. 5G network operators should consider **network densification** in critical automotive network points such as border crossings and additional potential measures such as advanced antennae technologies (eMIMO, Reconfigurable Intelligent Surfaces (RIS), etc.) as well as careful RAN planning and Tx-Rx fine tuning, which would allow to meet the stringent CAM use case requirements even in cross border scenarios. Additionally, OEMs and OBU designers should consider **optimum OBU design techniques** and **antennae placement** in the vehicle, to further improve the user experienced performance.

The service interruption is potentially one of the most critical metrics for CAM services, as it indicates the time interval that a vehicle will remain "isolated" from the world (no communication with other surrounding vehicles and/or CAM application servers) due to the inter-PLMN HO, which creates serious safety concerns. The network-oriented interruption, as measured via the MME traces of both neighbouring networks, was found to be approximately 193 ms (on average), irrespective of the PLMN interconnection method. This value is mostly due to the signalling time required to detach from one network and to attach to the other and cannot be further decreased with the existing trial setup, i.e., 5G NSA networks with S10 interface. Since control signalling is not really affected by the interconnection latency between the two PLMNs, it is not surprising that the performance remains similar under both configurations.

The main lessons learned from this analysis is **that Rel.15 5G NSA networks do not seem capable of providing the necessary performance when it comes to service interruption for cross-border CAM applications**, and alternatives should be considered. Network operators should perhaps consider directly deploying more advanced releases of 5G (e.g., Rel.16 and beyond) in Stand Alone mode in cross-border areas, as certain advanced features offered in these releases (e.g., SSC mode 3) may help mitigate the service interruption issue. At the same time, OEMs should consider significantly **investing in 'fail-safe' modes** for their vehicles, allowing them to temporarily operate in a 'reduced autonomy' mode until service is restored, while CAM application developers should also work towards **minimizing the application's dependency on connectivity** and explore new features that could further improve the application's integration with the 5G network (e.g., Network Applications).

Still, the network-induced interruption time only accounts for less than 25% of the total service interruption time for the HR routing scheme, as the most significant bottleneck is the CAM application induced service interruption time which is approximately 627 ms on average, leading to a total service interruption time (network + CAM application) of more than 800 ms. Performance significantly deteriorates when the LBO routing scheme is used, as the CAM application induced service interruption grows to more than 4300 ms (network interruption remains the same), leading to unacceptable levels of interruption for CAM services. Figure 76 depicts the measured service interruption time for HR and LBO and for different network interconnection settings, breaking them down into their individual components of network-induced interruption time and application-induced interruption time.

The network end-to-end latency as measured from the RTT of ping packets clearly shows the benefits of a direct fibre interconnection between the neighbouring networks compared to the industry standard of public GRX/IPX interfaces. While a network end-to-end latency of approximately 32 ms is achievable when roaming, with the first option, the second option leads to average latencies around 94 ms. This result comes as no surprise as there are no Quality of Service (QoS) guarantees on the GRX/IPX interfaces, which were practically designed as a “best effort” service. The analysis of the latency profile of the packets along the GR-TR CBC also indicates that despite the fact that for the most part the latency delivered by the 5G NSA networks is sufficient for CAM services, performance variations caused by propagation conditions may affect the experienced latency of some transmitted packets. As the use of a direct line to interconnect all neighbouring 5G networks arguably presents significant deployment challenges, alternative solutions on network and application level should be examined.

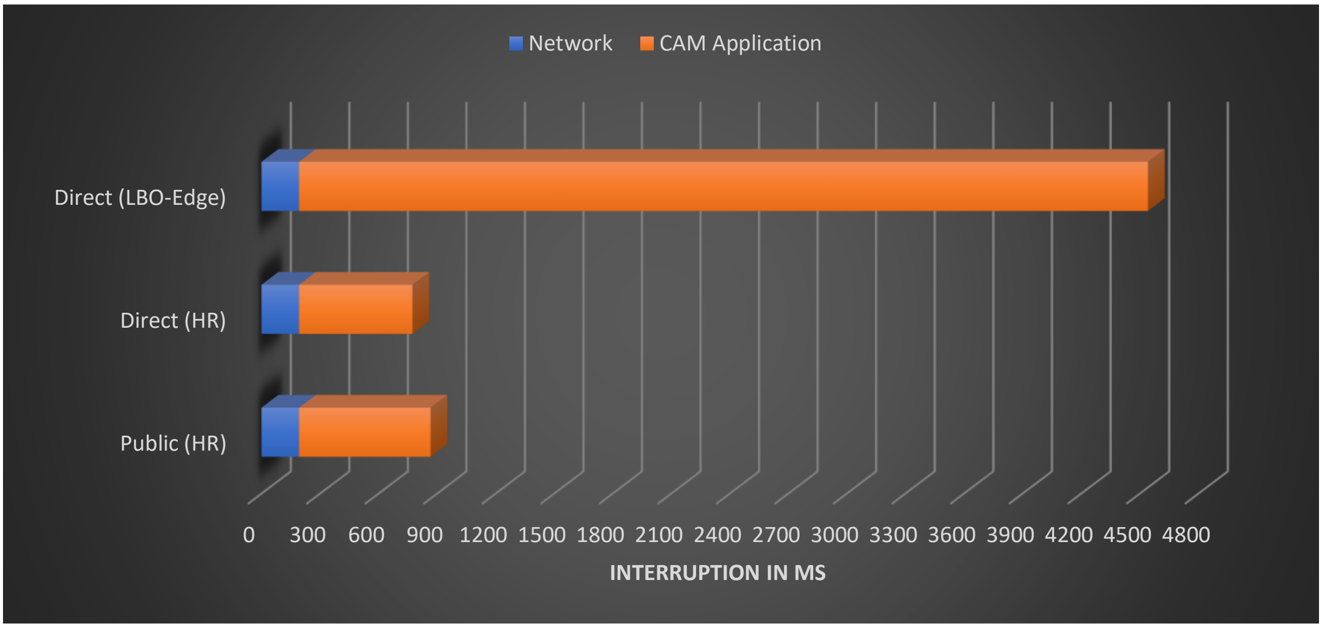


Figure 76: Overview of measured Interruption time on network and CAM application levels.

By investigating the whole picture of CAM provisioning services at cross-border conditions, the measured E2E service latency when the HR routing scheme is selected is significantly larger when the neighbouring networks are interconnected by a public GRX/IPX line, for both the network and the CAM application side, reaching a total of 212 ms (the network accounts for 94 ms while the application adds another 118 ms of latency on average). A significant improvement is observed on both the network and application layer latencies when a direct interconnection is used as the total E2E latency drops to 118 ms out of which the network only accounts for 32 ms while the application adds another 86 ms (on average). Finally, it was shown that E2E latencies as low as 99 ms (on average) are achievable in the field when using the LBO routing scheme with a direct interconnection and the use of edge servers. This is a very significant timing, as it proves that 3GPP Rel.15 5G NSA networks are capable of meeting the stringent CAM requirements under very difficult cross-border conditions. Figure 77 provides a very insightful overview of the measured latencies at network and CAM application levels for the different settings investigated in this work.

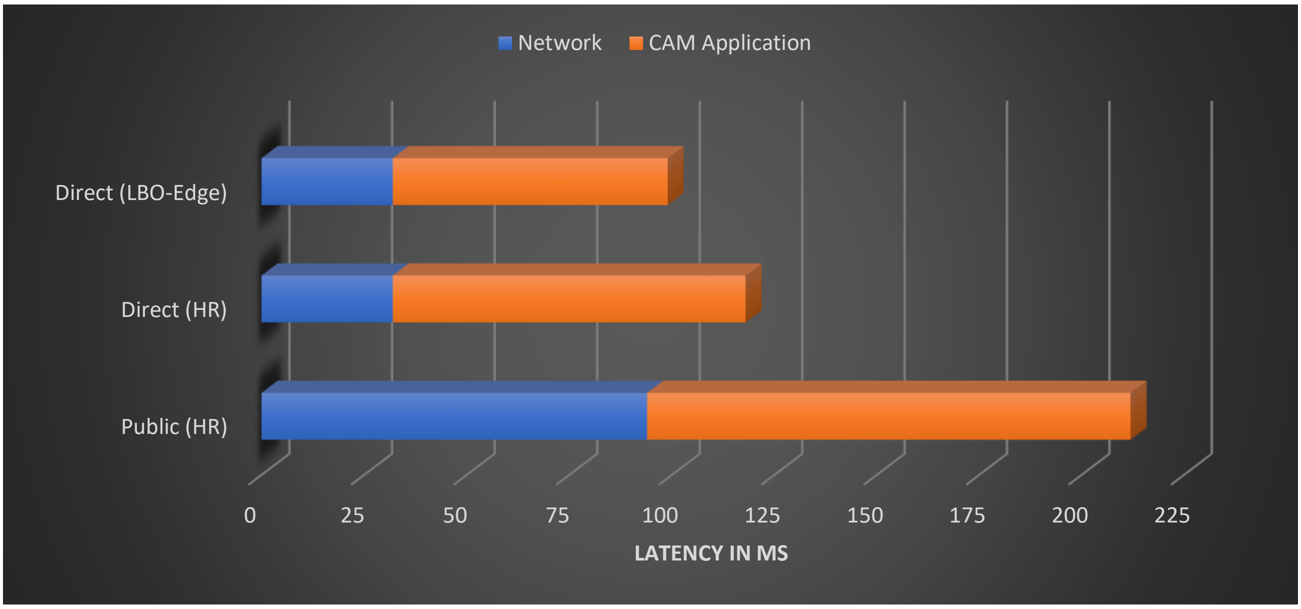


Figure 77: Overview of measured E2E latencies on network and CAM application levels.

The main lessons learned from the analysis of the latency measurements presented in this thesis, is that the **legacy GRX/IPX interface is not capable of supporting advanced CAM use cases** during cross border operations. Operators should consider using a direct interconnection with neighbouring PLMNs, but as the use of a direct line to interconnect all neighbouring 5G networks arguably presents significant deployment challenges and a CAPEX and OPEX increase, alternative solutions (such as national roaming) should be examined. Moreover, as application layer latency comprises the majority of the user experienced E2E latency, **CAM application developers should investigate mechanisms to reduce the application layer latency and/or to allow for operations in an "offline" mode** where the application functions in limited capacity without network connectivity for a limited amount of time. Finally, **national and EU authorities should attempt to establish a collaborative framework that would enable efficient cross-border handovers** without an extreme cost increase for operators, investigating different interconnection options and/or supporting the deployment of additional MM features for selected areas.

The advanced mobility management features of later releases of 5G SA are yet to be deployed in the field and as such have not yet been tested and validated in terms of real-world performance. Most notably Session and Service Continuity (SSC) mode 3 [2] promises to further mitigate the effect of inter-PLMN HO on interruption time and provide improved service continuity experience for CAM users. Moreover, a dedicated interface N32 is specified for communication between the Security Edge Protection Proxies (SEPP) of the H-PLMN and V-PLMN, in 5G SA networks [82], which is expected to significantly improve the user experience when roaming. Finally, the N9 interface is also established for 5G SA networks [2], which will facilitate the direct communication among the UPF of the H-PLMN and the V-PLMN, hence streamlining the roaming process. These features will offer direct communication between the Network Functions of the neighbouring networks, which will significantly reduce the service interruption time, which is currently the bottleneck of NSA networks for cross-border CAM service provisioning.

Most current Rel.16 SA deployments however do not seem to support these advanced Mobility Management (MM) features, as operators are reluctant to invest in such "optional" features, since there is no clear business case to achieve return on investment for supporting cross-border CAM operation. EU and regulatory authorities should consider incentives and/or the establishment of a clear framework with regards to operators' obligations on cross-border MM and CAPEX/OPEX support for 5G cross-border deployments.

6 Concluding Remarks

6.1 Main Conclusions & Response to Research Questions

The work presented in this dissertation, provides a detailed overview of the landscape, stakeholder views and European Union (EU) vision regarding the 5G enabled Connected and Automated Mobility, while it also provides the outcomes of the detailed State of the Art Study performed with regards to the current technical (Mobility Management / networking) and non-technical challenges for provisioning such services in cross-border environments. Moreover, a detailed description of the experimental set-up used, including the 5G network architecture, the autonomous vehicles, the Onboard units, the application design (developed specifically for this thesis) and the use case parameters, to perform some of the first-ever real-life measurements of 5G enabled Connected and Automated Mobility (CAM) application in cross-border conditions at the Greek-Turkish borders (GR-TR CBC) was provided, along with the first acquired field results (application and network level) and the corresponding analysis and insights.

With regards to the state-of-the-art it was shown that the challenges that arise from attempting to provide enhanced CAM services at complex, multi-stakeholder environments such as national borders, remain largely unaddressed. In view of the EU vision for connected transport paths by 2025 and the linked TEN-T initiative of pan-European transport corridors, the investigation of such cross-border challenges becomes increasingly important.

The work presented in this report, highlights the expected performance requirements for each of the five main CAM use case categories envisioned by 3GPP, as expressed by key stakeholders such as Mobile Network Operators (MNOs), network vendors, Original Equipment Manufacturers (OEMs) and automotive authorities. These Key Performance Indicators (KPIs) have to be met irrespective of the underlying network connectivity and the potential interruptions or delays that may be introduced by the inherent vehicular mobility, i.e., change of serving network. This analysis establishes that while non-critical automotive applications (e.g., traffic information, obstacle notification, etc.) may be able to tolerate the service interruption and larger latency introduced by cross-border mobility, ***the more advanced CAM applications envisioned by the involved stakeholders (and 3GPP), have extremely stringent service requirements which cannot be met with the current Mobility Management mechanisms***.

A detailed analysis of the factors that contribute to the experienced service interruption and/or reduced network performance when a user crosses national borders and is forced into an inter-Public Land Mobile Network Handover (inter-PLMN HO) has been performed and its output has provided significant insights into the challenges that need to be addressed for proper cross-border CAM service provisioning. ***Service and session continuity, Multi-Access Edge Computing (MEC) interconnection, inter-PLMN HO and data routing, MNO alignment, roaming configurations and data and protocol interoperability***, have emerged as the key technical challenges that need to be addressed. A significant insight of this study is that in order to be able to provide advanced CAM services at the borders, a number of ***non-technical challenges*** also have to be addressed, such as ***spectrum allocation issues, data security and privacy approach (GDPR issues), regulatory compliance, road and traffic regulation heterogeneity*** and more.

The solutions currently envisioned to mitigate or even completely resolve the identified challenges, where also presented and prioritized. These solutions range from enhanced Mobile Management (MM) mechanisms including e.g. Session and service Continuity (SSC) mode 3, V2V communication backup (sidelink) and novel interfaces (N9, N32) to predictive analytics mechanisms, resources pre-allocation and overprovisioning, application level proprietary solutions and more. The most prominent of these solutions and the ones applying to the considered use cases of the GR-TR CBC were tested in the field, and a detailed analysis under various experimental conditions was performed. The work focused on evaluating both the 5G networks performance and the user experience (i.e., application-level performance) based on KPIs such as the E2E latency, the mobility interruption time and throughput and proceeded to analyse the way each part of the chain (i.e., network vs application) affects the performance experienced by the user.

The study identified the complexities of maintaining service continuity across borders and offered valuable insights into optimizing network and application configurations to mitigate these challenges. More specifically, via the experimental results obtained from the real-life trials and the consequent detailed analysis, this study provides the first ever **insights into the posed research questions** in Section 1.3, as presented below.

- **Q**: What are the main challenges (technical and non-technical) that need to be addressed in order to provision CAM services in cross-border conditions? Which are the most promising solutions for each of these challenges?
  - A: The research presented in this study was able to identify the major challenges that inter-PLMN CAM operation currently faces and to categorize them into four main categories, namely **Telecommunication, CAM Application functionality, Security & Privacy** and **Regulatory** challenges. It was shown that besides the technical aspects that need to be resolved, there are several non-technical issues that also need to be addressed in order to successfully provision CAM services in cross-border environments (highlighting the complexity of cross-border environments). For each of the four categories, the most promising solutions / mitigation measures were also analysed while a sub-set of them was also tested in the field, measuring the respective performance under real-life conditions for the first time, and offering some first insights into the expected performance improvement with some of these solutions. Figure 17 to Figure 20 and *Table 10* offer a comprehensive overview of the identified challenges per category and their respective solutions.

- **Q**: What do the EU stakeholders consider as key factors & requirements to support CAM applications in cross-border conditions?
  - **A**: The presented study also takes into account the views of major EU CAM stakeholders, in order to better understand their expectations and the points requiring more attention. According to the interviews with stakeholders performed in the context of this study the support for **core enhanced Mobile Broadband (eMBB) functionality** and the support for **virtualization** are the most critical functional requirements for delivering high quality CAM services in cross border conditions. Both these features should become available with the deployment of 5G core solutions (i.e. SA implementations), while **mobility support and Ultra Reliable Low Latency Communication (URLLC) functionality** are also considered important as they will allow for further CAM applications to be supported. In terms of non-functional requirements there does not seem to be a clear winner, as multiple requirements are deemed critical for the successful provisioning of CAM services by 5G networks. **Scalability, upgradability, physical and cyber-security, commercial feasibility and reliability** are considered key factors that must be present for 5G networks to be able to support stringent CAM applications in cross-border conditions.

- **Q**: What are the optimum network configurations for 5G Non-Stand Alone (5G-NSA) enabled CAM operation in cross-border conditions?
  - **A**: The results indicate that among all the tested scenarios and considered solutions (Public vs Direct interconnection, Home-Routing (HR) vs Local Break-Out (LBO) roaming and Cloud vs Edge server placement), the configuration of LBO with Direct interconnection in combination with edge servers, is offering the best E2E latency, far exceeding the CAM use case requirements. However, the huge interruption time during the Packet Gateway (P-GW) change, renders this configuration an unrealistic solution for CAM applications at this stage (see Figure 76 and Figure 77). The **solid performance obtained by the HR/Direct interconnection** configuration, both in terms of E2E latency (on average achieving the use case requirements of ~100 ms E2E Round Trip Time (RTT) latency) and in terms of interruption time (not ideal, but good enough), renders it as the most suitable solution for CAM application support at cross-border conditions, for the time being (*conclusion only applicable for 3GPP Rel.15 NSA networks*). It must be noted though that the significant cost of the direct network interconnection and the necessary scale of

deployment it would take to support such connectivity among all national borders and all MNOs, creates challenges for the wide adoption of this solution.

- **Q**: What are the optimal frequency settings and Time Division Duplexing (TDD) frame structure for neighbouring cross-border 5G networks?
  - **A**: As TDD operation is the preferred scheme for most 5G network operators, this study presented an analysis and an approach for neighbouring MNOs to optimize their frequency settings for maximum CAM performance in cross-border scenarios. According to the findings, detailed ***network planning and drive-test measurements*** in the area between the MNOs is critical to identify the level of interference and to mitigate it as much as possible. Besides that, ***significant guard-bands (according to GSMA), common phase clock reference, similar or compatible TDD frame structure, use of Carrier Aggregation and URLLC operation friendly patterns*** (i.e., with several slots assigned to the Uplink for facilitating Vehicle to Everything (V2X) communication) further decrease interference between neighbouring MNOs, thus improving the performance at the cross-border area.

- **Q**: What is the effect of environmental & situational conditions on 5G network performance in hard border conditions??
  - **A**: The researched performed provided detailed information on the severe effect that environmental and situational conditions have on the experienced CAM performance. The multiple trials and test-runs performed under varying conditions indicated that the various ***environmental conditions such as the humidity, temperature and precipitation affect the observed performance*** as the signal reception from the respective gNBs weakens, and/or additional reflections and refractions are created. Furthermore, it was shown that the ***situational conditions around the cross-border area (i.e., the distance and Line of Sight status of the gNB, the existence of metal obstacles and the traffic on the road) have an even more significant effect on the experienced CAM performance***, as significant variations were observed in the network performance, depending on these conditions. These significant insights should be taken into account when designing the future cross-border corridors as certain redundancy and denser gNB deployment may be necessary in order to ensure that the CAM application requirements are met under any type of environmental and situation conditions.

- **Q**: What is the optimum configuration for the On-Board Unit (OBU) and other hardware placed on the autonomous vehicle?
  - **A**: The study suggests that the optimum OBU configuration should support multi-connectivity to enhance redundancy and reduce the risk of service interruption during handovers. Additionally, ***the integration of V2X communication modules and advanced sensors capable of processing aperiodic event-driven traffic is crucial for maintaining the reliability of CAM services***, while ***sub-ms sensor periodicity is necessary to support latency-critical applications such as Vulnerable Road user (VRU) protection***. Finally, it has been demonstrated that optimized integration of the OBU and its antennae on the vehicle (i.e., antennae should be mounted outside the vehicle for increased Signal to Interference and Noise Ratio) stands to further improve performance, especially in the rough condition of cross-border environments.

- **Q**: What are the expected pain-points during cross-border operation for autonomous vehicles and CAM applications? What design consideration need to be taken into account for CAM application operation in cross-border conditions?
  - **A**: The results presented in this study, indicate that while autonomous operation of a vehicle will be able to be maintained for the vast majority of its journey across a cross-border area, a 100% reliability cannot be guaranteed with 5G NSA networks, either due to volatile environmental and

situational conditions or due to the expected service interruption when performing an inter-PLMN HO. As such vehicle manufacturers (OEMs) and CAM application developers should take this into account and create fail-safes in the operation of autonomous vehicles and applications. **Imminent HO detection, pre-emptive resource allocation** and **proactive CAM application state transfer** between edge nodes have been proposed as mitigation mechanisms and tested in this study, showcasing the potential that such mechanisms have in improving the experienced performance. However, as critical failures cannot be 100% eliminated both the vehicle itself and the CAM application should be designed to handle such failures in communication when crossing the borders between countries (e.g., reduce the automation level or deactivate certain features/functionalities until a successful inter-PLMN HO has occurred).

- **Q**: What is the effect of key network settings on performance?
    - **A**: The research identifies several key network settings that significantly impact performance:
        - <u>Roaming Scheme (HR vs. LBO)</u>: HR provides more stable performance with reduced connection interruption times, whereas LBO offers minimal E2E latencies in ideal conditions but is prone to large service interruption intervals.
        - <u>Inter-PLMN Interconnection (GRX/IPX vs. Direct)</u>: Direct interconnection, though costly and complex to deploy, offers the best performance in terms of latency and reliability compared to GRX/IPX.
        - <u>Application Placement (Cloud vs. Edge)</u>: Edge placement of applications is critical for reducing latency and ensuring faster response times, making it the preferred option for CAM. Synchronization between neighbouring edge instances also stands to improve the performance of stateful-CAM applications.
        - <u>Mobile Management Entities (MME) interconnection</u>: For the 5G NSA architecture, the S10 interface between the two mobile networks operated by the different MNOs is crucial in order to enable cross-border radio handover in a seamless fashion (as much as realistically possible).
        - <u>Network planning / Radio coverage</u>: Proper network planning and joint radio coverage studies between the two neighbouring MNOs, are critical to guarantee maximised SINR at the cross-border area with minimal coverage gaps and overlap regions. The configuration of gNB placement, antenna tilting, Frequency band and TDD structure, as well as transmit power are critical for the successful provision of CAM services in cross-border areas.

- **Q**: What is the impact of handover (HO) on the E2E performance of a CAM user?
    - **A**: The analysis shows that handovers, particularly inter-PLMN HOs, are a significant source of service interruption and latency spikes. The study highlights that ***while HR with Direct interconnection mitigates some of these effects, further improvements are needed to fully meet the stringent requirements of CAM during inter-PLMN HOs***. The results presented indicate that HOs may cause message retransmission (e.g., due to the HARQ protocol) resulting into latencies up to (or even more than) 1000 ms for CAM messages, while they may also cause ping-pong effects, which may further deteriorate performance. Even though the direct interconnection between the neighbouring networks seems to mitigate some of these issues, the research suggests that mechanisms such as predictive analytics and pre-emptive resource allocation further assist in minimizing the impact of HOs on the perceived end user performance.

- **Q**: Can the stringent CAM requirements be met during an inter-PLMN HO? Which CAM applications could be supported and which not?
    - **A**: According to the analysis presented in this study, ***the E2E latency experienced by CAM users in cross-border conditions is not the biggest bottleneck*** as E2E latencies as low as 82 ms may be achieved under the proper network and application configuration (HR, Direct interconnection,

Edge servers), which are sufficient to meet even the most stringent requirements of CAM applications. However, ***the service interruption time (user experienced) that occurs during an inter-PLMN HO remains the biggest challenge*** as the lowest value achieved during this extensive study was in the order of ~700 ms, which is not enough to meet the requirements of critical CAM applications. These results indicate that ***5G-NSA networks will satisfy most of the CAM applications for most of the time, however critical CAM applications will face issues at the moment of the inter-PLMN HO***. The research indicates that significant improvements in this area may be expected by the advent of more advanced service and session continuity schemes (e.g., SSC mode3) and/or the adoption of 5G-SA networks, where service interruption is expected to be improved significantly.

- **Q**: What are the remaining challenges, and can they be expected to be addressed by 5G SA networks?
  - **A**: Several remaining challenges are identified, including the need for improved handover mechanisms, better coordination between MNOs, and more efficient spectrum usage. 5G Standalone (SA) networks are expected to address some of these challenges by offering enhanced network slicing and more robust mobility management (e.g., SSC mode3), as well as new interfaces such as the N32 and the N9 which will facilitate roaming management and direct communication among the User Plane Function of the Home-PLMN and the Visited-PLMN. However, the full realization of seamless CAM services across borders will require continued innovation and collaboration among stakeholders.

Based on the findings of this study, 5G NSA networks seem capable of supporting non-latency-critical CAM applications while crossing national borders, and the provided performance can be significantly improved through the careful provisioning and configuration of appropriate network and application mechanisms to cope with the inherent service interruption when performing an inter-PLMN HO. However, the full provisioning of latency critical CAM application with 100% reliability cannot be guaranteed by 5G NSA networks. In that sense 5G-NSA deployments should be treated as a "segway" towards the support of CAM by 5G SA networks and even further by 6G networks.

The transition to 6G networks is poised to revolutionize Connected and Automated Mobility in cross-border operations, addressing many of the challenges identified in the current 5G (NSA)-enabled systems. 6G is expected to introduce even lower latencies, on the order of sub-microseconds, which will significantly reduce the disruption experienced during cross-border transitions. Additionally, the development of intelligent network management systems powered by Artificial Intelligence (AI) and Machine Learning (ML) will enable predictive and adaptive resource allocation, further minimizing the impact of handovers and improving service continuity.

Another critical area of research is the integration of advanced sensing and communication technologies, such as terahertz (THz) communication and quantum sensing, which are anticipated to be key features of 6G. These technologies will enable much higher data rates and more accurate environmental sensing, supporting the real-time decision-making required for autonomous vehicles. With 6G, the concept of "network of networks" will also gain prominence, allowing seamless interoperability across different network types and technologies. This will enhance the scalability and flexibility of CAM systems, making it easier to support a wide range of use cases, from high-speed highways to urban environments, across multiple countries. Overall, 6G is not only expected to improve the technical aspects of CAM but also to facilitate more robust and secure cross-border operations, bringing us closer to the vision of truly autonomous and connected global mobility.

6.2 Overview of Key Contributions of this Dissertation

This dissertation delivers a cohesive body of work that advances the scientific state of 5G-enabled Connected and Automated Mobility (CAM) in cross-border conditions. Its principal contributions can be summarized as follows.

- **Comprehensive bibliographic and R&I landscape survey:** The dissertation begins with an extensive bibliographic review, covering standards evolution, research publications, and real-world trials that have shaped the understanding of 5G in the context of mobility. This includes a detailed examination of efforts under the 5G-PPP, 6G-IA, and 3GPP initiatives, alongside national and EU-level pilot projects. Particular attention is given to cross-border use cases, where gaps persist in network interoperability and mobility management. The review synthesizes trends and clusters technological solutions, policy developments, and stakeholder roles, creating a robust reference point for future research and deployment planning in 5G-enabled CAM.
- **Stakeholder-driven requirements analysis:** A thorough stakeholder-centric requirements engineering process was undertaken to capture the functional (e.g., low-latency handover, secure authentication, session continuity) and non-functional (e.g., scalability, maintainability, fault tolerance) demands for 5G-enabled CAM services operating across national boundaries. Using a MoSCoW prioritization approach, feedback was solicited from major European mobile network operators (MNOs), automotive OEMs, and infrastructure vendors. The process resulted in a ranked matrix of 24 critical requirements, further classified based on cross-border relevance and implementation complexity. These findings directly informed the architectural and application-layer decisions made in the thesis and serve as a practical guide for implementers and regulators.
- **Technology benchmarking for cross-border CAM:** A detailed technical comparison was performed between 5G-Non-Standalone (NSA) and competing or complementary technologies including IEEE 802.11p/bd, 4G LTE-V2X, and 5G Standalone (SA). Each was assessed with respect to its suitability for cross-border CAM services across metrics such as latency, bandwidth, mobility robustness, deployment cost, and standard maturity. The evaluation showed that while IEEE 802.11p remains relevant for direct vehicle-to-vehicle communication, it lacks the range and QoS guarantees needed for advanced cooperative services. 4G LTE-V2X offers a stepping stone but falls short in mobility and scalability. 5G-NSA, currently the most deployable option, emerges as the baseline for short-term deployments, while 5G-SA with features like Session and Service Continuity (SSC) and low-latency edge support presents a longer-term strategic platform.
- **Taxonomy of inter-PLMN Mobility-Management challenges & solution space:** One of the dissertation's core technical contributions is the development of a comprehensive taxonomy of challenges that arise in managing mobility across different Public Land Mobile Networks (PLMNs). These challenges are grouped into categories spanning telecom architecture (e.g., routing, session anchoring), security (e.g., trust establishment, user plane encryption), regulatory policy (e.g., spectrum alignment, jurisdictional control), and application behaviour (e.g., session disruption, state loss). The taxonomy is paired with a solution space analysis that includes novel enablers such as distributed mobility anchoring, make-before-break handovers, and inter-PLMN MEC federation. A decision-support matrix links these challenges and enablers to performance KPIs like latency, service continuity, and coverage reliability, providing a practical roadmap for cross-border mobility architecture design.
- **Design and development of a "zero-touch" border-crossing CAM application:** A key innovation introduced in this work is a 5G-enabled CAM application designed for "zero-touch" operation during border crossings, incorporating Vulnerable Road User (VRU) awareness functionalities. The application stack integrates with both cloud and Multi-Access Edge Computing (MEC) environments, with a real-time interface to the On-Board Unit (OBU). A purpose-built mobility-aware service orchestration module ensures seamless service migration between network domains. The architecture also supports real-time

VRU detection via server-side processing of sensor and video data, with dynamic prioritization of alerts to the vehicle. This application provides a testbed for evaluating handover-aware application behaviour and its role in maintaining service continuity in highly dynamic mobility scenarios.

- **Development and Optimization of Application-Level Service Continuity Mechanisms:** To address the inevitable disruptions that occur during inter-PLMN handovers, the dissertation proposes and implements three application-level mechanisms that work in tandem to preserve CAM service integrity: (1) imminent handover detection based on signal degradation and PLMN boundary knowledge, (2) proactive provisioning of new IP session parameters ahead of handover completion, and (3) a backup operation mode that caches essential application logic and data for short-term autonomous execution during temporary disconnection. These mechanisms were integrated into the CAM application and tested under real driving conditions. The optimized implementation demonstrated a >60% reduction in application-layer service interruption time compared to a baseline approach, offering concrete evidence of their effectiveness.

- **First large-scale real-life measurement campaign on a 5G-NSA cross-border corridor:** Taking advantage of the Greece–Turkey cross border corridor constructed for the 5G-MOBIX R&I project, the dissertation delivers one of the globally first comprehensive measurement campaigns in real-life cross-border conditions and the respective analysis of the enormous data set collected. Over 40 test-runs generate synchronised OBU, gNB, core-network and server logs, creating a unique dataset based on real 5G networks.

- **Multi-layer performance evaluation and KPI prioritisation:** The collected data was subjected to an in-depth comparative analysis focusing on the interplay between network configurations (e.g., local break-out vs home routing, GRX/IPX vs direct interconnection) and application-level performance. Key metrics such as end-to-end latency, session interruption time, throughput, and edge response time were analysed in the context of CAM KPIs. A KPI prioritization framework was applied to identify trade-offs and optimal configurations. Notably, the results demonstrate that a Local Break-Out model combined with direct interconnection and edge computing can reliably meet the CAM latency threshold of 100 ms, achieving a measured average of 99 ms while the Home Routing roaming approach can half interruption times compared to default roaming setups.

- **Actionable insights and stakeholder-specific recommendations:** Synthesising the above findings, the dissertation formulates targeted guidance and recommendations for key stakeholders, charting a pragmatic migration path from 5G-NSA pilots to 5G-SA and, ultimately, 6G-ready corridors. The recommendations urge ***MNOs*** to adopt direct interconnection or national roaming and invest in SSC-mode-3 support; ***OEMs/OBU*** vendors to implement multi-connectivity and HO-aware buffering; ***Application providers*** to exploit MEC and proactive IP hand-over and ***Policy-makers*** to incentivise cross-border Mobility Management features and harmonise spectrum-synchronisation rules.

Collectively, these contributions comprise some of the earliest end-to-end evidence that 5G networks—when carefully engineered, and under certain conditions—can meet stringent CAM requirements across national borders, and they lay a solid foundation for the evolution toward fully autonomous, pan-European mobility.

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Appendix 1: GR-TR CBC – Overview of Deployed Components

5G Networks											
	Operator & vendor	***NSA/ SA***	**Num. gNBs**	**Freq. Bands**	**BW**	**TDD Frames**	**Network Sync**	**Back haul**	**Core attributes**	**Core intercon nect**	**Key HO / roaming param.**
Greece PLMN 1	COSMOTE	NSA op.3 x	1	B7 :3050 N78 : 636666	LTE 20Mhz NR 100Mhz	TDD 383 (SCS:11:3:0)	GPS	2 Gbps (MW+ Fiber)	Virtualized Packet Core,	1 Gbps direct	EN-DC mobility SgNB addition LTE HO
Turkey PLMN 2	TURKCEL L	NSA op.3 x	3 In border 1 In Eskisehir	B7: 2850 N78: 646666	LTE 20Mhz NR 100Mhz	TDD 383 (SCS:11:3:0)	GPS	1Gbps (MW + Fiber)	DRAN, Virtualized Packet Core, Fronthaul (eCPRI	1 Gbps direct	EN-DC mobility SgNB addition LTE HO

5G Features / Technologies / Configurations addressed

(e.g., Home-Routing, Local Break-out, S1 base HO, S10 based HO, Direct line, SA slicing, Uu / PC5 communication, MEC/Edge based operation, Cloud based operation, multi-SIM, mmW etc.)

COSMOTE:
5G NSA, based on virtualized EPC Architecture.
Dedicated Network (Core & RAN) for the V2X applications, implemented at the EDGE site.
Node deployed: HSS, CUDB, MME, SGW, PGW, CNOM*, ENM*, EDA*).
3GPP Interfaces Deployed: S1-MME, S1-C, S1-U, S5/S8, S10, S11, S6a, S6d, Sgi
COSMOTE's underlying NTP (Stratum -1) infrastructure is re-used to synchronize 5G-EPC/RAN for date and time synchronization

TURKCELL:
5G NSA, based on virtualized EPC Architecture (CUPS Architecture).
Dedicated Network (Core & RAN) for the V2X applications.
Node deployed: MME/SGW-C/SGW-U/PGW-C/PGW-U/ CNOM*
Turkcell's underlying NTP (Stratum -1) infrastructure is re-used to synchronize 5G-EPC/RAN for date and time synchronization.

* Ericsson provisioning and operational supporting functions for the 5G NSA nodes

ROAMING:

- **HR Roaming with Session Continuity:**

  - S1 Handover Configuration and Neighboring PLMN(s) definition in RAN. Neighboring Cells for each frequency.
  - S8 and S10 Interfaces. EPLMN and Neighboring PLMN(s) definition in MME/eNBs.
  - Configuration of UE and APN restrictions in MMEs.
  - Static IMSI based PGW selection configuration. IMSI based GW selection in TR network for inbound roamers from GR, will point to GR PGW. Similarly, IMSI based GW selection in GR network for inbound roamers from TR, will point to TR PGW
  - Options for interconnection: 1) via direct line 2) IPX.

- **LBO without session continuity:**
  - S1 Handover Configuration and Neighboring PLMN(s) definition in RAN. Neighboring Cells for each frequency.
  - EPLMN and Neighboring PLMN(s) definition in MME/eNBs.
  - Configuration of UE and APN restrictions in MMEs.
  - Static IMSI based PGW selection configuration. Static IMSI based PGW selection configuration. IMSI based GW selection in TR network for inbound roamers from GR, will point to TR PGW. Similarly, IMSI based GW selection in GR network for inbound roamers from TR, will point to GR PGW
  - Options for interconnection: 1) via direct line 2) IPX.

RAN features:

- Control Channel Beamforming
  - Proprietary implementation of common channel cell shaping provides additional coverage gain vs. industry common implementation
- Ericsson Uplink Booster
  - High performing Physical Uplink Shared Channel (PUSCH) receiver for NR improving uplink coverage and superior interference suppression in all types of radio environments
- Massive MIMO Mid-band
  - single-user MIMO (SU-MIMO) is supported in downlink with up to four layers, and in uplink with one layer
- LTE-NR Downlink Aggregation
  - The LTE-NR Downlink Aggregation feature enables increased user peak bit rates by simultaneously transmitting downlink data on the LTE and the NR carriers of the EN-DC split bearer
- LTE-NR Uplink Aggregation
  - TE-NR Uplink Aggregation can improve uplink user throughput
- Physical Layer Mid-Band
  - The deployment of NR in mid-band allows to access 3.5GHz spectrum offering low latency services and higher data rates. DDDSUUDDDD (4 downlink + 2 uplink + 4 downlink) – the equivalent of LTR TDD UL/D configuration 2 is used with 6:4:4 SSF. Transform Precoding Disabled (CP-OFDM) is supported

both in downlink and in uplink. Modulation schemes are supported up to 256 QAM in downlink and up to 64 QAM in uplink. 30 kHz subcarrier spacing is supported on mid-band.

- Intelligent Connectivity
    - EN-DC allows the early introduction of 5G in a Non-Standalone deployment.

Appendix 2: Vehicle, OBU and Road-side equipment specifications

Vehicles						
		Type	**Make & model**	**SAE Level**	**Vehicle Sensors**	**Vehicle capabilities / functions**
Vehicles	**Vehicle 1**	N3, Truck	Ford, F-MAX	L4	Camera, Radar, RTK-GNSS	Precise Positioning, Autonomous Maneuvers, V2X Communication, Emergency Stop, Path Following, Platooning Maneuvers, Video Sharing
	Vehicle 2	N3, Truck	Ford, F-MAX	L4	Camera, Radar, RTK-GNSS, Lidar, CO2 sensor, NFC sensor	Precise Positioning, Autonomous Maneuvers, V2X Communication, Emergency Stop, Path Following, Platooning Maneuvers, Video Sharing

On-Board Units								
	Developer / Vendor	**Num OBUs**	**NumSIMs**	**OS**	**Sup. Mode**	**5G Chipset / Modem**	**V2V module**	**OBU sensors**
IMEC OBU	IMEC	2	2	Linux	V2N, V2V	Quectel RM500Q	Cohda MK6c (PC5)	GNSS
WINGS OBU	WINGS	1	1	Linux	V2N	Quectel RM500Q		GNSS, proximity, CO2, acceleration, NFC

Roadside & Other Infrastructure								
MEC / Edge nodes	**Num. Cloud instances**	**Num. RSUs**	**Num. ITS centers**	**Applications / User Stories**	**Message type**	**Supported interface**	**Supported / APIs**	**Road side sensors**
2	1x WINGS cloud 1x Tubitak Cloud	3	0	1. 5G Platooning 2. See What I See 3.Assisted Border Crossing 4 Autonomous truck routing	CAMes, DENM, proprietary	Uu, PC5	MQTT, HTTP, LiDAR	UHD camera, x-ray machine

Appendix 3: Overview of Extended Sensors for assisted border-crossing user story

Use Case Category	Extended Sensors
User Story Leader	WINGS ICT
Other partners	Cosmote, Turkcell, Ericsson GR, Ericsson TR, ICCS, IMEC
Objective	• Border inspection preparation based on predictive CCAM truck routing • Secure CCAM truck border crossing with increased inspection confidence • Increased border environment awareness for incoming drivers • Increased border personnel safety
Actors	• Autonomous truck • Border control agents • Additional devices (sensors, cameras, drones, wearables)
Pre-conditions	• Autonomous truck equipped with a multitude of sensors driving towards a border crossing • Border control agents equipped with smart phones / tablets / wearables • 5G network infrastructure with edge / MEC capabilities available at both sides of the border • Additional infrastructure at the site capable of communicating to the edge / MEC
User Story flow	1. As the truck approaches the border, the truck itself and potentially its cargo (sensors in the cargo hold) start transmitting relevant information towards the border authorities (mMTC). This could take place with a number of different technologies such as GPRS, NB-IoT, 5G-NR slice, etc. 2. Based on the transmitted information and on information gathered by surrounding environmental sensors, the cloud-based intelligence can predict the trucks route towards the border, hence initiating the inspection preparations (e.g. download relevant applications from the cloud to the edge / MEC to minimize functional interaction with the network, request information from authorities, setup additional slices, if necessary, etc.). The goal is to identify the truck, the kind/type of cargo, the size of the cargo, etc. (**5-10 km before the border crossing**). 3. The information transmitted by the truck can potentially be exchanged over 5G networks with the neighbouring country's authorities and request all relevant information for this truck, driver, cargo etc. For instance, if the truck is registered in the neighbouring country, information such as the driver's identity and license, his/her track-record, the truck's travel history and cargo

inventory can be transferred to the border authorities to facilitate verification & control.

4. Fusion of available information such as traffic on the road, traffic light status, feeds from street cameras, border control traffic, type of cargo and risk level to determine the trajectory / speed of the truck towards the border (e.g. assigned to specific control lane or crossing based on the type of material transported, or based on risk assessment, etc.) and to enable an increased cooperative environmental awareness.
   (**2-5 km before the border crossing**).
5. Deployment of extra remote inspection methods in order to acquire additional information about the approaching truck and to verify the received information (eMBB). This could be the deployment of drones, the feed from mounted cameras, thermal or x-ray imaging, weight analysis of the truck, etc. (**0-2 km before the border crossing**).
   i. The feed from the cameras / drones can optionally be transmitted over 5G networks to the neighbouring country authorities to prepare them for the arrival of the truck and for cross-checking purposes.
6. Based on data fusion originating from the truck, environmental sensors and cameras and wearables / smart phones that the customs agents are equipped with, the integrated assisted driving platform hosted at the edge server provides live updates of the maps to the navigation software of the truck, depicting the live location of the other road users and potentially additional information.
   i. Increased cooperative environmental awareness is achieved for the truck, identifying all road users and border ground personnel (even in blind spots)
   ii. Increased safety for the ground personnel in case of a predicted accident with an incoming truck. The Predictive analytics platform may issue a warning or order to the truck's OBU to brake or slow down (trajectory alignment is also possible) as well as warn the ground personnel about the imminent danger.
7. Final data fusion including all acquired information to perform predictive analytics and risk level assessment of the specific truck and to classify it according to the level of verification that was possible.
   i. If all data checks out, then the truck will be potentially capable of going through the border without human intervention ("zero touch" scenario).
   ii. If there are uncertainties, then different levels of risk assessment or doubt will trigger differentiated treatment by the border officers, according to the predicted level of risk.
8. Human intervention at the actual border crossing will depend on whether the gathered information was verified and on the assessment of the risk level for each truck.

Post conditions	• A truck that has successfully passed all remote inspection methods crosses the border without human intervention • Border inspection is categorized and prioritized based on risk assessment • Border inspections become more efficient and less time consuming • Border ground personnel is protected from potential accidents • Increased cooperative awareness of the surrounding, making more advanced CCAM scenarios possible.

Appendix 4: Table of Cross-Border Issues (XBIs) & Considered Solutions (CS)

XBI		Associated CS	
ID	Name	ID	Name
XBI_0	*Baseline*	*CS_0*	Feature OFF
XBI_1	NSA Roaming interruption	CS_1	S1 handover with S10 interface using an NSA network
		CS_2	Release and redirect using an NSA network
		CS_3	Release and redirect with S10 interface using an NSA network
XBI_2	SA Roaming interruption	CS_6	Release and redirect using an SA network
XBI_3	Inter-PLMN interconnection latency	CS_7	Internet-based Interconnection
		CS_8	Direct Interconnection
XBI_4	Low coverage Areas	CS_4	Multi-modem / multi-SIM connectivity - Passive Mode
		CS_9	Satellite connectivity
XBI_5	Session & Service Continuity	CS_4	Multi-modem / multi-SIM connectivity - Passive Mode
		CS_5	Multi-modem / multi-SIM connectivity-Link Aggregation
		CS_6	Release and redirect using an SA network
		CS_10	MEC service discovery and migration using enhanced DNS support
		CS_11	Imminent HO detection & Proactive IP change alert
		CS_12	Inter-PLMN HO, AF make-before-break, SA
		CS_13	Double MQTT client
		CS_14	Inter-MEC exchange of data
		CS_15	Inter-server exchange of data
XBI_6	Data routing	CS_16	LBO NSA
		CS_17	HR NSA
		CS_18	LBO SA
		CS_19	HR SA
XBI_7	Insufficient Accuracy of GPS Positioning	CS_20	Compressed sensing positioning
XBI_8	Dynamic QoS Continuity	CS_21	Adaptive Video Streaming

		CS_22	Predictive QoS
		CS_26	Network slicing
XBI_9	Geo-Constrained Information Dissemination	CS_23	Uu geobroadcast
		CS_24	PC5 geobroacast
		CS_25	mmWave 5G
XBI_10	mmWave applicability	CS_25	mmWave 5G
XBI_11	Network slicing applicability	CS_26	Network slicing

Appendix 5: Table of Traffic Flows (FL)

Flow #	*Name*	*Description*	*UL/DL*
FL1	*ECU measurements*	*Measurements received from the vehicles ECU (speed, revs, etc.), transmitted with a frequency of 2Hz (every 0.5 sec).*	*UL*
FL2	*OBU sensor measurements (non-delay sensitive)*	*Measurements from the vehicle sensors attached to the OBU (CO2 readings, GPS coordinates, NFC IDs of cargo, acceleration), transmitted with a frequency of 1Hz.*	*UL*
FL3	*OBU sensor measurements (Delay sensitive)*	*Measurements from the Lidar sensor attached to the OBU, transmitted with a frequency of 100 Hz (every 10 msec).*	*UL*
FL4	*Still-frame camera (RSI)*	*Pictures taken by a HD camera used to identify the license plate of the incoming vehicles.*	*UL*
FL5	*UE / wearable GPS coordinates (RSI)*	*GPS coordinates measured either by a UE or a wearable of the customs agent, transmitted with a frequency of 1Hz*	*UL*
FL6	*Vehicle registered info*	*Vehicle documentation and / or manifest transmitted from a server / database to the WINGS application*	*UL*
FL7	*CCAM instructions to OBU / GUI*	*Instructions & warnings (string) towards the OBU and/or driver GUI to instruct the vehicle to stop or change course. Ad-hoc transmission.*	*DL*
FL8	*Driver GUI*	*Multiple strings of information including readings of the ECU and other sensors, figures (maps) and live messages, transmitted with a frequency of 1Hz*	*DL*
FL9	*Customs GUI*	*Multiple strings of information including readings of the ECU and other sensors, figures (maps & license plate pictures) and live messages, transmitted with a frequency of 1Hz (multiple GUIs on both PLMNs may be supported)*	*DL*
FL10	*Road side infrastructure*	*Instructions transmitted towards the smart traffic light and the smart border-bar. Ad-hoc transmission.*	*DL*
FL11	*License plate SW*	*Transmission of license plate picture to an external SW (UL) for text recognition & reception of response (DL) (string). Ad-hoc transmission.*	*DL/UL*