Fifth Generation Communication Automotive Research and Innovation

Deliverable D3.3
Final 5G V2X Radio Design

Version: v1.0

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Executive Summary

Automated driving is one of the capabilities which will dramatically change the way that vehicles will be utilized in the future. Future driving autonomy will require vehicles to possess the capability of vehicle-to-anything (V2X) communications to increase safety and comfort of highly/fully automated driving. Despite the basic set of V2X services supported already, e.g. with the fourth generation (4G) wireless system, it is considered growingly important among both telecommunication industry and automotive industry that V2X evolution is necessary, especially considering the high level of automation as the focus of 5GCAR project. For these advanced applications, the expected requirements to meet the needed data rate, reliability, latency, communication range and speed are made more stringent.

Leveraging the latest technology, especially the newly established fifth generation (5G) New Radio (NR) in the Third Generation Partnership Project (3GPP), and targeting at fulfilling the most challenging key performance indicators (KPIs) identified by 5GCAR use case study in terms of reduced end-to-end communication latency (below 5 ms), high reliability (99.999%) and positioning accuracy (down to 5 cm) on top of the regular capacity requirement, this deliverable summarizes the 5GCAR radio interface concept which is targeted to be contributed to, for example, 3GPP Release 16 and future releases, to increase the impacts of the project. The proposed radio technology components (TCs) have a very broad coverage and can be classified into six key technology component clusters:

- Multi-antenna techniques
- Resource allocation and management
- Sidelink design
- Full duplex
- Reliability enhancement
- Positioning.

The proposed technology components can be applied to improve the identified KPIs in terms of capacity, latency, reliability and positioning accuracy for future autonomous driving.

Along the way of 5GCAR project, the outcome from our work has contributed to 5G standardization development when the relevant topics started in 3GPP, including V2V channel modeling, technology components related to radio air interface design (covering both the Uu interface and the sidelink interface) and positioning. More 5GCAR results will be brought to, e.g., 3GPP, and contribute to the whole society in the area of future automated driving.

Moving one step further to validate the proposed concepts, several radio technology components were also implemented in 5GCAR demos, for example positioning techniques for the use case of VRU protection, sidelink design for the use case of see-through.

Contents

List of Abbreviations and Acronyms

3GPP	Third Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
5GCAR	5G Communication Automotive Research and innovation
ACK	Acknowledgement
ACI	Adjacent Channel Interference
AD	Autonomous Driving
ADAS	Advanced Driver-Assistance System
AGC	Automatic Gain Control
AL	Aggregation Level
AOA	Angle of Arrival
AOD	Angle of Departure
BF	Beamforming
BIS	Block Interleaver Scheduler
BLADE	Blind Learning Algorithm for channel bias Distribution Estimation
BLER	Block Error Rate
BS	Base station
BSD	Blind Spot Detection
CAM	Cooperative Awareness Messages
CB	Code Block
CBG	Code Block Group
CCI	Co-Channel Interference
CDD	Cyclic Delay Diversity
CDF	Cumulative Distribution Function
CI	Cancellation Indication
CPE	Common Phase Error
CPM	Cooperative Perception Message
CSI	Channel State Information

CSIT	Channel State Information at the Transmitter
CSI-RS	Channel State Information Reference Signal
CTRV	Constant Turn Rate and Velocity
CU	Cooperative User
C-UE	Cellular UE
D	Deliverable
D2D	Device-to-Device
DENM	Decentralized Environmental Notification Message
DFT	Discrete Fourier Transform
DFTS-OFDM	DFT-spread OFDM
DL	Downlink
DMRS	Demodulation Reference Signal
DOA	Direction of Arrival
DOD	Direction of Departure
DSRC	Dedicated Short-Range Communications
DTX	Discontinuous Transmission
E2E	End-to-end
eCID	enhanced Cell ID
EDCA	Enhanced Distributed Channel Access
eMBB	enhanced Mobile Broadband
ETSI	European Telecommunications Standards Institute
EVM	Error Vector Magnitude
FD	Full-duplex
FR	Frequency Range
GA	Genetic Algorithm
gNB	Next Generation NodeB
GNSS	Global Navigation Satellite System

GoB	Grid-of-Beams
GPS	Global Positioning System
HARQ	Hybrid Automatic Repeat reQuest
HD	High Definition
IA	Initial Access
IEEE	Institute of Electric and Electronics Engineers
IMT	International Mobile Telecommunication
ISD	Inter-Site Distance
ITS	Intelligent Transport System
KPI	Key Performance Indicator
LBT	Listen-Before-Talk
LiDAR	Light Detection and Ranging
LLR	Log-Likelihood Ratio
LLS	Link Level Simulation
LMF	Location Management Function
LOS	Line of Sight
LPP	LTE Positioning Protocol
LR	Linear Regression
LS	Least Square
LTE	Long Term Evolution
MAC	Medium Access Control
MCS	Modulation and Coding Scheme
MILP	Mixed Integer Linear Programming
MIMO	Multiple Input Multiple Output
M-MIMO	Massive MIMO
MS	Mobile Station
MSE	Mean Square Error
MU-MIMO	Multi User MIMO
mmWave	Millimeter Wave
NACK	Negative Acknowledgement
NCU	Non- Cooperative User
NLOS	Non-Line-of-Sight
NR	New Radio

NW	Network
OBU	On Board Unit
OEM	Original Equipment Manufacturer
OFDM	Orthogonal Frequency-Division Multiplexing
OTDOA	Observed Time Difference of Arrival
PA	Predictor Antenna
PBMA	Priority Based Multiple Access
PBMCH	Physical broadcast multicast channel
PDCCH	Physical Downlink Control Channel
PDCP	Packet Data Convergence Protocol
PDPR	Pilot-to-Data Power Ratio
PDSCH	Physical Downlink Shared Channel
PEC	Perfect Electric Conductor
PF	Particle Filter
PHY	Physical
PI	Preemption Indication
PRS	Positioning Reference Signal
PTRS	Phase Tracking Reference Signal
P-UE	Pedestrian User Equipment
QoS	Quality of Service
RA	Receive Antenna
RACH	Random Access CHannel
RAT	Radio Access Technology
RB	Resource Block
RNTI	Radio Network Temporary Identifier
RRC	Radio Resource Control
RRM	Radio Resource Management
RS	Reference Signal
RSTD	Reference Signal Time Difference

RSU	Road Side Unit
RTT	Round Trip Time
SCI	Sidelink Control Information
SCS	Subcarrier Spacing
SC-PTM	Single-Cell Point-To-Multipoint
SC-FDMA	Single Carrier Frequency Division Multiple Access
SFN	Single Frequency Network
SIB	System Information Block
SINR	Signal-to-Interference and Noise Ratio
SIR	Signal-to-Interference Ratio
SIS	Self-interference Suppression
SNR	Signal-to-Noise Ratio
SP	Scattering point
SR	Scheduling Request
SRS	Sounding Reference Signal
STBC	Space-Time Block Codes
SUs	Secondary Users
TB	Transport Block
TBCC	Tail-biting Convolutional Coding
TC	Technology Component
TCC	Technology Component Cluster
TDD	Time Division Duplex
TDOA	Time Difference of Arrival
TOA	Time of Arrival
TS	Technical Specification
TTI	Transmission Time Interval
UC	Use Case
UCC	Use Case Class
UCI	Uplink Control Information
UE	User Equipment
UKF	Unscented Kalman Filter
UL	Uplink
ULA	Uniform Linear Array
UMa	Urban Macro
UMi	Urban Micro
URLLC	Ultra-Reliable and Low-Latency Communications
UTDOA	Uplink Time Difference of Arrival
VA	Virtual Anchor
V2I	Vehicle to Infrastructure
V2N	Vehicle to Network
V2P	Vehicle to Pedestrian
V2V	Vehicle to Vehicle
V2X	Vehicle to Anything
VRU	Vulnerable Road User
V-UE	Vehicle User Equipment

1 Introduction

Automated driving is one of the capabilities which will dramatically change the way that vehicles will be utilized in the future daily life. The basic functionality of automated driving is and will be continuously provided by different sensors and computing resources in the car. However, the automotive industry has recognized that connectivity via vehicle-to-anything (V2X) communications is vital to increase safety and comfort of highly/fully automated driving further.

A basic set of V2X communications have been specified in 4G from the 3rd Generation Partnership Project (3GPP). However, it is well envisioned among telecommunication industry and automotive industry that its evolution is necessary especially considering the high level of automation including full automation which requires transmission of larger messages, e.g., raw sensor data, vehicles' intention data, coordination and confirmation of future maneuvers, and so on, as identified in the 5GCAR project. For these advanced applications, the expected requirements to meet the needed data rate, reliability, latency, communication range and high-speed support are made more stringent.

The 5GCAR project aims to contribute to the overall 5G network design, and specifically to design V2X technology components which can address the demanding challenges for efficient support of future V2X use cases, for example the ones investigated within 5GCAR project. As analyzed in the deliverable D2.1 [5GCAR D2.1], the identified use cases impose a broad range of challenging and critical requirements on the 5G V2X radio interface. These requirements, together with other considerations, such as supporting the coexistence with mobile broadband services and operating with high spectral and energy efficiency, entail challenges specifically on the design of the 5G radio interfaces for efficient V2X communication support, including both the sidelink radio interface between user equipment (UE) (including both vehicle UEs and other types of UEs) and the radio interface between UEs and various infrastructure nodes such as cellular base stations (the Uu interface).

To meet the future V2X communication requirements such as the ones described in the 5GCAR project, including the requirements on E2E latencies (below 5 ms), ultra-high reliability (99.999%), high density of connected vehicles (e.g. capacity) and positioning accuracy (down to 5 cm), the 5GCAR radio interface design involves a rich set of technology components that can be selectively combined and deployed jointly such that these requirements can be met. Within 5GCAR, our study covers the most challenging research challenges, and a mapping between the research challenges and the proposed technology components can be found in Chapter 2. From a technical contribution point of view, we have proposed the technology component clusters (TCC) as indicated in the following:

- Multi-antenna techniques:
- Resource allocation and management

- Sidelink design
- Full duplex
- Reliability enhancement
- Positioning.

A more detailed description of the TCCs and the individual proposed technology components is included in Chapter 3. From a communication type point of view, our study covers technology components which are applicable to the Uu interface (uplink/downlink) and/or the PC5 interface (sidelink) and can be exploited for all types of V2X communications, e.g., Vehicle to Vehicle (V2V), Vehicle to Infrastructure (V2I), Vehicle to Network (V2N) and Vehicle to Pedestrian (V2P).

1.1 Objective of the Document

The objective of the present document is to summarize the radio interface concept proposed within 5GCAR project. However, it is worth to point out that many of the proposed concepts are built on top of the 5G NR system concept which is developed in 3GPP. First, the document provides a brief description of the main technical challenges that must be addressed in order to support the 5GCAR use case classes and use cases. In addition, we provide the mapping between the technology components and the targeted performance improvement. As a one step further, the main objective of this deliverable is to describe the radio interface concepts which are organized as key technology component clusters with new illustrative numerical results in case new results were obtained comparing to D3.1 [5GCAR-D3.1]. As a well-known principle, it would bring more impacts if the research outcome can be put into product in one way or another, for example via standardization contributions, which is one of the major directions to increase our impact. Several technology components were contributed to the 5G development in 3GPP, in addition to the channel measurement results and related V2V channel modeling discussions. Chapter 4 summarizes the contributions from our radio design concepts to V2X standardization.

1.2 Structure of the Document

This document is organized as follows. Based on the research outcome, especially wireless communication related key performance indicators (KPIs) on different 5GCAR use case classes (UCCs) and use cases (UCs), Chapter 2 starts with the overview of the key research challenges related to the radio interface, including a mapping from the identified use cases to the research challenges and the proposed technology components. As the major outcome from 5GCAR radio research work, Chapter 3 is devoted to radio interface design and it is further divided into six subsections to cover all the technology component clusters as discussed earlier.

Chapter 4 presents a high-level overview of the ongoing relevant standardization work, focusing on 3GPP Radio Access Network Working Group 1 (RAN1). Three Study Items (SIs)/Work Items (WIs) are mentioned, and we have been contributed 5GCAR concepts to all the three WI/SIs. The summary of the deliverable is given in Chapter 5.

In addition, Annex A provides further details on some different technology components, including, for example, additional performance evaluation results. Annex B summarizes the qualitative self-analysis of all 5GCAR TCs covering both radio aspect and network architecture aspect including their pros and cons.

2 Use Case Review and Radio Related Research Challenges

The design of the radio interface plays a crucial role in meeting the key requirements of the use cases targeted by 5GCAR project. In Deliverable D2.1 [5GCAR-D2.1] five different use case classes (UCC) were studied and a summary of different representative use cases (UC, one per each UCC) together with their corresponding key performance requirements is provided in Table 2-1.

Table 2-1 Summary of Use Cases and Key Performance Requirements

	UC1: **Lane merge** (UCC1: Cooperative maneuver)	**UC2:** **See-through** (UCC2: Cooperative perception)	**UC3:** **Network-assisted vulnerable road user protection** (UCC3: Cooperative safety)	**UC4:** **High-definition local map acquisition** (UCC4: Autonomous navigation)	**UC5:** **Remote driving** (UCC5: Remote driving)
Communication range	> 350 m	50 to 100 m	40 to 70 m in city areas; ~ 400 m on the country roads at night	Few kms	Several kms
Data rate per vehicle	1.28 Mbps	10 to 29 Mbps	0.128 Mbps	2.88 Mbps DL	1.28 Mbps to 29 Mbps
Reliability	99.9%	99%	99.99%	99.99%	99.999%
Latency	< 30 ms, depending on vehicle speed	< 50 ms	< 60 ms	<30 ms	5-30ms
Localization accuracy	< 1m to 4 m	~10 m	~25 cm	5 to 50 cm	5 to 50 cm
V2X communication types	V2V, V2I, V2N	V2V, V2I, V2N	V2P, V2I, V2N	V2I, V2N	V2I, V2N

As can be seen from Table 2-1, most of the targeted use cases and use case classes have at least one (typically several) very stringent key performance requirement, and the ranges of the KPI requirements across the use cases are wide. This makes the design of a single network meeting all the requirements really challenging, both in terms of radio interface and system architecture. It is also noted that unlike Day-1 safety use cases (e.g., forward collision warning, emergency stop, queue warning, etc.) targeted by existing V2X technologies (e.g., LTE V2X), where broadcast is the main mode of communication, most of the use cases targeted by 5GCAR require unicast and/or groupcast communication. Moreover, the communication can happen between vehicles and any of vehicles or vulnerable road users (VRUs) or a network node, anywhere with network coverage or out of network coverage or with partial network coverage (i.e., when an in-coverage device communicates with an out-of-coverage device). This leads to numerous challenges in terms of peer discovery, resource selection, beam and interference management, feedback and retransmission design, and so on. Additionally, the advanced use cases targeted by 5GCAR will need to coexist in the same geographical areas with the Day-1 safety use cases as well as with cellular communication services, in many cases also sharing the same spectrum, calling for advanced interference management techniques and smart resource allocation and sharing. At the same time, achieving ultra-reliable communication with low latency is a big challenge in terms of physical design since there is a fundamental trade-off between the two targets, especially given the fast-changing nature of the propagation and interference conditions due to vehicles' high mobility. Likewise, high mobility and diverse network topologies make it difficult to achieve high accuracy for absolute and relative positioning. Finally, as with any wireless communication technologies, we want to achieve high spectral and energy efficiency.

Based on the analysis of use case requirements, we have identified a number of technical challenges for the design of the radio interfaces for 5G V2X. Several key challenges are summarized in Table 2-2, together with a mapping to the most relevant use cases. The identification of these challenges is the first key step to the design and evaluation of relevant radio interface technology components. For more detailed discussion of the technical challenges, we refer the reader to an earlier deliverable of 5GCAR [5GCAR D3.1, Chapter 2]. It is important to note that these challenges cannot be addressed satisfactorily by existing technologies or technologies that are currently under discussion on various standardization organizations (for example 3GPP Rel-16) but require innovative solutions.

Table 2-2 5GCAR Challenges from a Radio Interface Design Perspective

Challenge	Description (Why is it a challenge?)	Comments	Mapping to the UCs / UCCs
Meeting the **low latency and high reliability** requirements, especially meeting them simultaneously and/or for high-speed vehicles.	In highly mobile environments, channel estimation and data reception are problematic. In particular, high Doppler and/or large delay spread, and pilot contamination effects represent difficult challenges, especially for direct V2V communications	Charactering and achieving a latency-reliability tradeoff is key. This challenge is present in several 5GCAR use cases and is especially severe in mmWave bands.	UC1, UC2, UC3, UC4, UC5
Increase the **reliability of sidelink unicast or multicast** communications, as well as **network capacity for sidelink broadcast** communication	Varying channel conditions, resource is selected and reserved by the transmitter without knowledge about the channel conditions and usage at the receiver side.	Unicast feedback is well designed comparing to broadcast or multicast. Feedback for broadcast or multicast should be investigated further	UC1, UC2
Mitigating interference when V2X communications coexist with cellular Uplink (UL) traffic.	Reusing cellular UL resources for V2X communications leads to intra-cell interference, whose mitigation is problematic.	Due to larger available spectrum and better QoS support in licensed band, there is a strong motivation to reuse cellular resources for V2X services.	UC1, UC2, UC3, UC4, UC5
Dynamic resource sharing between eMBB and URLLC V2X services.	Providing URLLC services and maintaining high data rates for eMBB services are contradictory requirements.	Addressing this challenge is expected to contribute to achieving high resource utilization by facilitating multiplexing different services in the same/overlapping resources.	UC1, UC3, UC5
Adaptive and robust **beam management for V2N and V2I broadcast/multicast services**	Transmit and receive beam alignment are problematic in highly mobile environments, especially in mmWave bands.	Broadcasting and multicasting services in mmWave bands can benefit several 5GCAR applications.	UC1, UC2, UC5
Providing **high quality links for V2N and V2I communications** (improve network capacity, energy and spectral efficiency)	As with the V2V link, in highly mobile environments, channel estimation and data reception are problematic for V2N and V2I links.	Due to short coherence time and limited coherence bandwidth, both channel estimation and data equalization are challenging.	UC3, UC4, UC5
Adjacent Channel Interference (ACI) mitigation for V2V communication	ACI is especially difficult to mitigate when a large number of vehicles communicate with each other.	This is a proven big issue in radio resource allocation/selection	UC1, UC2
Facilitate highly reliable and timely **peer device discovery for V2V** communications.	Low latency and highly reliable discovery with high resource reliability is problematic and is especially severe in dense scenarios (oncoming traffic).	Successful link establishment in V2V communications supported by an efficient discovery process benefit several 5GCAR use cases.	UC1, UC2
Support for **accurate and ubiquitous real-time positioning**	Accurate Time of Arrival (TOA), Angle of Arrival (AOA) and Angle of Departure (AOD) in frequency bands above 6GHz requires careful design of Positioning Reference Signals (PRS)	It is important to understand the synergies between positioning and communications. Positioning is also an enabler for some of the challenges mentioned above.	UC1, UC3, UC4, UC5

To address the identified technical challenges, the partners of 5GCAR project have come up with a rich set of technology components (TCs), whose detailed descriptions along with indicative performance evaluation outcomes are provided in Chapter 3 of the present deliverable. As a summary, in Table 2-3 we provide a mapping between the TCs and the most relevant technical challenges. In this mapping each identified radio interface challenge is associated with at least one TC and there are a number of TCs which can be associated with multiple challenges. Nonetheless, we would like to emphasize that this mapping is by no means exhaustive, and that many of our TCs can be used not only to fulfil the requirements of the 5G automotive use cases targeted by 5GCAR but also to improve the performance of existing V2X technologies (e.g., LTE V2X Rel-14/15).

Table 2-3 Research Challenges and Mapping to Technology Components

Radio research challenges	Mapping to technology components (TCs, indexed by the corresponding sections in this document)
Meeting the **low latency and high reliability** requirements, especially meeting them simultaneously and/or for high-speed vehicles.	3.1.1, 3.1.3, 3.1.4, 3.1.6, 3.1.7, 3.2.1, 3.2.3, 3.2.4, 3.2.5, 3.2.6, 3.2.8, 3.3.1, 3.3.2, 3.4.1, 3.4.2, 3.5.1, 3.5.2, 3.5.3, 3.5.4
Increase the **reliability of sidelink unicast or multicast** communications, as well as **network capacity for sidelink broadcast** communication	3.1.8, 3.2.4, 3.2.5, 3.2.6, 3.2.7, 3.2.8, 3.3.1, 3.3.2, 3.3.3, 3.4.1, 3.4.2, 3.4.3, 3.5.1, 3.5.2, 3.5.3, 3.5.4
Mitigating interference when V2X communications coexist with cellular Uplink (UL) traffic.	3.2.1, 3.2.7, 3.4.3
Dynamic resource sharing between eMBB and URLLC V2X services.	3.2.1, 3.2.7
Adaptive and robust **beam management for V2N and V2I broadcast/multicast services**	3.1.6, 3.1.7
Providing **high quality links for V2N and V2I** communications (improve network capacity, energy and spectral efficiency)	3.1.1, 3.1.2, 3.1.3, 3.1.4, 3.1.5, 3.1.6, 3.2.1, 3.2.2, 3.2.3, 3.2.7
Adjacent Channel Interference (ACI) mitigation for V2V communication	3.2.4
Facilitate highly reliable and timely **peer device discovery for V2V** communications.	3.3.3
Support for **accurate and ubiquitous real-time positioning**	3.6.1, 3.6.2, 3.6.3, 3.6.4, 3.6.5, 3.6.6

3 V2X Radio Design

In this chapter, we will introduce 5GCAR V2X radio concepts. The proposed technology components are classified into six TCCs since some TCs are closely linked with each other, for example,

- they are addressing different aspects of the same issue
- or they can be seen as different alternatives
- or some TCs can easily work together and they are complementary to each other.

The six TCCs are: multi-antenna techniques, resource allocation and management, sidelink design, reliability enhancement, full duplex, and positioning.

Multi-antenna techniques: High dimensional multi-antenna arrays are one of the most important elements in the coming 5G system. Within 5GCAR, we have investigated issues related to predictor antenna concept, beam management for unicast/multicast/broadcast communications, and optimal antenna design for V2V communications.

Radio resource allocation and management: Efficient resource usage is always one of the key objectives in all wireless communication systems including the coming 5G V2X radio interface. Within 5GCAR, we have studied different aspects of this problem: concepts to improve the overall V2N/V2I system performance, optimized pilot-to-data power setting. Both centralized (i.e. NW assisted V2V resource allocation) and distributed V2V scheduling schemes are studied, and also the hybrid mode.

Sidelink design: While the 5G NR Uu interface has been defined in 3GPP Rel-15, a 5G NR sidelink (SL) interface is still under development in Rel-16. This TCC covers the basic concepts for SL operation ranging from sidelink discovery, which is used to identify the most suitable UEs for pairing, SL synchronization design by introducing synchronization source hierarchy, and SL reference signals design. Different TCs are looking at different aspects of SL design, and the proposed solutions can smoothly work together.

Full duplex: Full duplex provides the capability of simultaneous transmission and reception, which opens up many opportunities to improve the performance of V2X communication. In this section cognitive resource usage for V2V communication and collision detection/avoidance are studied on top of the general study on the benefits of full duplex in terms of system capacity and latency.

Reliability enhancements: Reliability is one of the key aspects which has not been seriously considered in earlier generations of V2X. Starting from a fundamental trade-off analysis between reliability, latency and throughput, we have looked into how to make use of channel diversity to increase the overall reliability. Retransmission for either data or control or both data and control are efficient means for achieving the required high reliability.

Positioning: Accurate positioning is of growing interest from many vertical applications, and V2X is one of the domains where the accurate positioning can bring clear benefits for quite many use cases.

The following Figure 3-1 illustrates the TCCs and the current status related to the 5G development in 3GPP. As can be seen, the work done in 5GCAR not only contribute to the upcoming releases of the 3GPP 5G NR V2X specification, but also cover more future-looking technology components.

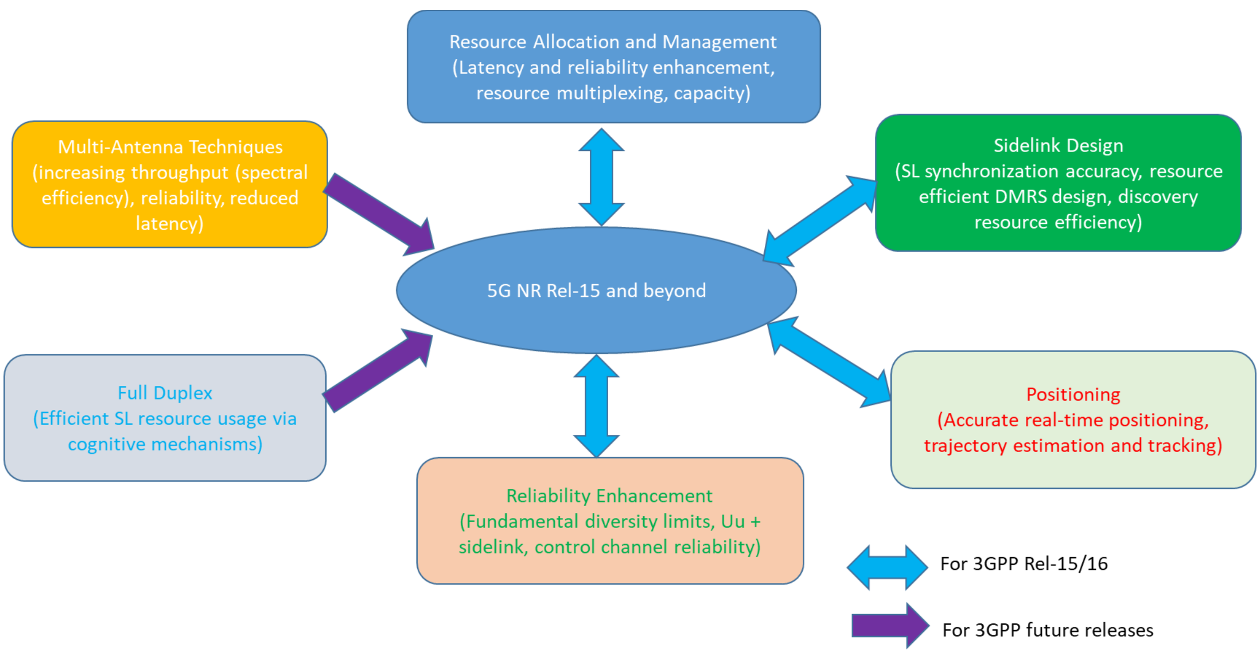


Figure 3-1 Integration of 5GCAR concepts with 5G NR in 3GPP

It is worth to point out that although most of the proposed TCs are for the cases with network coverage, there are TCs especially SL related TCs can be applied to the cases without network coverage as well. In the following, we will discuss all TCCs in detail.

3.1 Multi-Antenna Techniques

Multi-antenna techniques are considered as key 5G V2X technologies, as they can be used to increase the spectral efficiency as well as improve link reliability for highly mobile V2X scenarios. The benefits of antenna beamforming and multiple-input multiple-output (MIMO) signal processing are shown in this section by novel technologies and solutions. Besides unicast, multicast and broadcast schemes are also considered.

Available antennas are used to predict the radio channel for future time instants and compensate in this way the effects of channel aging caused by mobility. Practical aspects such as sensitivity analysis of coupling effects between antenna elements and efficient rate adaptation are studied. The extension of predictor antennas for massive MIMO systems and experimental validation show the practical feasibility and high potential of this technology.

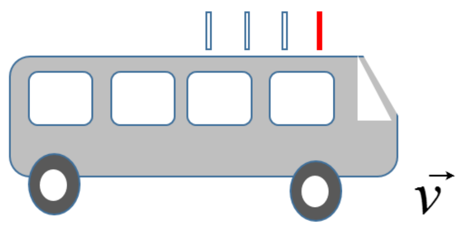
In order to guarantee URLLC, fast and reliable initial access and beam refinement and tracking are investigated, resulting in a novel codebook-based beam refinement scheme also suitable for the mmWave frequency bands.

Utilization of multicast / broadcast transmission at mmWave bands enables high data rate V2N/V2I communication links with resource-efficient transmission of common content to multiple users. Beamforming is used to provide coverage and high reliability. Due to directivity of angular beams at mmWave frequencies, beam management for multicast/broadcast imposes a challenge in highly-dynamic scenarios, which are very typical for the V2X use cases. Development and performance analysis of beam-based broadcast schemes for V2X scenarios with different beam patterns, beam configurations, frame structures, and block error rates requirements are presented. When multiple users are geographically close to each other, redundant information of neighboring beams can be exploited to enhance the received signal quality and enable the usage of high-order modulation and coding schemes (MCS) that improves the achievable data rate. At the same time, the network exploits feedback sent from the users as acknowledgment or negative acknowledgment (ACK/NACK) to enhance the reliability of the broadcast/multicast service.

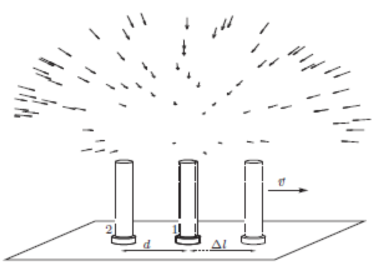
Finally, for V2V links often having LOS and deploying MIMO schemes, the antenna separations at the transmitting and receiving vehicles are optimized to maximize the spatial degrees of freedom. The impact of separation on the rank of the channel is analyzed for different distances between the vehicles. It is found that larger antenna separations can be preferred for the design over a range of distances between the two ends of the link.

3.1.1 Sensitivity Analysis of the Predictor Antenna System

System Model



The predictor antenna system. The red line indicates the predictor antenna while the others are antennas used for data transmission.



A sample scenario for the analysis, in which two monopoles above a perfect electric conductor (PEC) plane move with speed of v in an isotropic environment.

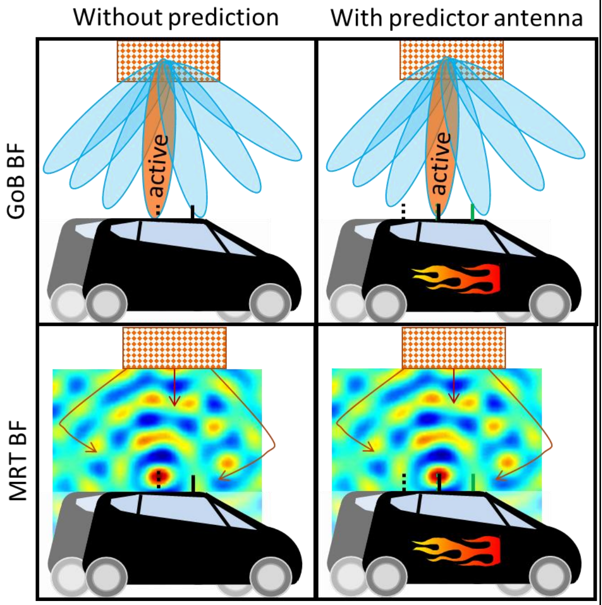
Main Idea

1. The predictor antenna concept is used to obtain channel state information at the transmitter side (CSIT) with multi-antenna systems for high speed vehicles, which is a key enabler for robust V2I links. The overall goal is to design multi-vehicle ultra-reliable 5G-V2I ITS links and spectrally efficient 5G eMBB links to fast moving vehicles, also at mmWave carrier frequencies.
2. In this work, we provide a generic formula for the covariance matrix of received signals at the ports of a moving multiport antenna system.
3. We quantify the adverse effect of velocities, different from the target velocity, on prediction performance of the predictor antenna system.
4. In case open-circuit decoupling is necessary, the sensitivity of the predictor antenna system performance with respect to the accuracy of the input network parameters is disclosed.

Use cases	Main Benefits
1. The performance gains with the predictor antenna system are particularly useful to meet the requirements in UC4 and UC5.	1. The predictor antenna system can substantially improve both throughput and reliability of the V2N links at high speed. Also, latency can be improved with high quality CSIT, by avoiding retransmissions. 2. By substantially improving the efficiency of these links, network capacity can also be improved to accommodate network slices with stringent requirements. 3. The CSIT can also be used to support massive MIMO beamforming for coverage extension and network energy efficiency. 4. We clarified that the pattern deformation in the presence of coupling reduces these systems' performance. 5. The impact of accuracy of the self-impedances on the open-circuit decoupling method is negligible.

For further details and results, see [5GCAR-D3.1, Sec. 3.2.1].

3.1.2 Predictor Antenna for Massive MIMO (M-MIMO) Adaptive Beamforming (BF)

System Model	Main Idea
 Due to the displacement of the car during the delay between channel measurement and BF, mis-pointing occurs. In a straight-forward implementation of the Predictor Antenna concept, mis-pointing is avoided by having the measurement made by an additional antenna (the Predictor Antenna), spaced from the target antenna by a distance equal to the displacement.	Adaptive M-MIMO BF schemes such as Grid-of-Beams (GoB) BF and Maximum Ratio transmission (MRT) exploit channel feedback and CSIT, respectively, to reduce the cost of networks in terms of transmitted power and spectrum usage. Adaptive M-MIMO beamforming (BF) schemes are therefore essential to provide efficient 5G V2N links. Naturally, due to the delay τ between channel measurement and BF, these schemes are only exploitable up to a limited speed v of the vehicle. Beyond this “Wall of Speed” v, the network falls back to non-adaptive and less energy efficient and less spectral efficient schemes. Simulation studies previous to 5GCAR project have shown that the Predictor Antenna make adaptive M-MIMO work for very fast-moving connected vehicles. **However, up to 5GCAR project, this concept was lacking experimental proof.**
Use Cases	**Main Benefits**
The TC improves the KPI of spectral and energy efficiency for V2N communication with high velocity UEs and thus addresses all 5G-Car use cases.	Practical experiments have proven that the predictor antenna works well in practice and can support velocities of up to 500 km/h.

Description of Technology Component

We summarize hereafter the detailed TC description from [5GCAR-D3.1]. In a straight-forward implementation, the Predictor Antenna, in line with the target antenna, is used for channel measurement, and DL BF based on this measurement matches the target antenna at the condition that the displacement of the vehicle during the delay between measurement and BF equals the spacing between the target antenna and the Predictor Antenna. Practical solutions based on spatial interpolation of multiple measurements exist to make sure that a fixed antenna spacing at the car side does not prevent from compensating all velocities up to $v = d/\tau$, where d is the largest antenna spacing on the car and τ is the delay between channel measurement and BF. Simulation studies previous to 5GCAR project [PHS+15] [PHS+16] [F5G-D2.3] assume that the predictor antenna provides enough accurate predictions of the target antenna's channel, despite the fact that the two antennas are physically distinct antennas. Before 5GCAR project, this assumption had been validated experimentally for SISO only. It had never been checked for adaptive MIMO BF**.**

Illustrative Numerical Results from Practical Experiments

Based on the 5GCAR channel measurements at 2.180 GHz and the evaluation methodology detailed in [5GCAR-D3.2] [5GCAR-D3.1] [PWB+18], we compare three prediction schemes (ideal prediction, without prediction and with predictor antenna), under the same displacement δ during the delay τ between the channel measurement and BF. Therefore, for the predictor antenna scheme we set: $d = \delta$. For each BF and prediction schemes, we compute the following metric: the received power obtained with the considered BF and prediction schemes, normalized by the received power obtained with the same BF scheme but ideal prediction. Figure 3-2 illustrates the CCDF (over measurement samples) of the metric for GoB BF and MRT BF, respectively, for δ=42 cm (which corresponds to a maximum supportable velocity of $v = \frac{\delta}{\tau}$ of 300 km/h for $\tau = 5ms$). With the predictor antenna, both BF schemes perform close to ideally. More precisely, as illustrated in Figure 3-2, in comparison with the ideal scheme, all the predictor antenna based schemes only lose between 0dB and -2dB in received power, whereas, GoB BF schemes without prediction lose between 1 dB and 8 dB, and MRT BF scheme without prediction loses between 1dB and 14dB. More results on MRT BF and GoB BF are available in [PWB+18] and Annex A.1, respectively. GoB BF without prediction is more robust to speed than MRT BF without prediction, due to the fact that GoB BF is less “precise”. Nevertheless, GoB BF benefits similarly from the predictor-antenna-based prediction.

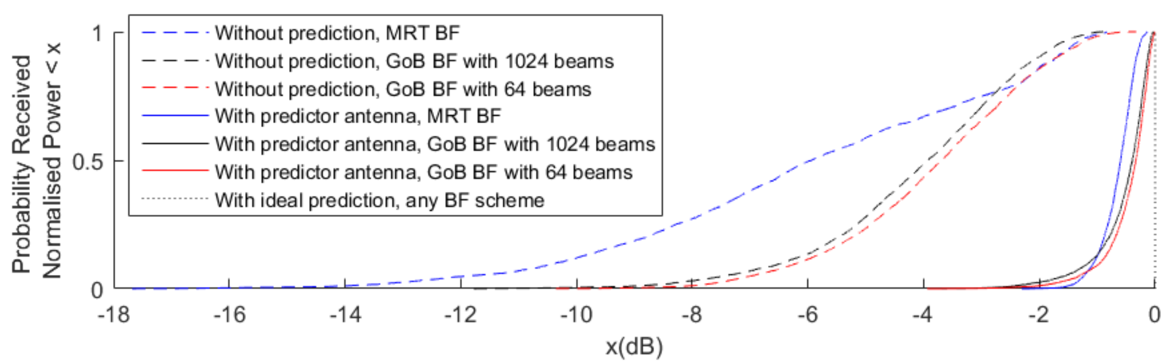


Figure 3-2 CCDF of the normalized received power metric based on practical experiments

These results show that the channel estimates provided by the Predictor Antenna are accurate enough to make adaptive M-MIMO (GoB BF and MRT BF) work for speeds computed in Table 3-1. As already explained earlier, all velocities up to these values, can be supported thanks to spatial interpolation [PHS+15].

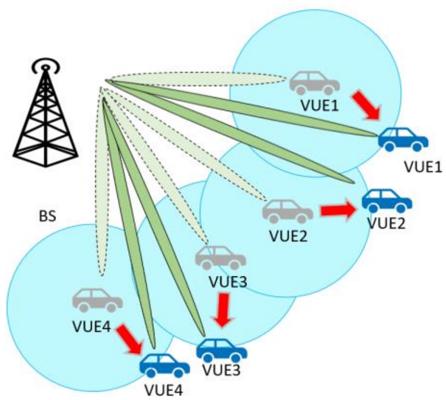
Table 3-1 Supported speeds $v = \delta/\tau$ corresponding to a displacement of δ=42 cm during the delay τ (ms) between channel measurement and BF

Delay τ (ms)	1	2	3	4	5

Speed v (km/h)	1512	756	504	378	302

3.1.3 Genetic-Algorithm Based Beam Refinement for Initial Access in Millimeter-Wave Mobile Networks

System Model



Beam tracking Network with proposed GA-based scheme in a MU-MIMO System. Blue circles indicate potential moving range for vehicle users during a certain time slot.

We propose a beam refinement scheme to include beamforming at both the transmitter and the receiver in millimeter wave multiuser multiple-input-multiple-output (MU-MIMO) networks with moving vehicle users.

The goal is to perform a system-level rate optimization by proposing and analyzing a genetic algorithm (GA) based scheme with the knowledge of user positions. Cooperative side links, i.e., vehicle-to-vehicle (V2V) links which allow users sharing their received message to further increase the throughput are also considered in one of the cases.

Main Idea

1. In order to overcome the power limitation and high path loss constraints at mmWave bands, we perform beamforming or so-called beam refinement during the initial access (IA) procedure. We adopt a codebook-based beam refinement to reduce the complexity of acquiring CSIT.
2. To match the low latency requirement, we design an efficient GA-based beam refinement scheme and compare it with the state-of-the-art methods. We add the algorithm running delay into the metric to see how the updating procedure affects the performance.
3. We apply the designed algorithm in the case of tracking beams for users with mobility. Spatial correlation can be utilized by setting the queen, i.e., the optimal beam set, of the previous position as the initial guess of the current position.
4. To further increase the throughput, we consider the case of cooperative side links among users to form a virtual antenna array.

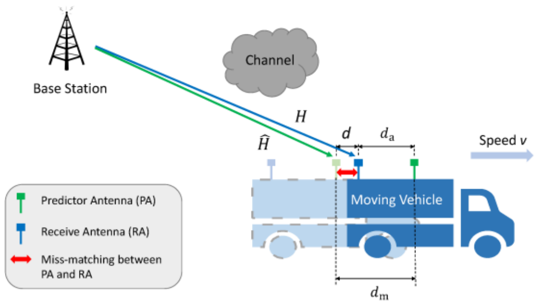
Use cases	Main Benefits
1. The gains with the proposed beam refinement scheme are particularly useful to meet the requirements in UC4 and UC5. 2. The cooperative users case could also be very useful to meet the requirements in UC2, when implemented using network assistance, due to the improved latency constrained throughput improvements.	1. This GA-based beam refinement scheme for initial access can substantially improve the delay constrained throughput of the V2N links, also when mobile. 2. The proposed GA-based scheme can reduce the beam refinement delay by utilizing the spatial correlation. 3. Beam tracking for moving vehicle users with the proposed GA-based algorithm show substantial gains in delay constrained throughput compared to the state-of-the-art schemes. 4. We show that cooperative users can substantially improve the system-level performance compared to non-cooperative users, at the expense of computation complexity and side-link communication overhead.

For further details and results, see [5GCAR-D3.1, Sec. 3.2.3].

3.1.4 Rate Adaptation in Predictor Antenna Systems

<table>
<tr><th>System Model</th><th>Main Idea</th></tr>
<tr><td>

- V2I communication between moving vehicle and the BS



- One vehicle deploying two antennas on the roof with one predictor antenna (PA) positioned in the front of the moving direction and another receive antenna (RA) aligned behind it. One transmitter antenna at the BS.
- Rayleigh fading channel between the BS and the vehicle.
- Considering downlink transmission in the BS-RA link with additional CSIT acquired from the PA.

</td><td>

- PA concept is used to improve the outdated CSIT for high speed moving vehicles.
- However, if the RA does not arrive in the same position as the PA before, the actual channel for RA would not be identical to what has been estimated using PA.
- We have in previous works showed that interpolation at the BS can mitigate this so-called miss-matching problem, but it comes with additional complexity. On the other hand, the BS can potentially adjust the transmission rate to mitigate the miss-matching problem, which is the focus of this TC.

- We study the problem of imperfect CSIT estimation in PA systems. The goal is to maximize the throughput as well as to minimize the outage probability in the presence of imperfect CSIT. Particularly,
  - ➢ We model the miss-matching problem as an equivalent Rician fading model, and
  - ➢ we derive closed-form expressions for the rate adaptation, and
  - ➢ we study the system performance in temporally-correlated fading conditions.

</td></tr>
</table>

Use cases	Main Benefits
1. The obtained throughput gains are particularly useful to meet the requirements in UC4 and UC5. 2. The cooperative user case could also be very useful to meet the requirements in UC2, when implemented using network assistance, due to the improved throughput improvements.	1. The predictor antenna system can substantially improve both throughput and reliability of the V2N links at high speed. Also, latency can be improved with high quality CSIT, by avoiding retransmissions. 2. The CSIT can also be used to support massive MIMO beamforming for coverage extension and network energy efficiency. By substantially improving the efficiency of these links, network capacity can also be improved to accommodate network slices with stringent requirements. 3. For delay-constrained scenarios of vehicle communications, we show that rate adaptation can effectively compensate for the miss-matching problem in PA systems. 4. Adaptive rate adaptation leads to considerable performance improvement compared to the no CSIT case.

Description of Technology Component

Predictor antenna (PA) system is referred to as a system with two sets of antennas on the roof of a vehicle, where the PA positioned in the front of the vehicle is used to predict the channel quality observed by the receive antennas (RAs) that are aligned behind the PA. This TC studies the performance of PA systems in the presence of the miss-matching problem, i.e., when the channel observed by the PA is not exactly the same as the channel experienced by the RA because the RA does not arrive at the same point as the PA when it receives information. Particularly, we study the effect of spatial miss-matching on the accuracy of channel state information estimation and use these expressions to derive the rate adaption scheme. We derive closed-form expressions for instantaneous throughput, outage probability, and the throughput-optimized rate adaptation. Also, we take the temporal evolution of the channel into account and evaluate the system performance in temporally-correlated conditions.

Illustrative Numerical Results

In the following results, we evaluate the expected data rate in our system in three cases: full CSIT, partial CSIT and No CSIT. For partial CSIT, which is our proposed PA design with miss-matching problem, we present the results both from numerical simulation (exact value) and analytical approximations. Also, the full CSIT is the case with perfect spatial matching between PA and RA while in no CSIT case we assume no PA deployed and we have a fading channel for RA. Moreover, we consider the temporal correlation of the channel which is modeled by the normalized correlation factor β for two successive channel realizations. This correlation represents the *spatial stability* of the channels, independent of the speed of the vehicle itself. A large β represents that the channel changes slowly.

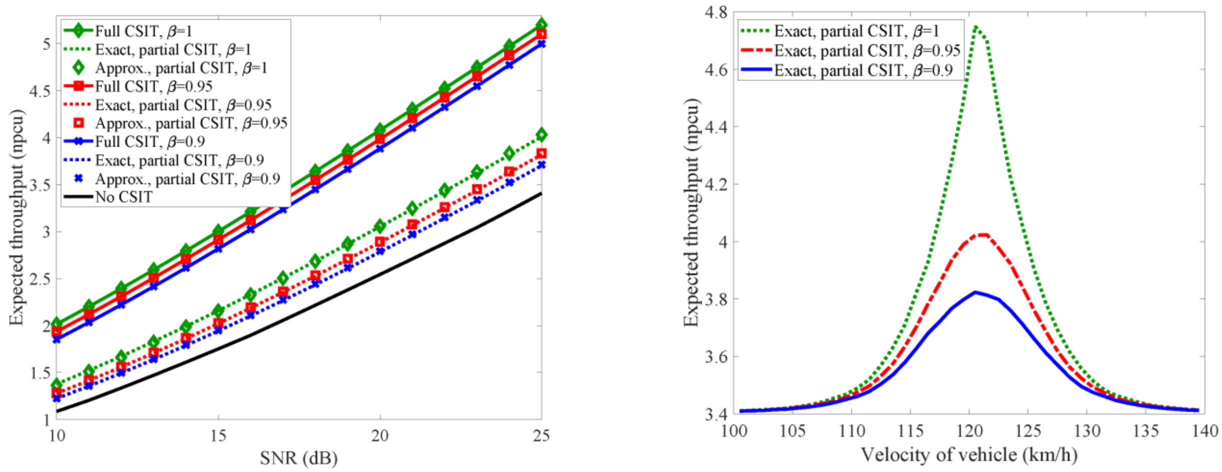


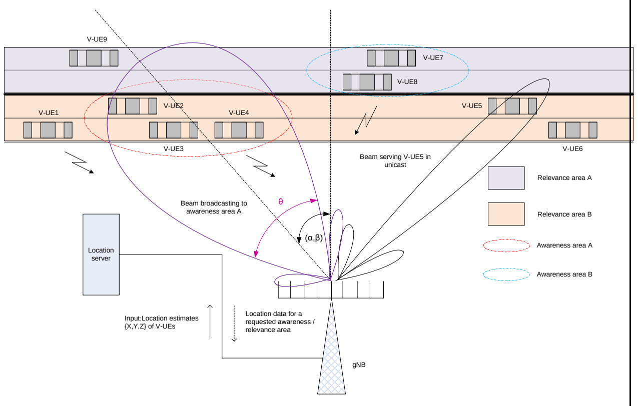
Figure 3-3 (left) Expected throughput in different cases, V = 117 km/h. (right) Expected throughput for different velocities with SNR = 25 dB.

Figure 3-3 (left) shows that the expected rate in our system increases with the SNR as well as β when the speed of the user is set to V = 117 km/h. With deployment of the PA, remarkable throughput gain is achieved especially in high SNRs, up to approx. 70% of the full CSIT gains compared to no CSIT. Also, as can be seen from the figure, our approximation for the partial CSIT case is quite tight for a broad range of SNRs with different β. It is worthwhile to see that the gain between full CSIT and partial CSIT is relatively small at low-SNR, which is promising since most of the vehicle links work on those regimes. Another notable result is that the gain between partial CSIT and no CSIT is slightly increasing with SNR.

Figure 3-3 (right) shows the expected rate as a function of speed. For fixed carrier frequency, antenna spacing as well as control loop delay, different speeds would end up with different miss-matching distance. For example, with the parameter setting in Figure 3-3, the theoretical optimal speed is about 120.9 km/h. As can be seen from the figure, the optimal speed from simulation matches the one from straight-forward calculation. Also, the throughput becomes less sensitive to the speed as β decreases. Moreover, the expected throughput is sensitive to the speed in the regime around the optimal speed. I.e. the rate adaptation gains vanish with a speed miss-match larger than +/-20%. For further details and results related to outage probability, see [GMS+19].

3.1.5 Beam-domain Broadcasting for V2N/V2I Links

<table>
<tr><th>System Model</th><th>Main Idea</th></tr>
<tr><td>



Single-cell V2I/V2N network model considered.

The single-cell V2I/V2N system is modelled as a single-cell multi-user multiple-input multiple-output (MU-MIMO) system, in which at a given time a downlink multicast/broadcast transmission is activated on-demand / triggered by an event to deliver a common message to a subset of V-UEs within a certain geographical region.

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Utilization of multicast / broadcast transmission mode at mmWave band could enable high data rate V2N/V2I communication links with resource efficient transmission of common content to multiple V-UEs.

Due to event-triggered or periodic (non-continuous) nature of requirement for multicast/broadcast mode of operation, the overall design must guarantee efficient multiplexing with unicast traffic. Another aspect is that, due to directivity of angular beams at mmWave frequencies, beam management for multicast/broadcast, including beam alignment and tracking, impose a challenge in highly-dynamic scenarios that are characteristic for the V2X use cases.

This technology component builds upon the SC-PTM (single-cell point-to-multipoint) transmission scheme and comprises algorithms aiming i) to coordinate the beam-domain broadcast message delivery across V2N/V2I links utilizing geographical criteria and ii) to reduce the overhead associated with beam alignment and tracking procedures.

</td></tr>
<tr><th>Use Cases</th><th>Main Benefits</th></tr>
<tr><td>

Especially for UC1, UC3 and UC4, the spectral efficiency KPI can be improved for V2N/V2I links utilizing this TC with overall impact on enhanced network capacity.

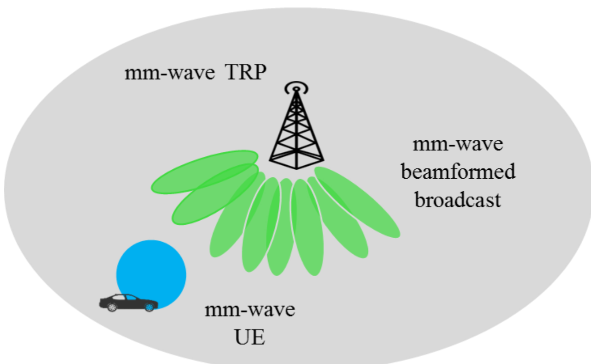
</td><td>

- Resource efficient mechanism for the delivery of group common messages over V2N/V2I links, which scales well with the increased bit rate requirement of the message (high data rate applications) as well as the number of concerned V-UEs (especially important in dense deployments).
- Reduced beam alignment overhead.

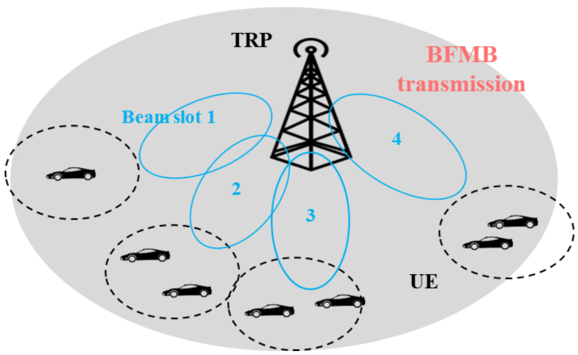
</td></tr>
</table>

Sec. 3.2.4 of [5GCAR-D3.1] contains further details on the concept and in Annex A.2, performance evaluation of the concept is included. Overall, the obtained results indicate that the beam-domain multicast scheme can increase the spectral efficiency of the network-to-vehicle links in the highway deployment scenario and consequently improve the DL cell throughput.

3.1.6 Beam-based Broadcast Schemes for V2X Applications

System Model	Main Idea
 Without loss of generality, we envision a single cell downlink standalone network with one mmWave transmission/reception point (TRP) at its center of radius r = 100 m. In general. UEs (vehicles) are assumed to be randomly "dropped" in the network. The above figure shows an example of a considered network, here a *single-cell standalone mmWave network with one TRP.*	On the one hand, mmWave bands provide large amount of bandwidth, which is suitable for broadcast with large data amount. On the other hand, the very small wavelengths of the mmWave signals, combined with advanced low power CMOS RF circuits, enable the exploitation of beamforming. As a result, reliance on highly directional transmission and reception considerably complicates the beam-based broadcast for V2X communications, which is expected to be designed properly considering different beam patterns, beam configuration, and multiplexing schemes, etc. This TC addresses the selection of the beam scan scheme, which depends on the targeted performance metric. Specifically, single beam exhaustive scan was found to be optimal in terms of the initial transmission latency. By contrast, multiple beam simultaneous scan achieves the lowest overhead defined as the portion of resources allocated for initial/broadcast transmission out of all resources available in the cell.
Use Cases	**Main Benefits**
V2N initial access requiring low latency and V2N data broadcast requiring high efficiency and low overhead. Hence, it addresses use cases UC3 and UC4. Addressed challenges: Fulfill the latency and efficiency requirements of different use cases.	The beam-based broadcast schemes allow flexible configuration to achieve tradeoff between latency and overhead Leveraging the analysis and the simulation results to provide insights into the selection of beam scan scheme.

3.1.7 Beamformed Multi-Cast with HARQ Feedback and Retransmission

System Model	**Main Idea**
	The key idea is to exploit the fact that UEs that are geographically close to each other can be served by the same beam which contains common messages for such UEs. Redundant information of neighbouring beams can be exploited to enhance the Rx signal. Furthermore, the TRP exploits feedback from UE acknowledgment or negative acknowledgment (ACK/NACK) schemes which have been designed to trigger retransmissions for enhancing the reliability of the broadcasting/multicast service.
Use Cases	**Main Benefits**
An infrastructure node such as a gNB or RSU, (commonly referred to as a transmission/reception point, TRP) provides reliable multicast transmission to UEs within the cell coverage. Addressed use cases: UC1, UC2, UC3, UC4. Addressed challenges: How to assure reliability while reducing HARQ overhead.	Thanks to the redundant copies of data received on adjacent beams (time division multiplexed) by each UE, this scheme achieves significantly higher data rates in the medium and high SNR ranges. Receiving redundant copies enable the usage of high-order MCS that improves the achievable data rate. Further, the ACK/NACK scheme enhances reliability of the broadcast/multicast service.

Description of Technology Component

The Physical broadcast multicast channel (PBMCH) is defined for multicast and broadcast. The necessary downlink control information associated with the PBMCH transmission allows the receiving UEs to decode the PBMCH messages. This control information consists of information regarding the applied modulation and coding scheme (MCS), as well ACK/NACK indication. The resources for these pieces of information are either pre-allocated or allocated using the standardized physical downlink control channel (PDCCH).

For HARQ feedback, different timing indications of ACK/NACK feedback are supported. Specifically, the UL HARQ feedback can be sent either immediately after each of the beams that cover the entire cell area, or after all beams have scanned their corresponding distinct coverage areas. Since geographically close UEs belong to a single group, these UEs may receive signals from adjacent scanning beams, on which different levels of received signal power may be experienced. To improve the spatial reuse gain, UEs belonging to the same group are enabled to combine signals either from all beams they received signals from, or from the single beam with the highest receive power (the "best" beam). The selection of the "best" beam can be realized, for example, by linking to the synchronization of the "best" beam from the received synchronization signal block or the received channel state information reference signals utilizing channel reciprocity.

Finally, for retransmissions, a similar beam selection scheme can be utilized, as illustrated in Figure 3-4. Specifically, the packets on retransmission links are identical within each beam or group of beams, if HARQ feedback is transmitted along all beam directions. Alternatively, if HARQ feedback is transmitted only along the "best" beam, the packets on the retransmission links are specific to each beam/group and supported by beam/group-specific PDCCH indications.

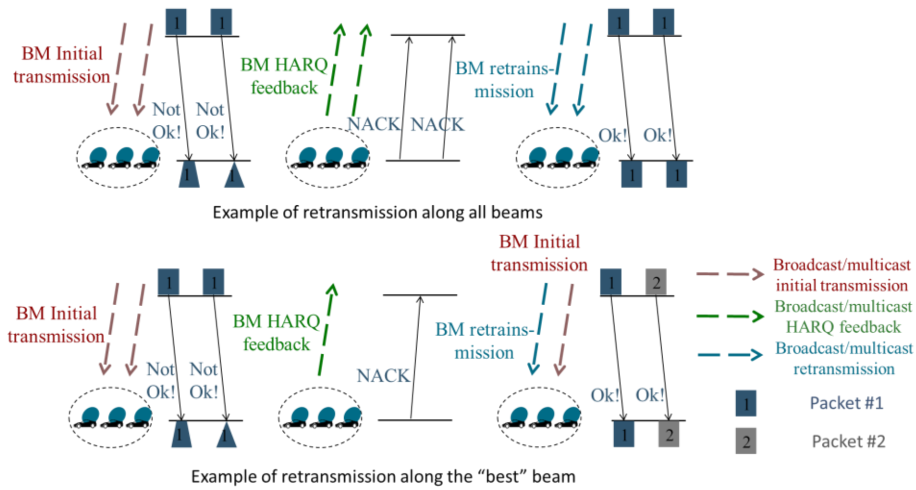


Figure 3-4 Illustration of HARQ feedback and retransmission (BM: Broadcast Multicast).

Illustrative Numerical Results

The proposed scheme is compared with two benchmark schemes, namely broadcast schemes in LTE-V2X [3GPP-37885] (without beamforming and retransmission, *LTE-V*) and LTE-V2X with retransmission (without beamforming, *LTE-V+HARQ*), in terms of achievable data rate and latency. The simulation parameters are summarized in Table 1 (Figure 3-5 left). The results in Figure 3-5 show that the proposed scheme considerably outperforms the benchmark broadcast/multicast schemes both in terms of latency and achievable data rate.

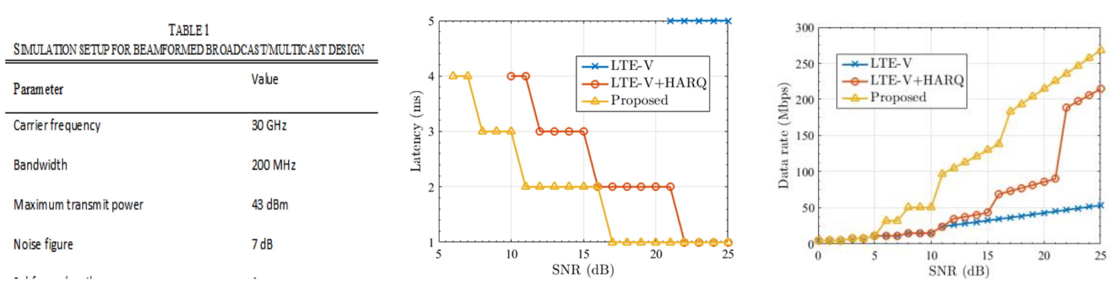


TABLE I
SIMULATION SETUP FOR BEAMFORMED BROADCAST/MULTICAST DESIGN

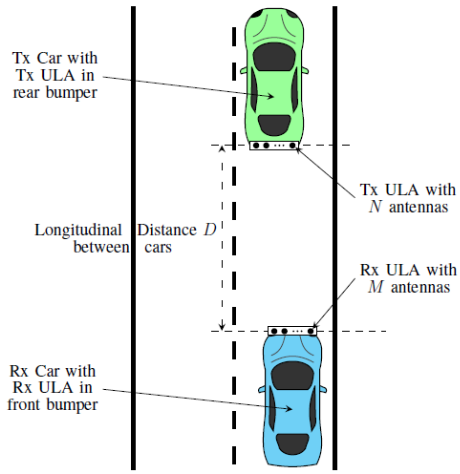
Parameter	Value
Carrier frequency	30 GHz
Bandwidth	200 MHz
Maximum transmit power	43 dBm
Noise figure	7 dB

Figure 3-5 Simulation parameters (left) and performance comparison in terms of the latency middle) and achievable data rate(right).

3.1.8 LOS MIMO Design for V2V

System Model

- V2V communication between vehicles with same velocity and on the same lane



- Arrays are placed in the front and rear bumpers of the cars.
- Transmit (Tx) and Receive (Rx) arrays consist of *uniform linear arrays* (ULAs).
- LOS channel between Tx and Rx arrays:
  - Ground reflection ignored

Main Idea

- For LOS MIMO channels, the antenna separations at the Tx ULA and Rx ULA need to be <u>optimized</u> to maximize the spatial degrees of freedom:
  - Without a proper antenna separation, LOS MIMO channel can be rank deficient (i.e. rank 1)
  - For V2V communication, maximizing the spatial degrees of freedom enables spatial multiplexing and high data rates.
- Antenna separation is usually optimized for a fixed distance between arrays.
- We exploit multiple solutions of the optimum antenna separation product for the antenna placement in a LOS MIMO channel of a V2V link, considering:
  - a range of distances between the Tx vehicle and Rx vehicle,
  - max array length due to space constraints on the car bumpers.

Use cases

1. LOS MIMO design applicable to:
   a. Lane merging (UC1)
   b. Cooperation perception (UC2)
2. Major contribution: results provide guidelines to maximize the spatial multiplexing and diversity gain for V2V.

Main Benefits

1. An antenna separation may be optimum at several distances.
2. In contrast to design for fixed distance, larger antenna separations can be preferred for the design over a range of distances between the Tx and Rx ULAs.

Description of Technology Component

Multiple antennas allow to exploit spatial degrees of freedom in rich scattering environments. In LOS MIMO channels, however, the antenna separations at the Tx and Rx ULAs need to be optimized to maximize capacity and the degrees of freedom. By designing orthogonal LOS MIMO channels with the spherical wave model, in [CIS18] we revisit the derivation of the product of the optimum antenna separations at the Tx and Rx ULAs, which leads to multiple optimum solutions. In prior works on LOS MIMO design, for equal antenna separations at the Tx and Rx ULAs, only the first solution is considered as this results in the smallest arrays. In addition, as the optimum antenna separation depends on the distance between arrays, varying the distance between Tx and Rx (as in a V2V link) leads to a capacity reduction. To reduce the sensitivity to distance variations, non-uniform linear arrays have been proposed, but with the optimum antenna placement found via exhaustive search. We propose to exploit the multiple solutions for the optimum antenna separation, which have been derived in [CIS18], for the LOS MIMO design over a range of distances between the Tx and Rx arrays in a V2V link.

Illustrative Numerical Results

We consider a V2V link (at 28 GHz) between cars separated by a distance D as shown above. For all considered distances D, we assume a receive SNR=13 dB, i.e. assuming sidelink power control, to abstract the impact of pathloss at different distances and to focus on the channel rank. We set the number of antennas in the Tx and Rx ULAs to 3 and assume the same antenna separation d at both arrays. In order for the Tx and Rx arrays to fit into the bumpers of a standard car, the length of the arrays needs to be less than 1.8 m. Thus, with 3 antennas in the arrays only antenna separations d < 0.9 are considered. For the given setup, the multiple solutions (denoted by the variable p) are given by $d = \sqrt{p \, \frac{\lambda D}{M}}$ for $p \in \{1,2,4,5,7,8,10,11,\dots\}$, where λ is the wavelength. Multiple solutions (denoted by p) of the optimum antenna separation as a function of the distance between cars are depicted in Figure 3-6. Compared to the first solution p = 1, the curves for p > 1 result in larger antenna separations which also maximize capacity. For each distance D up to 100 m, there are at least two possible antenna separations which result in a 3x3 orthogonal LOS MIMO channel. Some antenna separations are optimum at several distances. For example, the LOS MIMO channel designed with antenna separation d=0.5976 is orthogonal with three equally strong eigenmodes at D = 10, 12.5, 14.3, 20, 25, 50 and 100 m. However, at other distances between the cars some eigenvalues go to zero and the LOS MIMO channel resulting with d=0.5976 becomes rank deficient, e.g. at D=34 and D=68 the rank is 1 and 2, respectively. As the optimum antenna separation depends on the distance between the cars, the LOS MIMO channel (obtained with the spherical wave model) for distances which move away from the design distance may no longer have three equally strong eigenmodes, and thus the capacity is reduced. In Figure 3-6, the capacity of the LOS MIMO channel for different antenna separations d=0.5, d=0.5976 and d=0.7 is depicted. For d=0.5976, the maximum capacity is achieved for the previous set of distances. For d=0.5 and d=0.7, the maximum capacity is achieved at other sets of distances. In fact, there is a stretching and shift to the right of the capacity curve as the antenna separation d increases.

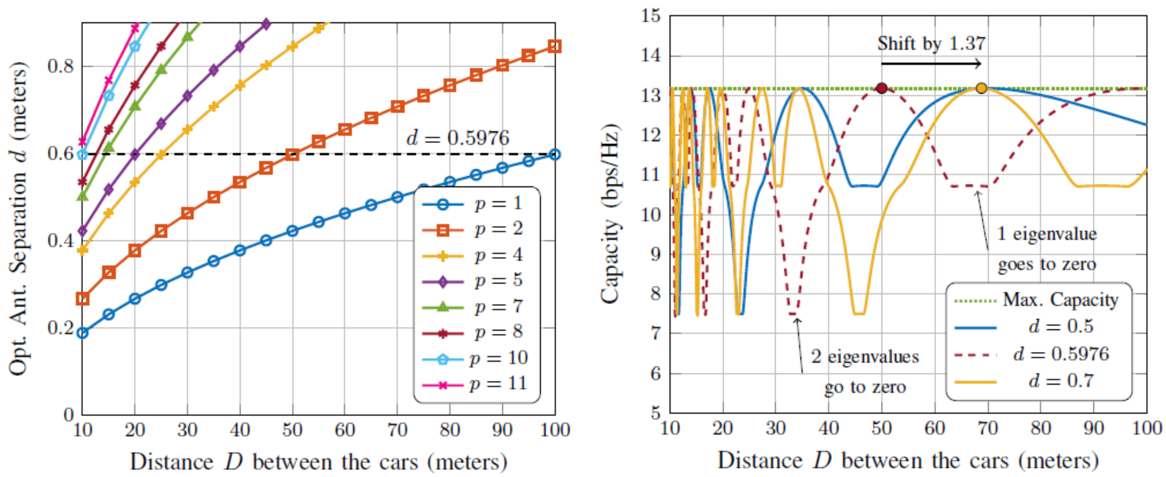


Figure 3-6 Optimum antenna separation (left) and capacity (right) as a function of the distance between cars in succession

3.2 Resource Allocation and Management

In the V2X radio interface framework, a key design aspect is the radio resource management (RRM). More specifically, how can we efficiently allocate resources to vehicular UEs and potentially also conventional mobile UEs so that their respective service requirements are satisfied? Note that here resources include various dimensions, such as time, frequency, space, code resources and also transmit power. To address this challenge, a set of technology components are proposed in this section, covering a wide range of scenarios.

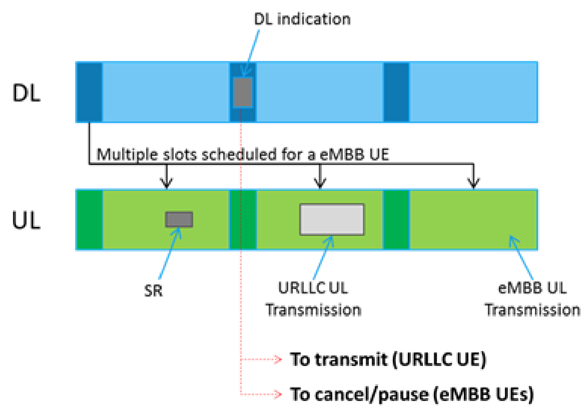
As already described in Chapter 2, the five representative use cases identified by Deliverable D2.1 [5GCAR-D2.1] require different types of communications, including V2N, V2V, V2I and V2P. Obviously, these different types of communications would have different considerations in RRM design.

For V2N communication, it is similar to cellular links in the sense that one endpoint of the communication is the network. Then, conventional UL/DL scheduling algorithms may be reused here. However, different from the eMBB services, V2N applications, e.g., remote driving, can have very stringent requirements on latency and reliability. Therefore, [3.2.1] and [3.2.3] exploit URLLC for V2N communications and propose several mechanisms to improve the overall system performance. In addition, [3.2.2] considers a multi-cell scenario and proposes advanced receiver design as well as pilot-to-data power setting to enhance V2N transmission reliability.

When it comes to V2V/V2P communication, it is interpreted as sidelink or direct device-to-device (D2D) link since both of the communication endpoints are UEs. In this scenario, there are typically two modes of RRM: network scheduled mode (a.k.a. centralized mode) and autonomous mode (a.k.a. distributed mode). More specifically, in network scheduled mode, the network determines the exact resources used by vehicular UEs, assuming that the network has certain knowledge about the link conditions between UEs. [3.2.4], [3.2.5], [3.2.7] propose RRM mechanisms along this direction. On the other hand, in autonomous mode, vehicular UEs select transmission resources by themselves, without the need of network assistance. In this regard, [3.2.6] proposes a distributed RRM scheme targeting unicast V2V communications. Last but not least, [3.2.8] considers a hybrid of network assistance and autonomous selection to achieve a trade-off between latency/signaling overhead and reliability.

3.2.1 Efficient Preemption-based Multiplexing of Services

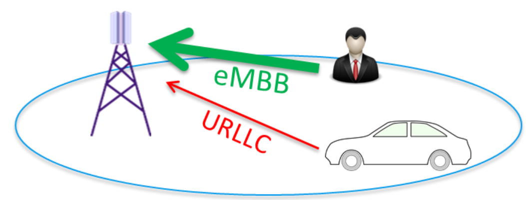
System Model



Cancellation indication enables scheduled eMBB resources to be used for bursty URLLC transmissions.

We consider a single-cell environment with multiple vehicles and other users where resources are shared dynamically between eMBB and URLLC traffic. The goal is to maintain high data rate eMBB service despite preemption from sporadic URLLC transmissions while at the same time ensuring URLLC requirements.

Main Idea



Dynamic resource sharing between eMBB and URLLC traffic in UL.

UL cancellation indication can be used to inform UE to cancel/pause its scheduled eMBB transmission so as a URLLC transmission can take place. The main idea here is to use a *continue* indication (i.e. ensure eMBB UE that no interrupting URLLC transmission occurs) for the few eMBB UEs in bad channel condition; *Cancel* indication (i.e. making eMBB UE aware of an upcoming interrupting URLLC transmission) is used for the rest UEs. Furthermore, the use of a resource pool that can be shared between and data and SR for URLLC UL transmission is proposed

Use Cases	Main Benefits
This technology component targets use cases requiring multiplexing of high data rate services with high reliability and low latency services in DL or UL. It particularly applies to UC 2, 4 and 5. The concept can be also extended to V2V communication. Addressed challenges: a) Dynamic resource sharing between eMBB and URLLC V2X services; b) Providing high quality links for V2N and V2I communications; c) Meeting simultaneous requirements on low latency and high reliability	1. The efficient design for the UL cancellation indication ensures that missing the indication will not lead to collision between UL transmissions (i.e. ensures URLLC performance) while at the same time signaling overhead is significantly reduced. 2. The efficient SR-based approach can also provide significant benefits on signalling overhead.

Description of Technology Component

URLLC traffic can be bursty and sporadic, therefore, allocating dedicated spectrum is spectrally inefficient. For this reason, dynamic multiplexing mechanisms have been explored for NR. Rel-15 specified preemption–based multiplexing in downlink to allow short-duration higher priority transmission (e.g. URLLC) preempt an ongoing long-duration lower priority one (e.g. eMBB) [3GPP-38213]. A pre-emption indication (PI) is introduced to indicate whether a block of time-frequency resource is pre-empted or not, so that an impacted eMBB UE can null the corresponding part in its buffer. For this DL case, in [5GCAR-D3.1], we have proposed enhancements on HARQ feedback design and on scheduling design for retransmission before HARQ feedback to reduce signaling overhead and improve eMBB throughput performance. Further information on these solutions can be found in [3GPP-R1-1718708] and [3GPP-R1-1808973]. Here, we tackle the UL case.

Efficient URLLC/eMBB multiplexing in UL

In UL, multiple URLLC vehicles could access UL resources based on contention. But limited by the collision probability which is determined by the reliability requirement of URLLC services (as shown in Annex A.3), it is not realistic to configure many URLLC UEs to share the same resources. Mechanisms for dynamic multiplexing of eMBB/URLLC transmissions with different time intervals are being explored for Rel-16 NR and solutions based on power-control and cancelation-indication are supported for further design [3GPP-38824]. We focus on enhancements on the latter considering the case where different URLLC vehicles transmit on dynamically scheduled resources. These resources are normally used by eMBB UEs when not needed for URLLC services but must be able to be released quickly. Note that grant free transmission may lead to excessively wasted reserved resources considering the short latency requirement and the infrequent arrival of URLLC packets.

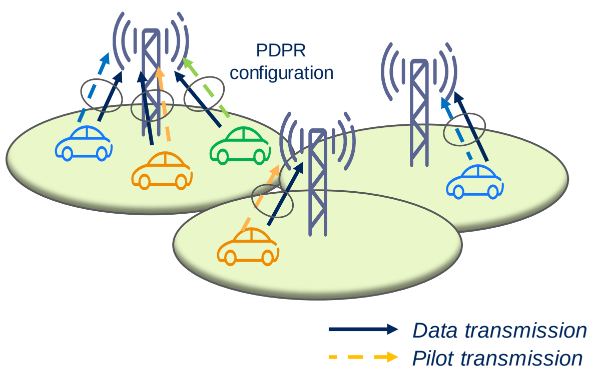
Dedicated scheduling request (SR) can be used by a URLLC UE to indicate gNB when it wants to access the resource. Then a DL indication ensures the resource access. However, this SR-response step increases latency of initial UL transmission. Big amount of SR resources needs to be reserved for all active URLLC vehicles and if SR is transmitted infrequently (as is the case with URLLC) most of the SR resources will be wasted. Instead, a RACH-like channel can be considered for SR transmission, where multiple URLLC UEs can be configured to share the same set of SR resources. More information on the proposed approach can be found in Annex A.3 and [3GPP-R1-1900683]

Furthermore, we propose an efficient design for the UL cancellation indication (CI). Such indication will be monitored at mini-slot level (i.e. multiple times per slot) by eMBB UEs with scheduled UL transmission in order to identify if an *interrupting URLLC transmission* has been scheduled within part of their resources. We propose a combined solution, where UL CI is designed to indicate continue for the few eMBB UEs in the cell that are in bad channel condition, while indicating cancel to UEs in good channel condition. Such approach ensures that no collision between eMBB and URLLC transmissions can happen; if a continue indication is lost by eMBB UE due to bad channel, it will just cancel its eMBB transmission – in contrary, if only cancel indication is configured for eMBB UEs, when indication is lost due to bad channel the UE will go on with its transmission, resulting in collision with URLLC transmission.. At the same time, the signaling overhead is significantly reduced since the majority of eMBB UEs (i.e. UEs in good channel condition) will only receive indication when URLLC transmission is scheduled on their UL resources. Using link level simulations for PDCCH performance and DL geometry distribution we can evaluate the probability X of UL CI monitored by an eMBB UE in bad channel condition, e.g. $X = 1\%$. From this, we can evaluate overhead reduction and an example numerical result is given in the table below for different probability P of interrupting URLLC transmission per scheduled eMBB slot. More details on the proposed approach and the evaluation methodology can be found in Annex A.3 and [3GPP-R1-1902129].

Table 3-2 PDCCH overhead (in number of CCEs) for UL CI. Aggregation Level (AL) of 4 is assumed to be used for Continue and Combined indication, while AL of 16 is used for Cancel Indication.

Interruption Probability (P)	5%	15%	25%	[Notes]
Continue Indication	4	4	4	= 4
Cancel Indication	0.8	2.4	4	= 16*P
Combined Indication	0.238	0.634	1.03	= 4*(P+(1-P)*X)

3.2.2 Decentralized Pilot-to-Data Power Ratio Configuration in Multi-Cell Multi-User MIMO Systems

System Model	Main Idea
 Same color indicates the same pilot sequence (pilot contamination) *Multicell V2N Network as a MU-MIMO System* The multicell V2N system is modelled as a multicell multiuser MIMO (MU-MIMO) system, in which both the uplink data and pilot transmissions cause interference to each other. The pilot interference (contamination) is caused by intercell pilot transmissions, whereas for data both intra- and intercell interference is present. This system is modelled as a non-cooperative game, in which the players correspond to vehicles. Each player aims to minimize its own mean squared error of the uplink received data symbols. A very important part of the system model is a novel MU-MIMO receiver that is designed to be robust with respect to channel state information errors.	The main idea consists of two intertwined technology components: (1) a novel and robust MU-MIMO receiver design [AFT+19] and (2) a decentralized pilot-to-data power ratio (PDPR) setting for minimizing the mean squared error (MSE) of the uplink received data symbols [MSF+17], [ZFD+18]. The first technology component uses the estimated channels of all simultaneously served users to minimize the MSE of each user [AFT+19]. The second technology component contributes to the MSE minimization by allocating the optimal PDPR ratio when assuming uplink pilot signal-based channel estimation and uplink data transmission under a sum-power constraint [MSF+17], [ZFD+18]. Previous studies have shown that the pilot-PDPR setting in MU-MIMO systems has a large impact on the system performance. This technology component enables vehicles to tune their PDPRs such that the MSE of the received uplink data symbols is minimized. When the vehicles tune their PDPR, they affect the MU-MIMO interference as well as the pilot contamination level in the multicell system. This technology component contains a distributed algorithm based on a non-cooperative game, in which each vehicle is a player, and minimizes its own MSE by continuously tuning its data and pilot power level. In the single cell case, this non-cooperative game converges to a Nash equilibrium using 1-3 iteration(s) that is close to a global minimum sum-MSE. In the multicell scenario, we use system-level simulations to investigate the system performance.

Use cases and KPI	Main Benefits
1. Single cell environment with uncorrelated/correlated Rayleigh/Rician fading channels 2. Multicell environment with correlated channel models. This technology component addresses the research challenge related to providing high quality links for V2N and V2I communications in UC3, UC4 and UC5 (Table 2-2). The global KPI that is improved therefore the uplink capacity through improving the SINR for all users.	1. The main benefit is that the MSE of all vehicles is reduced – as compared with a fixed PDPR setting -- and thereby the sum spectral efficiency improves. 2. The channel estimation quality at the BS improves, which in a TDD system can also be used for precoding in the downlink.

Illustrative Numerical Results

The aggregate effect of the two intertwined technology components -- a novel and robust MU-MIMO receiver design [AFT+19] and decentralized pilot-to-data power ratio (PDPR) setting for minimizing the mean squared error (MSE) of the uplink received data symbols [MSF+17], [ZFD+18] -- is illustrated in Figure 3-7. The proposed receiver minimizes the MSE of the uplink received data symbols and thereby results in higher sum spectral efficiency than the state- of-the-art CSI-error aware MU-MIMO receiver proposed in [FMT15]. As the figure shows, the sum spectral efficiency can then be maximized along the curve associated with the proposed receiver (red curve) by setting the pilot-to-data power ratio such that the sum spectral efficiency is maximized. (For further details, refer to Annex A.4.)

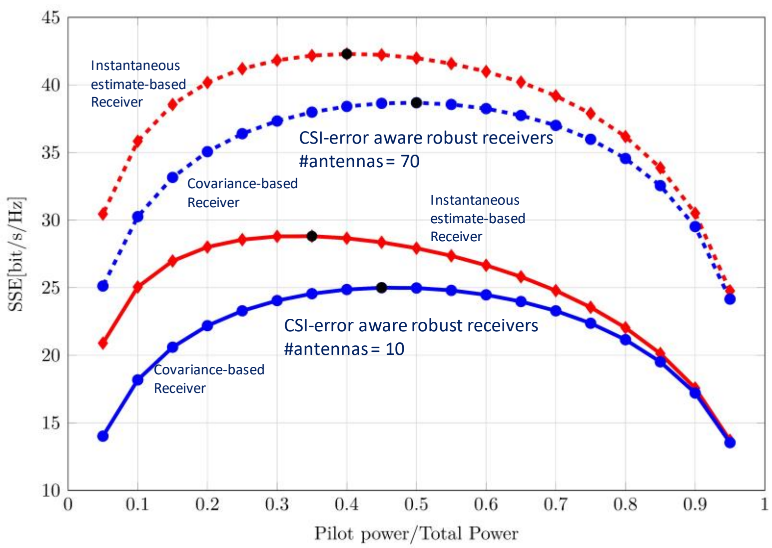


Figure 3-7 Performance of the proposed CSI-aware robust MU-MIMO receivers in terms of the sum spectral efficiency as the function of the pilot-to-data power ratio (PDPR). The instantaneous estimate-based receiver achieves higher spectral efficiency than the covariance-based receiver.

3.2.3 Joint Optimization of Link Adaptation and HARQ Retransmissions for URLLC Services in a High-Mobility Scenario

System Model	Main Idea
A high-mobility scenario is adopted, where a BS communicates with a vehicle moving at a very high speed. Under this scenario, we assume that the BS knows only the average SNR and not the instantaneous one. We also assume a block fading channel with Rayleigh fading. The received SNR then remains constant during a packet transmission and is independent and identically distributed (i.i.d.) between different transmissions.	We consider both link adaptation and HARQ schemes. A short Transmission Time Interval (TTI) (i.e. mini-slot) is considered so that URLLC services can be supported. Our aim is to maximize the spectral efficiency of the adopted system given latency and reliability constraints. To this end, we propose a joint HARQ retransmission and link adaptation scheme, where the optimal maximum number of HARQ transmissions and the optimal Modulation and Coding Scheme (MCS) level are determined for each URLLC service and average SNR.
Use Cases	**Main Benefits**
For all use cases, the spectral efficiency KPI at the network side is improved, for each **V2N link** supporting this TC. The global KPI that is improved is therefore the **network capacity of V2N link.**	The proposed scheme increases the system performance in terms of spectral efficiency. It also increases the flexibility of the scheduling mechanism.

Description of Technology Component

We briefly summarize hereafter the TC description detailed in [5GCAR D3.1].

We consider a short TTI (i.e. mini-slot as defined in NR), which is denoted by T_{TTI}. Let T_{RTT} represent the Round-Trip Time (RTT), which is defined here as the duration of time between the transmission of a packet and the reception of the corresponding ACK/NACK, including the processing times at the transmitter and the receiver. In a classical approach, the retransmission is done after a time equal to $x=0$ (in ms) after the reception of a NACK, i.e. immediately. Here we propose the following transmission policy:

- If an ACK is received, the next packet is sent in the next TTI;
- If a NACK is received, the same packet is retransmitted again but after a waiting time equal to x, which can be different from 0; A packet can be transmitted a maximum number of times equal to $K(x)$ under the target latency budget; i.e. the maximum number of allowable retransmissions is $K(x)$-1.

Let $S_e(x,m)$ denote the spectral efficiency metric of the considered radio link. $S_e(x,m)$ is a function of the waiting time x and the MCS level (i.e. mode) m being used by the radio link (under a given SNR). In a classical solution, the link adaptation mechanism finds the optimum value m_{op} of m to maximize the spectral efficiency $S_e(x,m)$, x being set to 0. We denote $S_e(0, m_{op})$ the obtained spectral efficiency. Note that this value depends on the SNR of the considered radio link. In our solution, we propose to jointly find the optimum values m_{op} and x_{op}, of m and x, respectively, that maximize $S_e(x,m)$. We denote $S_e(x_{op}, m_{op})$ the obtained spectral efficiency. Note that this value depends on the SNR of the considered radio link. More details on our TC can be found in [5GCAR D3.1].

Illustrative Numerical Results

We consider T_{RTT} = 0.5 ms and T_{TTI} = 0.125 ms, which is one among many possible timing attributes related to downlink HARQ for a flexible timing approach in 5G [5GCAR D3.1]. In Figure 3-8 we compare the spectral efficiency $S_e(x_{opt},m_{opt})$ obtained thanks to our optimization, with the spectral efficiency $S_e(0,m_{opt})$ obtained with a state-of-the-art solution. The reliability target is set to $1\text{-}10^{-4}$, and two latency budgets of 5 and 10 ms are considered. The spectral efficiencies $S_e(x_{opt},m_{opt})$ and $S_e(0,m_{opt})$ are illustrated for different values of average SNR. It can be noticed that, unlike $S_e(x_{opt},m_{opt})$, $S_e(0,m_{opt})$ does not always increase with the average SNR. This results from the fact that $S_e(0,m_{opt})$ is not the maximum spectral efficiency for each value of the SNR (i.e. $S_e(0,m_{opt})$ is optimized to meet the target delay and target BLER, rather than the spectral efficiency). Furthermore, the gain in terms of spectral efficiency is higher for greater latency budget. Further details on our TC performance (such as the range of values of x_{opt}) are available in [5GCAR D3.1][DEA+18].

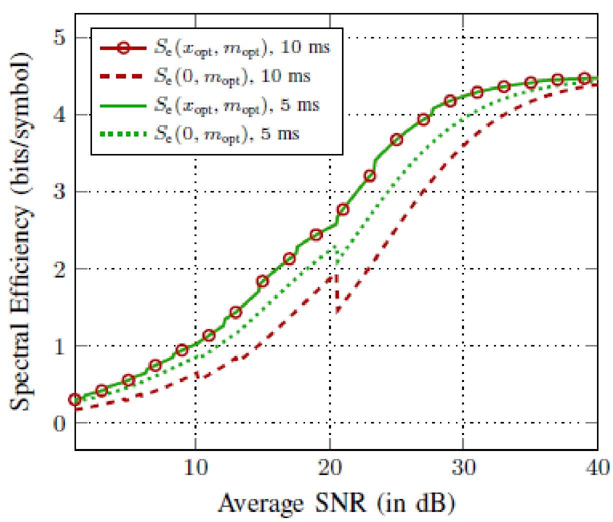


Figure 3-8 Optimal Spectral Efficiency $S_e(x_{opt},m_{opt})$ and spectral efficiency $S_e(0,m_{opt})$ vs Average SNR for different latency budgets, with reliability target of $1\text{-}10^{-4}$.

3.2.4 Power Control and Scheduling to Mitigate Adjacent Channel Interference in Vehicle-to-Vehicle Communication

System Model

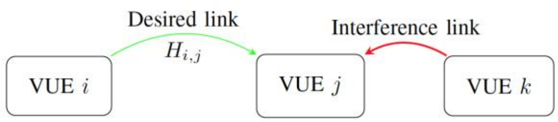
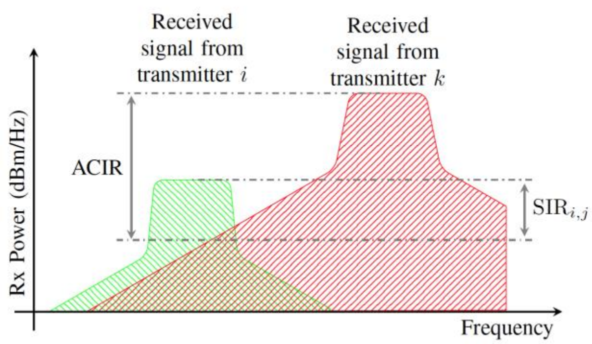


Fig. 1: System model



A sample scenario where V-UE *i* is transmitting a packet to V-UE *j* and V-UE *k* is interfering. Even though V-UE *k* is transmitting on an adjacent frequency slot, the signal to interference ratio (SIR) of the packet is affected by the adjacent channel interference from V-UE *k*. This problem is severe when V-UE *k* is closer to V-UE *j* than V-UE *i* and/or when the transmit power of V-UE *k* is high compared to V-UE *i*.

We say that V-UE *i* and V-UE *j* are *connected* if the received signal-to-interference and noise ratio (SINR) of V-UE *j* is above a certain threshold. The threshold is determined by the reliability requirement and the small-scale fading statistics. Latency is controlled by limiting the scheduling interval duration (*T* timeslot durations). The proposed algorithms need knowledge of the slow channel state information (CSI), i.e., pathloss and large-scale fading, between all VEUs. However, knowledge of fast CSI (small-scale fading) is not needed, which will reduce the CSI measurement and signaling overhead.

Main Idea

1. The performance of V2V and V2I communication links depend on both co-channel interference (CCI) and adjacent channel interference (ACI). However, given enough frequency slots, CCI can be avoided by scheduling V-UEs in non-overlapping frequency slots. but this does not remove ACI. In this work, we verify that ACI is indeed a significant problem and propose scheduling and power control schemes to mitigate ACI. The scheduling and power control schemes are easily extended to include V2I links as well.
2. We provide a generic problem formulation for joint scheduling and power control to maximize the number of connected V-UEs as a mixed integer linear programming (MILP) problem.
3. We also formulate the scheduling problem (given a fixed power allocation) as a Boolean linear programming problem, and the power control problem as a simplified MILP problem.
4. Since finding the optimal scheduling and power control values is highly computationally complex, we propose heuristic scheduling and power control schemes, with polynomial time computational complexity.
5. Since finding the optimal scheduling can be numerically sensitive, we propose methods to reduce the impact of numerical errors when computing the solution to the optimization problem.

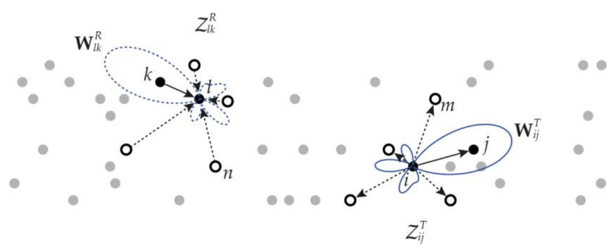
Use Cases	Main Benefits
The technology component targets use cases requiring reliable V2V communications, with strict latency constraints. Hence, it particularly applies to UC 2 and 3. The concept can easily be extended to V2X communication and thereby be relevant also for UC 5. Addressed challenges: a) meeting simultaneous requirements on low latency and high reliability; b) increase the reliability of sidelink communication; c) mitigating adjacent channel interference (ACI) for V2V communication	• We quantified the impact of ACI and show that ACI is indeed a problem in V2V communication systems in the absence of CCI (i.e., when the V-UEs are scheduled in non-overlapping frequency slots). An ACI aware scheduler can improve performance compared to a non-ACI aware scheduler. • The problem of optimal joint scheduling and power control is formulated mathematically. The optimal joint scheduling and power control seems to significantly improve the communication link performance. • Heuristic schemes proposed for scheduling and power control are less complex than the optimal approach, and still improve the system level performance compared to other approaches.

Description of Technology Component

The determining factor for reliability in typical communication is CCI, i.e., crosstalk from two different transmitters using the same time-frequency slot. However, we can remove CCI by allocating non-overlapping time and frequency resources to different V-UEs. If two transmitters simultaneously operate on two non-overlapping frequency slots close to each other in the frequency domain, power from one transmitter spills over into the frequency band of the other transmitter, which is referred to as ACI (see the example in the figure in the table above). The ACI is mainly due to the nonlinearities in the power amplifier in the transmitter, which cause the transmitted spectrum to spread beyond what was intended.

In this work, first we quantify the impact of ACI in V2V communication (see Annex A.5). Next, we study scheduling and power control strategies to reduce the impact of ACI. We consider scheduling N V-UEs in F frequency slots and T timeslots. We observe that the optimal scheduling and power control problem is an NP hard problem. We mathematically formulate the problem of optimal joint scheduling and power control as an optimization problem. We also propose low computational complex schemes for scheduling and power control, which improves the system performance. For all details, please refer to [HSB+17].

3.2.5 Sidelink Resource Allocation with Network Assistance Using Multiple Antennas

System Model	Main Idea
We consider a cellular network with UEs, which are in cellular coverage, are connected to the BS and can communicate in sidelink. The UEs perform measurements and report information to their BS, while the BS controls the sidelink transmission and assigns physical resources. It is assumed that at least a subset of UEs has multiple antennas, which can be used to transmit and/or receive by using multi-antenna techniques.  	A method to increase sidelink radio resource reuse by making the sidelink scheduler (BS) aware of the UEs' ability to mitigate interference to/from nearby UEs by means of multi-antenna transmission and/or reception.
Use Cases	**Main Benefits**
The solution targets use cases requiring highly reliable V2V communications, which may also entail strict latency constraints. Hence, it particularly applies to UC 1 & 2 (Lane merge, see-through).	1. Increase in system capacity, as the BS can take advantage of the UEs' interference suppression capabilities (e.g., transmit and/or receive nulling sets) to reuse resources more aggressively by allowing nearby transmitters to use the same time/frequency resources, as interference is suppressed at the physical layer. 2. Low overhead (reporting of nulling sets to BS), compared to the overhead that would be incurred if the full channel state information (CSI) was reported.

Description of Technology Component

In *scheduled resource allocation* mode (NR sidelink mode 1), V-UEs may report their location to the base station (BS), or this is determined by the BS. Having no sidelink channel knowledge, the sidelink scheduler (BS) is forced to allocate orthogonal resources (in time and/or frequency) to nearby UEs, in order to prevent mutual interference. However, transmissions from nearby V-UEs may not need to be orthogonalized by the sidelink scheduler if the UEs have multiple antennas. In other words, a radio resource may be reused by nearby transmissions – thus increasing system capacity – if UEs make use of *multi-antenna* transmission techniques to mitigate mutual interference.

Multi-antenna transmission techniques, such as beamforming and MIMO (Multiple-Input Multiple-Output), are powerful tools for interference mitigation and SINR enhancement.

The potential of MIMO processing (e.g., through data precoding and post-coding/detection) scales with the number of available antennas:

- Compared to single-antenna transmission, SINR gains of above 20 dB can be achieved by using, e.g., 16 transmit and receive antennas, mainly through interference rejection [BMI+16].
- Depending on the particular pre-/post-coding scheme, available antennas can be used for interference mitigation or diversity and data multiplexing gains.

The proposed efficient integration of beamforming/MIMO techniques in the sidelink with BS-assisted resource allocation is described in what follows. Given two (or more) nearby UEs with data to transmit, the sidelink scheduler must decide whether the same radio resource (i.e., time/frequency channel) may be used by both transmitters. Rather than reporting the full CSI (Channel State Information) to the BS – which would incur considerable control signaling overhead – we propose that UEs report their ability to use multi-antenna transmission/reception to cancel interference to/from nearby UEs.

Nulling sets

Specifically, as shown in Figure 3-9, a UE i may inform the network (BS) about a set of one or more nearby UEs m toward which it can form nulls when transmitting to a UE j. In general, it is assumed that topology estimation is performed by the UEs, meaning that UEs are aware of their neighboring UEs (e.g., by receiving periodic broadcast messages from neighboring UEs, such as CAM/BSM). Moreover, based on the certain pilot assignment scheme, UEs can estimate the channel to a set of these nearby UEs. We refer to such a set as transmit nulling set $\mathcal{Z}_{ij}^{T}$. Similarly, a UE l may inform the network (BS) about a set of one or more nearby UEs n toward which it can form nulls when receiving from a UE k. We refer to such a set as receive nulling set $\mathcal{Z}_{lk}^{R}$.

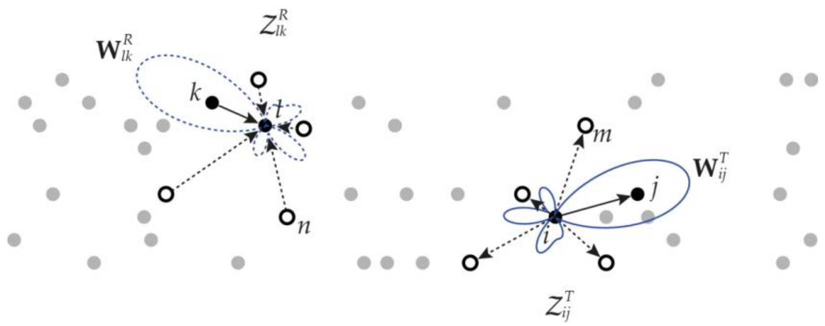
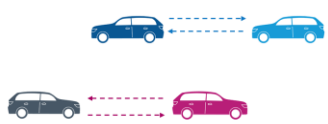


Figure 3-9 Illustration of transmit- and receive side nulling sets, denoted by Z_{ij}^{T} and Z_{lk}^{R}, respectively.

In general, the sets Z_{ij}^{T} and Z_{ij}^{R} do not necessarily need to be identical. In analogy to uplink/downlink non-symmetries, the beamforming/MIMO capabilities can be different between sidelink transmission and reception, e.g., if a different number of antennas and/or precoding schemes is available. In this case, both transmit and receive nulling sets need to be reported.

3.2.6 Distributed RRM for Direct V2X Communication

System Model	Main Idea
 Example of unicast communications in see-through application  Example of group communications in platooningWe consider a highway environment and group of vehicles (2 or more) communicating by means of unicast V2V links or via broadcast. The group can be formed for a long travelling distance (e.g. platooning) or temporarily to perform some cooperative tasks (e.g. cooperative perception). We assume an out of network coverage scenario and focus on non-assisted sidelink communication.	A distributed RRM that enhances the performance of semi-persistent scheduling and sensing mechanisms and adapts them to the unicast transmissions or for group communications (e.g. within a platoon). The idea is to use a cooperation between the sender and receiver in order to jointly optimize the resource selection and reservation schemes. The feedback about local sensing results and channels measurements is used to adapt the transmission parameters.

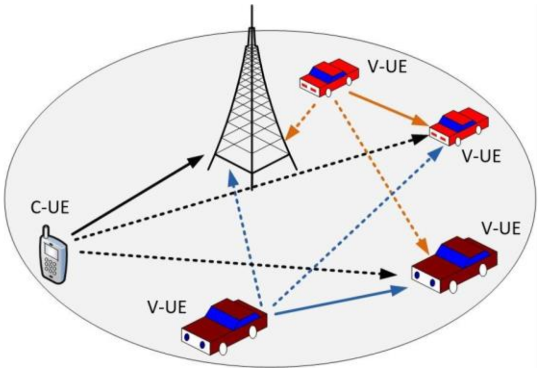
Use Cases	Main Benefits
Periodic V2V unicast messages with high reliability and strict latency constraints. Addressed use cases: cooperative perception UC2 (both see-through form and the form based on cooperative perception messages (CPM). Addressed challenges: How to assure reliability for unicast communication or broadcast within a group (two or more vehicles).	• Increase the reliability of the unicast transmissions and communications within a group of vehicles by reducing the collision probability and exploiting the advantage of semi-persistent scheduling. • Better resource utilization and better throughput to guarantee a minimum quality of service for see-through type of applications over the direct V2V interface also in the absence of network coverage.

In [5GCAR D3.1] we have proposed a distributed procedure for radio resource management for unicast transmissions which could be used for example to improve the performance in the cooperative perception use case. It was assumed that both unicast and broadcast communications share the same resource pool and that sidelink control information is used in both cases so that all users can receive and decode the control information and identify which resources are reserved independently whether they are for unicast or broadcast type of traffic. The idea is based on cooperation between the pair of users forming the unicast link where the sender and the receiver share the results of their local sensing mechanism and adjust the parameters of the semi-persistent scheduling accordingly. This includes adapting the amount of resources which could be reserved, the reservation duration (by means of the reselection counter), and the modulation and coding schemes. For example, if the receiver fails to decode a packet and detects a collision occurring within the resource blocks indicated in the sidelink control information (SCI) due to other interfering transmission, it signals back to the sender to trigger a new resource reselection. Also, using its channel measurements, the receiver might recommend to the sender to increase or decrease the modulation and coding or to adjust the amount of resources reserved to send the same amount of data. Alternatively, the receiver might suggest to the sender to increase (or decrease) its reselection counter so that the resources could be reserved for a longer (or shorter) period.

We propose to extend the approach in [5GCAR D3.1] to support communication within a group of vehicles moving together, for cooperative perception (e.g. see-through using 3 vehicles) or for platooning. The main idea now is to coordinate the resource reservation procedure by one of the group members, denoted coordinator (e.g. the first vehicle in the group), who initially selects the resource pattern (i.e. the number of resources, their periodicities, the reservation validity) depending on the applications needs. The information is shared in the SCI. Then, each group member includes the same resource pattern description into their transmitted SCI in order to increase the reliability of the information by means of redundancy and make sure that all the vehicles in the vicinity receive the information. An information about the traffic priority (e.g. application type) is also included in the reservation information broadcasted as part of the SCI. The coordinator uses the sensing mechanism to initially identify unoccupied resources that could be potentially used as part of the resource patterns reserved for the group. In case the amount of available resources is not sufficient to accommodate all the traffic created by the group, the coordinator uses an indication about the traffic priority, to revoke the resources used by other traffic with lower priority, e.g. non-safety critical messages, CAM, etc. As a result, each vehicle when receiving the SCI information and the indication about the reserved resource patterns, it refrains from using these resources if it they have been selected by a neighboring group for a higher priority traffic. The group coordinator may also decide to change the resource reservation patterns to avoid using the same resources reserved by another group in the vicinity. The other group members might detect (or predict) potential collision, based on the results of their own sensing, and they can signal their coordinator to trigger a resource pattern reselection and reservation procedure.

The exchange of the local information can start directly after the discovery phase where group members jointly select the initial parameters of the semi-persistent scheduling. The reservation might cover resources to be used in a bi-directional link (sender-receiver) or resources for transmissions originated by all the group members. The set of resources are then marked as resource reserved for the link or for the group depending on the applications and the corresponding configuration agreed during the discovery phase. All the group members continue sharing their information periodically or on a need basis, e.g. collision detection, channel condition changes, etc. This approach is expected to increase the reliability of the unicast communications as well as communications within a group. In fact, the cooperation between a group of users helps achieving a better view about the resource reservation in the vicinity. Thus, it optimizes the results of the sensing mechanism and decreases the hidden terminal problem by preventing a group member using the same resource used by a neighbor of one of the other group members.

3.2.7 Radio Resource Management in 5G-Enabled Vehicular Networks

<table>
<tr><th>System Model</th><th>Main Idea</th></tr>
<tr><td>
UL radio resources are shared by C-UE and V-UEs
• Single cell with simultaneous UL and direct V2X transmissions
• Orthogonal RB allocation of C-UEs
• Potential RB sharing between one C-UE and multiple V-UEs</td><td>A two-stage RRM framework is proposed, where semi-persistent RB and power allocation is conducted for the V-UEs in the first stage and flexible resource allocation methods are applied to the C-UEs on a dynamic basis in the second stage. RRM problem of the first stage is mathematically formulated, which is unfortunately NP-hard. Hence, a heuristic algorithm is proposed to solve the problem approximately. Additionally, along with the algorithm derivation, it is also proposed a novel sufficient and necessary condition on the feasibility of RB sharing among multiple UEs under general linear power constraints.</td></tr>
<tr><th>Use Cases</th><th>Main Benefits</th></tr>
<tr><td>This TC can satisfy the reliability requirement of sidelink transmissions and the data rate requirement of cellular links at the same time.
The benefit of the TC is particularly useful to meet the requirements in UC4 and UC5.</td><td>With the proposed two-stage RRM framework and heuristic RRM algorithm, the respective requirements of V-UEs and C-UEs can be satisfied simultaneously.</td></tr>
</table>

Description of Technology Component

Recently, D2D underlay has been identified as an appealing component for direct V2X communications including V2V, V2I and V2P [BSF+15, SSB+14, SSB+15, SYS+15, SYS+16]. To improve the reuse gain of D2D layer and also system spectral efficiency, UL radio resources can be shared by V-UEs and conventional C-UEs simultaneously. In this case, BS can act as a central coordinator to schedule multiple transmissions and allocate resources to both C-UEs and V-UEs. However, due to the challenges identified in Chapter 2, RRM mechanism needs to be carefully designed.

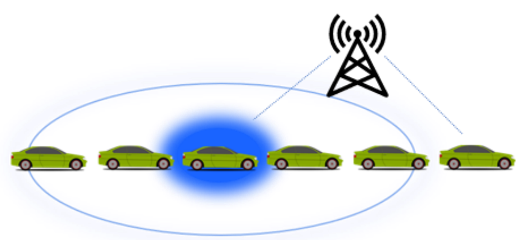
We consider a single cell environment where C-UEs and V-UEs share the available UL radio resources, and the current D2D underlay is only used by V-UEs. We assume that both C-UEs and V-UEs are using SC-FDMA waveform. Following the basic principle of UL scheduling, RBs are allocated to C-UEs in an orthogonal manner. On the other hand, an RB is allowed to be shared by one C-UE and multiple V-UEs simultaneously.

Under this assumption, we propose a two-stage RRM framework which can nicely tackle the challenges identified in Chapter 2. The main components of the proposed solution are described in the following.

- The original reliability requirements of V2X services are usually expressed as requirements on outage probability, i.e., $p_{out} \leq p_o$, where p_{out} is the calculated outage probability and p_o is the maximum tolerable outage probability specifically set for certain V2X service. If we include the expression directly in the RRM problem formulation, the RRM design will become much more complex due to the probabilistic constraint. To circumvent the hurdle, we derive a lemma that transforms the original outage probability requirement into a new constraint that 1) is computable with only slowly varying CSI, 2) is easy to cope within the RRM framework, and 3) implies that the original requirement is satisfied. Note that the transformed constraint is the one used later in the proposed RRM framework.
- We propose a two-stage RRM framework. In the proposed framework, the BS first allocates RBs and power to V-UEs, i.e., the UEs with more strict requirements, on a semi-persistent basis, and then in the second stage conducts C-UE scheduling on a dynamic basis.
- In the first stage, the BS conducts RB and power allocation for V-UEs, which is mathematically formulated as an optimization problem. More specifically, the goal is to minimize the total interference from V-UEs to the BS, under the condition of SINR requirements and transmit power constraints of V-UEs.
    - Due to the NP-hardness of the formulated problem, we propose an efficient heuristic algorithm to approximately solve it. There are three steps of the proposed algorithm: 1) feasibility check of RB sharing; 2) V-UE clustering; and 3) RB and power allocation.
    - Along with the derivation of the algorithm, we also propose a new sufficient and necessary condition on the feasibility of RB sharing among multiple UEs under a set of general linear power constraints.
- In the second stage, the BS assigns RBs and power to C-UEs on a dynamic and short-term basis to optimize their performance. In our proposed framework, this stage is flexible since the BS or operators can select various performance metrics based on their specific needs.
- With the proposed RRM framework, the following benefits can be achieved.
    - By dividing the RRM procedure into two stages and concentrating on V-UEs in the first stage, the stringent latency and reliability requirements of V-UEs are prioritized.

- For V-UEs, the semi-persistence of RB and power allocation allows an acceptable level of signaling overhead and therefore the offloading gain of D2D underlay.
- For C-UEs, the short-term basis of RRM keeps the dynamic scheduling gain as in LTE/NR. Moreover, flexible performance metrics and fairness rules can be applied to C-UEs according to the specific needs.

3.2.8 V2V Resource Allocation and MAC Capacity

<table>
<tr><th>System Model</th><th>Main Idea</th></tr>
<tr><td>
Vehicles moving on a highway are connected to the network. They are using sidelink to broadcast their periodic or non-periodic messages to surrounding vehicles. The two ends of the road are connected (wrapped around) to create interference at the ends. A message is considered to be successfully delivered if Signal-to-Interference and Noise Ratio (SINR) is above a certain threshold.</td><td>1. Use hybrid of periodic scheduling for periodic messages and slotted aloha for non-periodic messages.
2. Introduce geographical zones to avoid collisions due to partial spatial overlap of transmissions and improve spatial reuse of resources.
3. Network assigns some channels to individual vehicles for periodic messages and allocates shared pool of channels for non-periodic messages based on geographical zones.
4. Network is only involved in managing channel assignments on slow time scale driven by mobility and does not directly engage in MAC decisions made autonomously by vehicles on fast time scale.</td></tr>
</table>

Use cases	Main Benefits
Vehicle-To-Vehicle communication of periodic and random messages with high reliability demand and strict latency constraints for example UC1, UC2 and UC4. Addressed challenges: a) meeting the low latency and high reliability requirements, b) increase network capacity for sidelink broadcast communication	1. Minimizes required signaling. 2. Keeps low, limited delays for non-periodic messages and acceptable delays for periodic messages. 3. Increases system capacity. 4. Boosts effective coverage range by decreasing interference.

Description of Technology Component

Considered scenario involves a group of vehicles which generate a mixture of periodic messages (e.g. position and velocity updates) with a certain delay tolerance and highly urgent alert messages (e.g. emergencies, detection of obstacles), both of which need to be broadcasted to all other vehicles with a certain target transmission range. We assume that a specified amount of wireless spectrum is available which can be partitioned into channels that are orthogonal in frequency and/or time. The MAC mechanism serves to govern the transmission activity of the V2V communication devices installed in the vehicles, in particular when to broadcast the regular and alert messages, and which channel to use.

In this work, called Network-Assisted Resource Allocation, by using a hybrid of periodic scheduling and slotted aloha, together with geographical zone allocation and smart resource allocation, we achieve a scheme that meets the latency and reliability requirements, while minimizing required signaling.

Illustrative Numerical Results

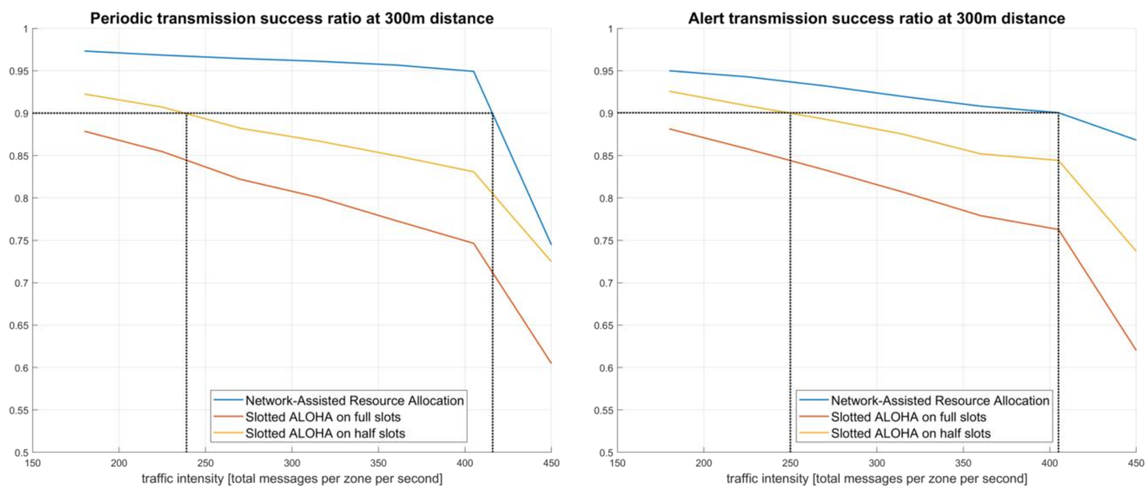


Figure 3-10 Transmission success ratio at 300m distance vs. traffic intensity

Figure 3-10 presents the transmission success ratio at 300m for periodic (left plot) and alert (right plot) messages vs. traffic intensity for proposed Network-Assisted Resource Allocation scheme and two reference Slotted ALOHA schemes with different slot lengths. Network-Assisted Resource Allocation can maintain over 90% alert transmission success ratio for almost twice as much traffic as Slotted ALOHA procedures.

3.3 Sidelink Design

In the context of 5GCAR project, besides infrastructure-based solutions, various enhancements of the sidelink interface for V2X communications have been devised to address specific research challenges introduced by the identified 5GCAR use cases [5GCAR-D2.1]. The 5GCAR sidelink-based V2X technology components enable the delivery of V2X services in the absence of infrastructure nodes and take advantage of network assistance under infrastructure coverage. In particular, the three different technology components proposed for sidelink interface design include synchronization and reference signals design for direct device-to-device communication and a network-assisted discovery mechanism.

Section 3.3.1 addresses the time synchronization problem for V2V sidelink. In all vehicular use cases, time synchronization among participating nodes is rendered necessary in order to achieve time alignment of all over-the-air signals and avoid interference between multiple links. In this context, the proposed TC proposes a novel design of sidelink synchronization signals that allows for a more efficient usage of the time/frequency resources allocated for synchronization. In addition, the sequence design enables the inclusion of additional information in the synchronization signals, e.g., coverage status or type of synchronization source.

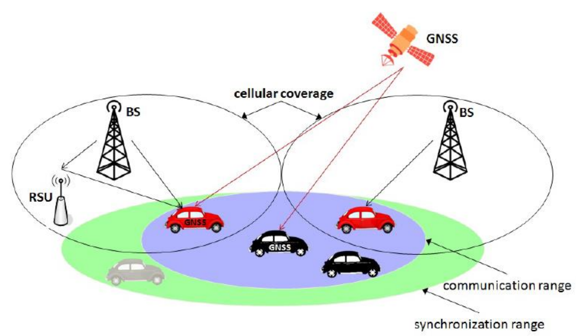
Section 3.3.2 focuses on the design of robust reference signals for direct V2X communication and it is tailored to all 5GCAR use cases. The proposed TC design aims at an efficient mitigation of the adverse propagation conditions and is complimented by methods to address pilot contamination due to overlapping transmissions. The rationale for the reference signals design accounts for the vehicle speed while the symbol configuration is performed in a way that maximizes the resource utilization and ensures low-latency decoding.

Section 3.3.3 focuses on the V2X discovery problem for reliable sidelink establishment between vehicles located in close proximity with each other. Several 5GCAR use cases, i.e., lane merge, see-through and VRU protection, involve a discovery process among vehicles and/or road-side users prior to a sidelink data transmission. Since event-triggered V2X discovery becomes particularly challenging in highly-dense scenarios which may compromise reliability and system scalability, the proposed TC aims to minimize the signaling overhead based on a flexible structure of the discovery signatures and improves the utilization of the scarce radio resources by adopting the principles of code-expanded random access.

In what follows, an overview of the technology components for sidelink design is presented along with indicative performance results.

3.3.1 Synchronization for the V2V Sidelink

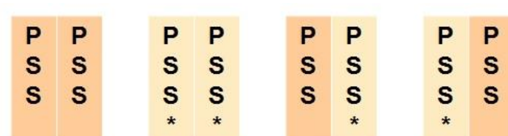
<table>
<tr><th>System Model</th><th>Main Idea</th></tr>
<tr><td>



A scenario with users in coverage and out of cellular coverage is considered. In order to achieve synchronized V2V transmission, a common time reference must be agreed by all sidelink users. For the sidelink, different synchronization sources are available, including base stations, GNSS, as well as users serving as synchronization sources. Out of coverage users without GNSS will have to rely on synchronization signals sent in the sidelink by other users. In order to prioritize between multiple synchronization signals received in sidelink, the information about the synchronization source type followed by the transmitting user must be provided.

</td><td>

The main idea is to convey the information of the synchronization source through the V2V synchronization sequences. Although such information can be also provided through a sidelink control or broadcast channel, the benefit of providing it through the (primary) synchronization signal is that it can be available earlier to the receiving user. This allows for prioritizing and selecting the synchronization signals sent by the user with the highest priority synchronization source. An efficient way to design such signals is to use multiple symbols, where each one carries a sequence selected from a set of two possible sequences. Using Zadoff-Chu sequences as building elements, two sequences being complex conjugate and orthogonal with each other can be chosen to enable efficient receiver-side detection, as shown in the following figure In thie example, each combination corresponds to a different synchronization source type.



</td></tr>
<tr><th>Use Cases</th><th>Main Benefits</th></tr>
<tr><td>

Particular relevance for V2V synchronization of users without cellular coverage, i.e. UC1 (lane merge) and UC2 (see through). Robust and reliable synchronization also for out of coverage users reduces the time of initial access and the interference due to synchronization misalignments.

</td><td>

Providing such information about synchronization source type through the sidelink synchronization signals assists the receive user to synchronize to the transmit user with the right synchronization source.

</td></tr>
</table>

Receiver-side synchronization algorithms and performance evaluation

Following Figure 3-11 shows an implementation of the two-step detection of the PSS at a receiver. In addition to the basic cross-correlation based operations, phase shifts due to time/frequency offsets are estimated and compensated, before the estimation is refined in a second stage.

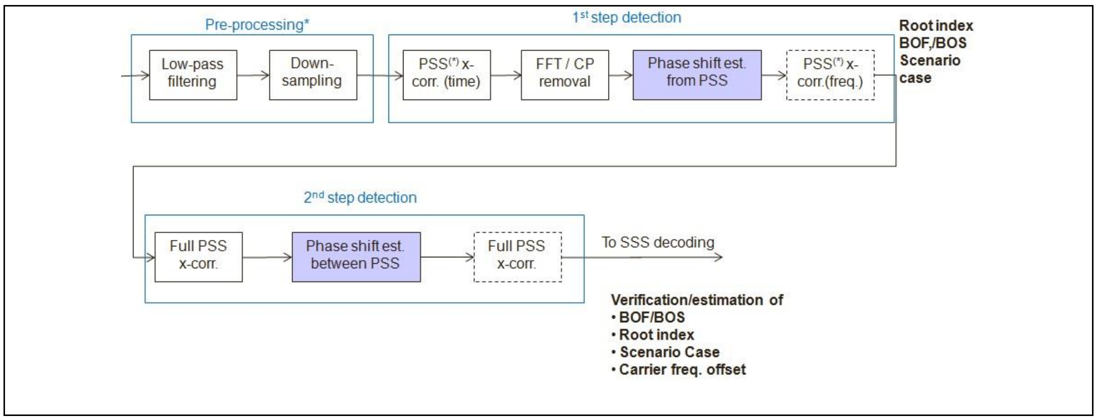


Figure 3-11 Receiver-side detection of primary sidelink synchronization sequences. A two-stage approach is used to refine the estimation and mitigate time and frequency errors.

Figure 3-12 shows the sequence detection probability over the SNR, as evaluated over 10^3 independent, identical distributed (i.i.d.) realizations of a multipath channel with time-continuous Rayleigh fading and a (relative) user speed of 240 km/h, as well as for the AWGN channel for reference. Results show that for SNR values around 0 dB, the detection probability approaches 100%, even under fast-fading channel conditions. For more details on this work refer to [MXC17]. For further details and results see [5GCAR-D3.1, Sec. 3.3.3].

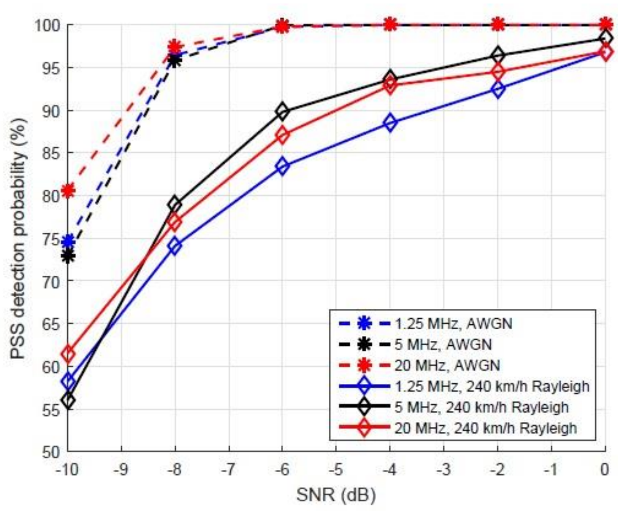
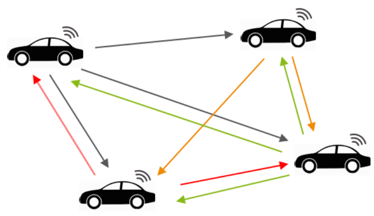


Figure 3-12 Primary synchronization sequence (PSS) detection probability over the SNR.

3.3.2 Reference Signals Design for Direct V2X Communication

System Model	Main Idea
 *Direct communication between vehicles* The direct device-to-device (sidelink) V2X system is modelled as a broadcast and possibly also multiple unicast system. A node can either send a message to all other nodes or to a subset of the other nodes. As such, transmissions from different UEs can overlap in time and frequency. This poses a question of how to design reference signals so that they are robust to both adverse propagation conditions and the pilot contamination problem.	To obtain a robust design, a single link in the system is the focus. The type of communication (broadcast / multicast / unicast) and impacts of Doppler and delay spreads as well as of other sources of errors will be considered. The design will be complimented by methods for mitigating the pilot contamination effect, i.e., the multiuser or multilink aspects. A key target is balancing the robustness and the induced overhead. The design is applicable to both in-coverage and out-of-coverage scenarios, concerning both V-UEs and P-UEs but focuses more on V2V.
Use Cases	**Main Benefits**
All use cases in [5GCAR-D2.1]. The relevant KPI is BLER versus SNR at link level. Addressing research challenges: - Meeting the low latency and high reliability requirements, especially at high speed. - Increase the reliability / spectral efficiency of sidelink broadcast / unicast / groupcast.	The design enables acquisition of channel state information at the receiver and the transmitter, allowing for reliable sidelink communication. Main benefits over known designs, particularly LTE sidelink-based V2X, include more resource-efficient, support of low-latency decoding.

Description of Technology Component (TC)

The most important reference signals (RS) used in 3GPP technologies include the demodulation reference signals (DMRS), used for channel estimation and demodulation at the receiver, and the reference signals for obtaining channel state information at the transmitter (often referred to as CSI-RS). In this TC we seek for an effective design of these RS for 5G sidelink V2X by fulfilling the targets elaborated in [5GCAR-D3.1, Section 3.3.5], namely efficient mitigation of adverse propagation conditions, allowing effective separation of RS at the receiver, minimizing the RS overhead, and facilitating CSIT acquisition when necessary.

Aiming at supporting the relative speed up to 500 km/h [5GCAR-D3.1, Annex A], we come up with a reference design illustrated in Figure 3-13 for the DMRS and CSI-RS for the 5G sidelink V2X. This design can be adapted to suit a real deployment, e.g., depending on the vehicle speed or on the operating numerology (i.e. subcarrier spacing, SCS), a DMRS symbol can be replaced by a data symbol to increase the data throughput. Note that leveraging the flexibility in frame structure and numerology is also one of the key concepts in the 5GCAR demonstrations

[5GCAR-D5.1, Section 3.2.1]. The concepts and results in this TC were also presented in contributions to the 5G NR V2X study and work items in 3GPP Rel-16 (see section 4.1).

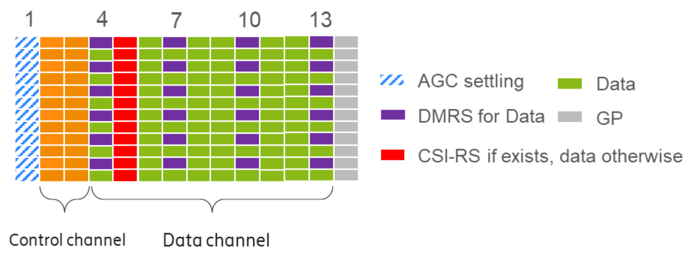


Figure 3-13 A reference design for DMRS and CSI-RS for sidelink V2X

Our reference design is based on a 3GPP New radio (NR) slot of 14 OFDM symbols (OS):

- We assume the automatic gain control (AGC) settling time takes up the first OS, and the GP takes up the last OS in the slot. Two OS are used for the control channel and ten OS are for the data channel.
- Up to 4 DMRS symbols are needed to support very high vehicle speeds. In each symbol, the DMRS subcarriers are comb-interleaved with the data subcarriers. A DMRS symbol are equidistant to the neighboring ones, facilitating hardware implementation.
- In some cases, e.g., at reasonably low vehicle speeds and/or at high subcarrier spacings, less than 4 DMRS symbols can give satisfactory performance. Therefore, multiple DMRS configurations is allowed to maximize the resource utilization. Early decoding of data using the first DMRS is also supported.
- Thanks to the comb structure, multiple DMRS ports can be multiplexed in the subcarrier domain for orthogonalization. They can also be orthogonalized in the code domain using orthogonal cover codes. DMRS from different users use orthogonal sequences.
- In the case of unicast and groupcast, a single CSI-RS can be placed in one of the OS, multiplexed with data or with DMRS.

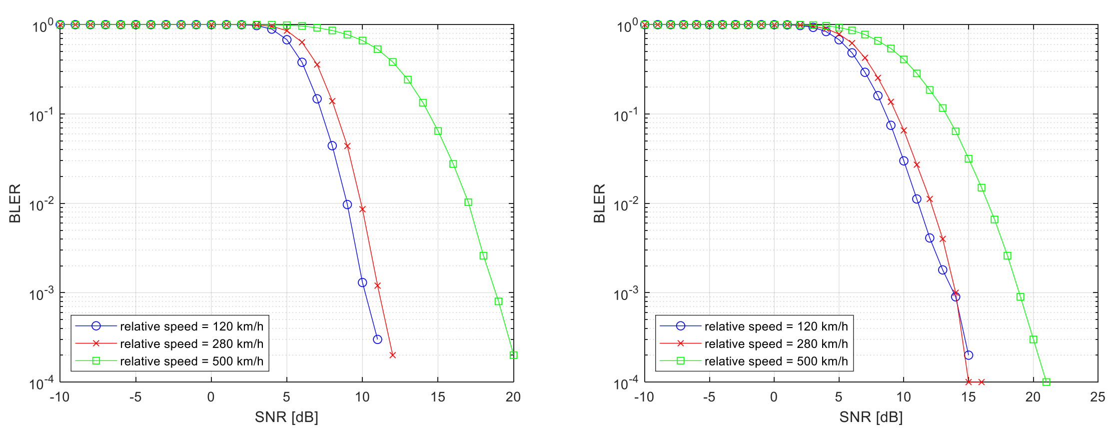
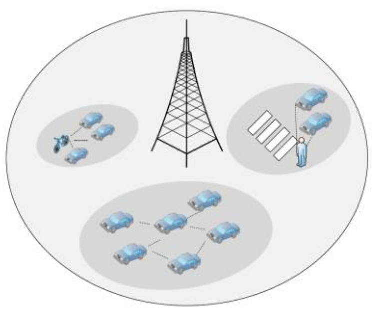


Figure 3-14 Link-level evaluation of DMRS design. 6GHz carrier, 30kHz SCS, 16-QAM, code rate 0.8. Left: line-of-sight channel. Right: non-line-of-sight due to vehicle blocking.

Figure 3-14 shows the performance of the proposed design under various conditions of vehicle speed and coding and modulation scheme (MCS). The evaluation uses the channel models developed in [5GCAR-D3.2]. It can be seen that the proposed design provides good channel estimation for up to 500 km/h relative speed, at high MCS.

3.3.3 Code-Expanded Random Access for Reliable V2X Discovery

System Model	**Main Idea**
 *Network snapshot with vehicles/users in discovery groups* Each vehicle/user is interested in discovering a part of vehicles/users in its close proximity for sidelink communication establishment. The discovery scheme follows the principles of random-access procedure and consists of three sequential phases of message exchange among a transmitting (Tx) vehicle/user, each receiving (Rx) vehicle/user within a discovery distance, and the discovery entity.	Conventional discovery schemes fail to address the stringent requirements in high-mobility and/or dense vehicular environments due to the increased signaling overhead. This TC inherits the advantages of a code-expanded radio access mechanism to address discovery problems in event-based vehicular scenarios. The scheme relies on a discovery entity, i.e., residing at the BS, which gathers information relevant to the proximity of the vehicles, to discover sidelink-capable pairs. The proposed discovery scheme adaptively allocates uplink resources in response to the number of discovery links and allows the discovery entity to obtain full knowledge about the proximity relations in a given area.
Use Cases	**Main Benefits**
The TC primarily addresses use cases where a discovery process is required prior to sidelink data transmission, i.e., (UC1), (UC2) and (UC3). Relevant KPIs are the link discovery probability, the average delay of discovering all links and resource efficiency. A single cell scenario is considered with independent Rayleigh fading channels. Main research challenge addressed: Facilitate highly reliable and timely peer device discovery for V2V communications.	Due to the lower signaling overhead compared to conventional beacon-based V2X discovery, radio resource utilization improves as well as the minimum required latency for discovering all potential links. These benefits can be capitalized in V2X scenarios with high mobility and/or density of vehicles.

Description of Technology Component (TC)

As detailed in [5GCAR-D3.1], the discovery scheme consists of three consecutive message-exchange phases. In the first phase, a preamble is sent by a Tx vehicle/user to its nearby vehicles/users (i.e., its discovery group) via a newly introduced uplink physical channel, coined

V2X-RACH (Random Access CHannel). At a second phase, each Rx vehicle/user (within the discovery distance) listening to the V2X-RACH, upon the reception of the preambles, sends a signature to the BS (discovery entity). The signature generation relies on Bloom filter principles and it is constructed in a way that contains information on the identity (ID) of the Rx vehicle/user as well as on the indices of the preambles received by the activated Tx vehicle(s)/user(s) during the first phase. In the third phase, the BS allocates an uplink resource block for each reported preamble so that Tx vehicles/users which initially sent a V2X-RACH preamble, can report back to the BS revealing their ID. The discovery process is concluded when the BS acknowledges the discovered Tx-Rx pairs by comparing their IDs.

To optimize the discovery scheme, the signature properties, i.e., the length of time slots and the number of required hash functions, are dynamically tuned based on the network load to minimize the false-positive probability, i.e., the probability of an inactive signature being perceived as active by the BS. The preamble collision probability can be also improved by proper spatial allocation of the available orthogonal preambles along the different discovery clusters [KAZ17]. For performance analysis, stochastic geometry tools have been used to derive analytical expressions of fundamental metrics, such as collision probability (at all discovery stages) and link discovery probability. Figure 3-15 illustrates the link discovery probability for different vehicle intensities and discovery distances. It can be observed that discovery performance heavily depends on the traffic load and the maximum discoverable distance of the vehicles. The performance of the proposed discovery scheme was also assessed in Figure 3-16 against beacon-based discovery schemes in terms of minimum required time slots for completion of the discovery process and resource utilization. The numerical results demonstrate the superiority of the proposed discovery process especially in the high traffic load regime where it substantially outperforms the benchmark scheme which suffers from uncontrolled collisions. In addition, allocation of discovery resources is performed in response to the number of discovered pairs, thus preventing the underutilization of the scarce radio resources due to beacon collisions and false-positive signatures.

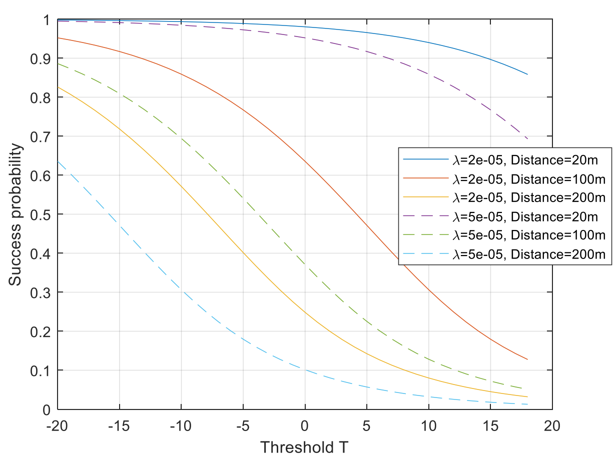


Figure 3-15 Link discovery success probability for various vehicle intensities and discovery distances.

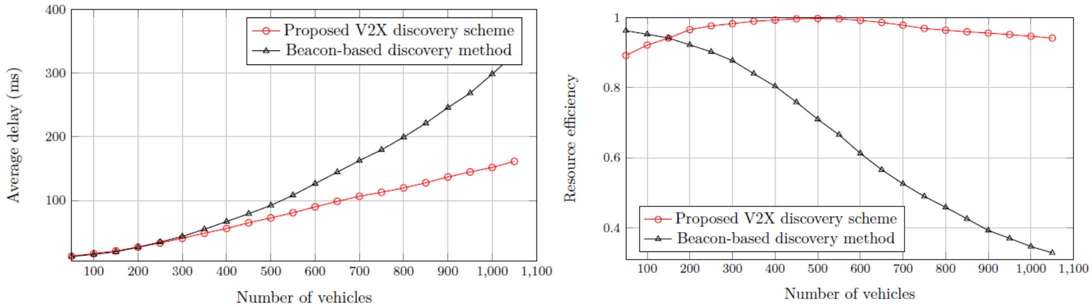


Figure 3-16 Improvements in terms of average latency and resource efficiency against beacon-based discovery.

3.4 Full Duplex

In-band full duplex (FD) communication (simultaneous transmission and reception over the same frequency band) has the potential of double the throughput, and half the latency in theory. In addition, full duplex sensing and transmission will enable the wireless transceivers to detect other interfering simultaneous transmissions and avoid the long collision durations accordingly. The main challenge in implementing full duplex technology is cancellation of the strong self-interference from the transmitter to its own receiver, which has been made possible recently.

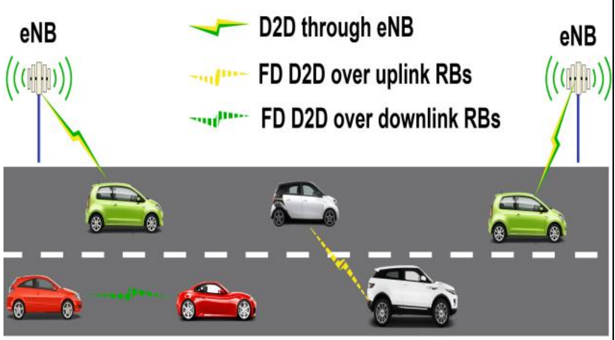
Unlike the majority of mobile devices, vehicular on-board units are good candidates to host complex full-duplex transceivers because of their virtually unlimited power supply and powerful processing capacity.

Bilateral full duplex communication is a D2D connection between two nodes which require a low latency channel for transfer of real-time information. Section 3.4.1 proposes a cognitive scheme for an autonomous FD D2D connection in a 5G network. In this scheme, V-UEs may access the Resource Blocks which are not dedicated for D2D connections according to 3GPP Rel-14 and Rel-15 standards (Modes 3 and Mode 4).

Section 3.4.2 proposes a method for detecting the collision of Cooperative Awareness Messages (CAMs) in a V2X-5G network, and a cross layer MAC protocol for a prioritized system of messaging. Although connections in Mode 3 or Mode 4 in V2X-5G result in lower probability of collision of CAM messages, the number of collisions in a dense vehicular network would increase considerably. The FD sensing and transmission method proposed in section 3.4.2 detects such incidences and takes the appropriate action based on the priority of messages in collision, according to the cross-layer MAC protocol.

And finally, section 3.4.3 illustrates the general benefits of application of FD technology in a vehicular network in terms of increased bandwidth and decreased latency.

3.4.1 Cognitive Full Duplex Communications in V2X networks

System Model	Main Idea
 Red cars are in the coverage area of a BS or gNB and white cars are out of coverage area of any gNBs. *Bilateral full duplex communications between two cars over downlink or uplink channels of a 5G network in an autonomous D2D manner.* A cognitive scheme for full duplex D2D communication of two secondary users (cars) over downlink or uplink channels of a 5G cellular network is proposed. In this scheme, D2D connection is autonomous without any control or involvement of 5G network.	Two cars which decide to establish a bilateral D2D communication check their distance periodically through a beaconing protocol. If in proximity area, they will consider a direct full duplex D2D communication, otherwise they will establish their indirect connection through 5G cellular network. Secondary users (SUs) will detect the available downlink or uplink channels in a cognitive manner. If at least one of the SUs is in the coverage area of a gNB, then the D2D connection would be over available downlink resources. Otherwise, SUs will use uplink channels in order to cause less interference to cellular users. The secondary users (D2D connection pair) will be informed of the return of any primary users through error detection method. Such incidence will force SUs to switch to another available channel.
Use Cases	**Main Benefits**
Bilateral exchange of real-time data between a pair of vehicles, such as in infotainment or security forces (police). Interconnection between vehicles in a platoon of driverless or semi-driverless vehicles.	Providing a high speed and low latency D2D connection between a pair of vehicles in a V2X network. Less interference than conventional underlay D2D methods.

Description of Technology Component

Full Duplex technology is a promising answer to the demand of high speed and low latency D2D connections in vehicular networks. In addition, it improves the reliability and timeliness of V2V safety messages by counteracting direct collisions. In D2D mode, vehicles in close proximity communicate directly, which eventually decreases the latency and offloads the traffic from gNBs.

A cognitive full duplex scheme for D2D communications between two cars over the unoccupied downlink or uplink cellular resources is considered. Peer discovery and range estimation is carried out through periodic beaconing by the two cars (secondary users) in question, and spectrum sensing, and selection is carried out cooperatively to minimize collision and interference to cellular users (primary users). As detailed in [5GCAR-D3.1, Section 3.3.9], the vehicles may operate over uplink or downlink resources of a 5G system. Awareness of a primary user's signal appearance is acquired through collision event and resulting error in D2D communication. It is shown that the size of transmission frame in terms of number of included packets has a considerable effect on the probabilities of false alarm and detection.

In addition to the results presented in [5GCAR-D3.1, Annex B14], the effect of frame size on probabilities of false alarm and detection and D2D connection throughput, for the same system model and simulation scenario as in [5GCAR-D3.1, Section 3.3.9] are presented.

Illustrative Numerical Results

Figure 3-17 (left) depicts the probability of detection and false alarm of the proposed scheme based on error detection in FD D2D transmission mode against number of packets in each frame. As it is seen, when the frame length increases, and error detection is carried out over more packets, detection probability increases, and false alarm probability decrease. Figure 3-17 (right) shows the effect of the self-interference suppression (SIS) factor on these metrics. We see that poor SIS capability (more residual self-interference) results in poor detection and false alarm probabilities.

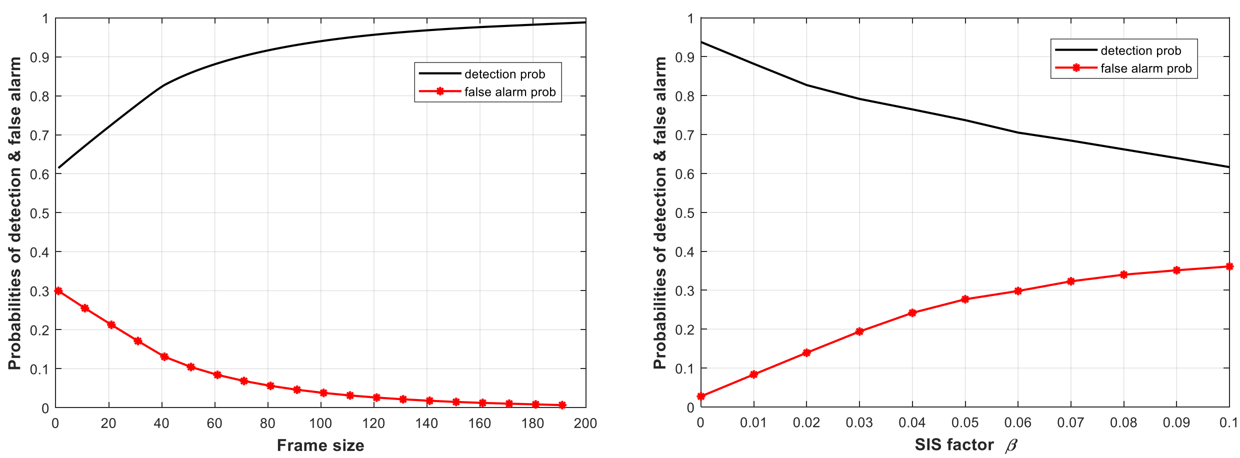


Figure 3-17 Probabilities of detection and false alarm vs. frame size of D2D communication (left) and vs. SIS factor (right)

Figure 3-18 (left) shows the normalized average throughput of FD D2D communication against SIS factor. With more residual self-interference the detection probability decreases, and false alarm probability increases, which means more collisions and more lost transmission opportunities. In addition, we see that increasing number of packets in a frame will improve the throughput slightly when SIS is poor, as depicted in Figure 3-18 (right).

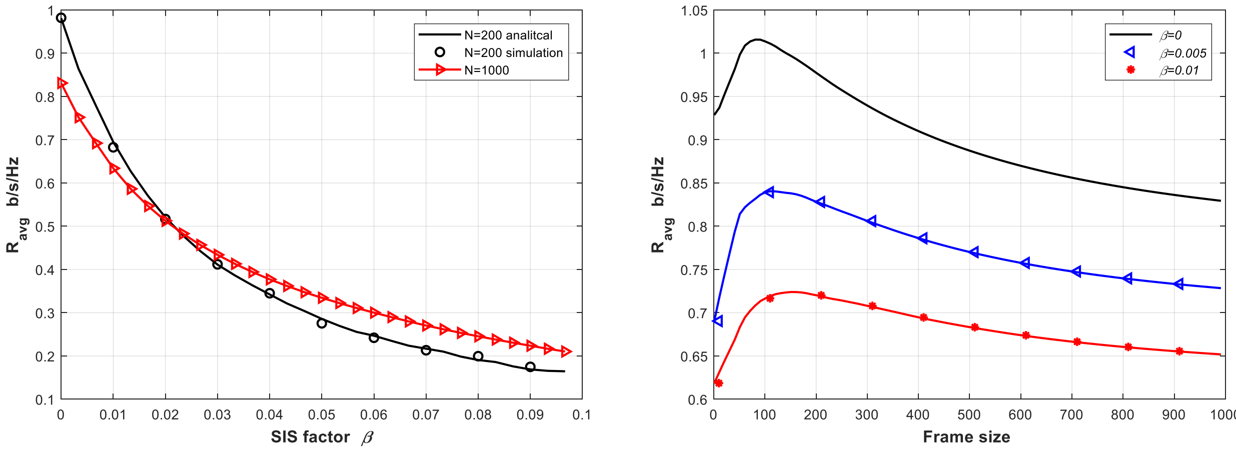
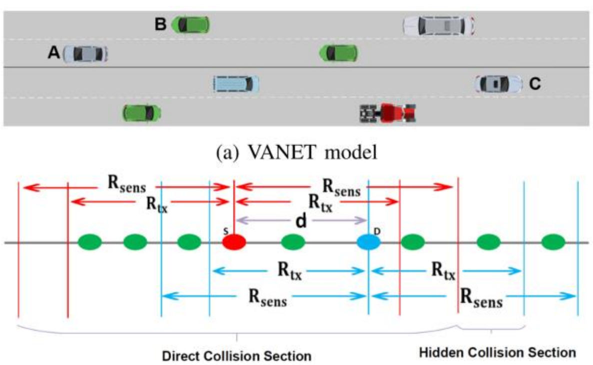


Figure 3-18 Normalized average throughput of full-duplex D2D communication vs. SIS factor (left) and vs. number of packets in each frame (right).

3.4.2 Full Duplex Collision Detection in V2X Networks

<table>
<tr><th>System Model</th><th>Main Idea</th></tr>
<tr><td>


A Vanet model and analysis of sensing and detection ranges based on positions of vehicles.

Full Duplex transmission and sensing in order to detect and avoid any probable collision between messages of two or more vehicles.

In this work FD capability of OBUs in simultaneous transmission and reception has been exploited for detection of any collision of broadcast messages of vehicles, and a cross layer MAC protocol has been proposed to avoid such collisions and guarantee the delivery of important messages with higher priorities.
</td><td>
A vehicle broadcasting periodic safety messages, may be able to detect and other concurrent transmission provided that it has FD capability of simultaneous transmission and reception.

Upon detection of any collision, the vehicle may take different actions to avoid it. In a system where messages are classified with different priority levels (e/g/ emergency, normal), the action should be in favor of higher probability message delivery, and interruption of lower priority ones.

In this model, four levels of priorities have been considered and a novel cross layer protocol, utilizing FD capability of OBUs have been proposed which will make proper decision in a very short time since a collision happens.
</td></tr>
</table>

Use Cases	Main Benefits
Detection and avoiding any collision of CAM messages in a dense or semi-dense vehicular network.	Avoiding long collisions and loss of safety information vital for a safe vehicular network.
Prioritized system of Messaging in a vehicular network.	Increased network throughput, and shorter waiting times.

Description of Technology Component

We consider a VANET in which vehicles will broadcast CAMs periodically with CAM repetition interval tCAM. All vehicles are equipped with FD capability. The transmission range (Rtx) is less than sensing range (Rsens) of each vehicle in order to minimize the probability of collisions due to hidden nodes.

In order to cope with the priority issue between different vehicles, we propose a novel MAC protocol called priority based multiple access (PBMA) mechanism. Similar to the Enhanced distributed channel access (EDCA) mechanism, CAMs are categorized into four types - emergency message of type 1 (Me1), emergency messages of type 2 (Me2), normal update messages of type 1 (Mn1) and normal update messages of type 2 (Mn2). Me1 messages have the highest priority and Mn2 messages have the lowest priority. The operation of the proposed PBMA protocol is as follows:

When a CAM is generated at a generic node, same as legacy HD EDCA protocol, it first probes the medium for tsecs time to determine whether the channel is busy or idle. If the channel is idle, CAM is broadcasted immediately in a FD manner, (TS mode). Otherwise, it defers its transmission of a random delay (the backoff process). After each successful transmission, the vehicle has to wait for another tslot duration before sending the next frame, known as the guard interval. However, if the total waiting time goes beyond the CAM repetition interval, tCAM, the vehicle will start the contention process for the new frame instead of waiting for the guard interval time. Collision happens when other vehicles generate a packet or finish the backoff process at the same time. Unlike HD EDCA mechanism, CD capability is enabled. So, vehicles that have Me1 and Me2 CAMs would not initiate backoff process immediately. Instead they will re-attempt to transmit in the following time slot. If another collision is detected, vehicles with Me2 CAM will go through a backoff process and vehicles with Me1 CAM will re-attempt for one more slot before it goes to the backoff process. Such a mechanism is depicted in Figure 3-19.

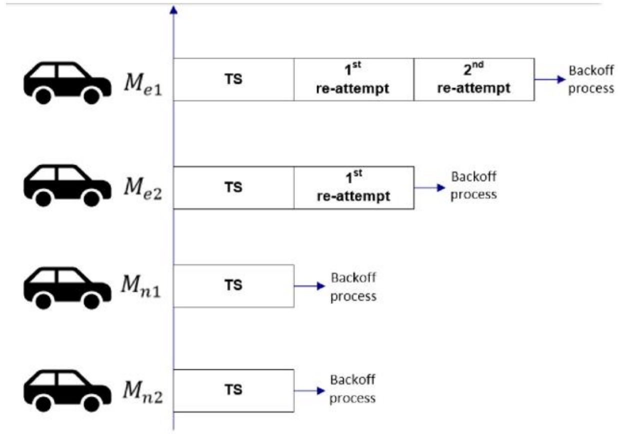


Figure 3-19 Transmission process of PBMA mechanism

Illustrative Numerical Results

Figure 3-20 (left) shows the effect of residual SI on the probabilities of detection and false alarm. When the self-interference cancellation (SIC) factor η increases, false alarm probability increases too. In order to achieve detection probability to be at least 90% and false alarm probability to be at most 10%, our model would have acceptable performance when SIC factor is less than 15%. In other words, our system does not operate only when SIC is extremely well, it works quite acceptable when SIC is relatively poor.

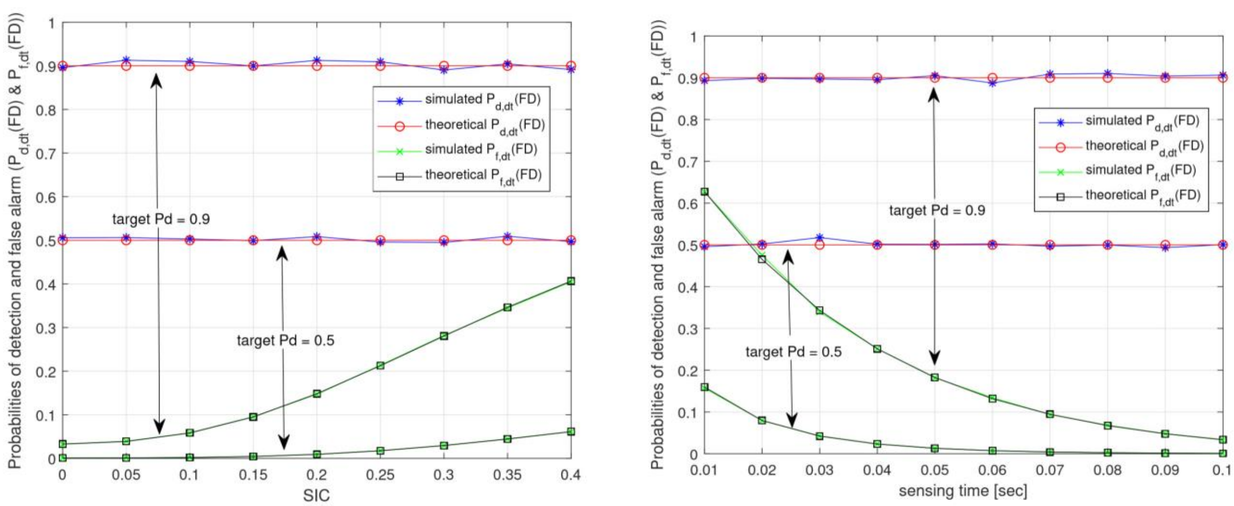


Figure 3-20 Probabilities of detection Pd,dt(FD) and false alarm Pf,dt(FD) vs. SIC factor η (left) and vs. sensing time (right)

Figure 3-20 (right) shows the impact of the sensing time on the precision of detection. The longer the sensing time is, the lower chance the system would wrongly alarm an impending collision. This is because we are measuring and averaging the received energy over a longer period of time, which gives a more accurate detection result.

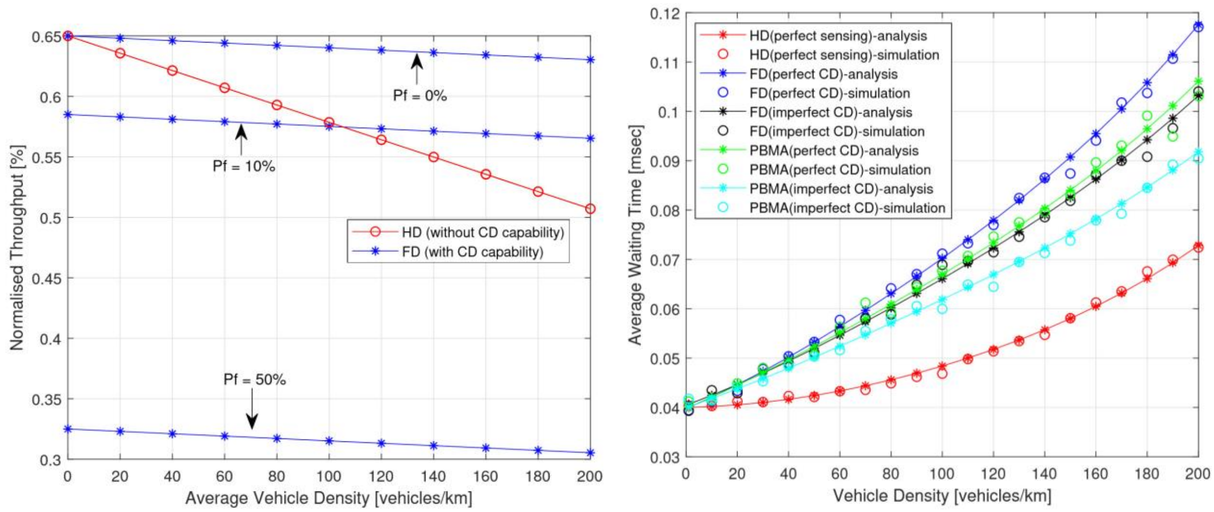
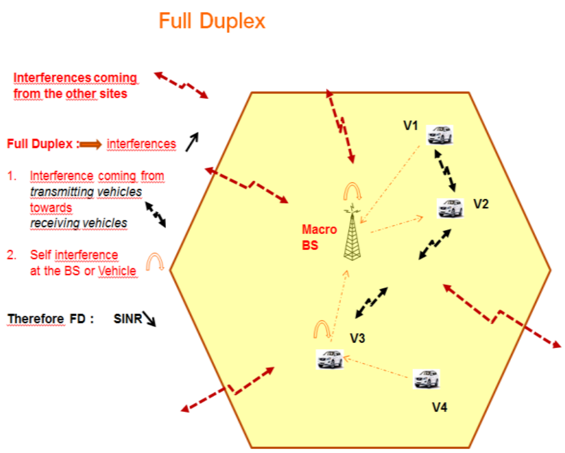


Figure 3-21 (Left) Normalized throughput vs. average vehicle density under different probabilities of false alarm. (Right) Waiting time VS average vehicle density

Figure 3-21 (left) demonstrates the normalized throughput of the system. With perfect detection and no false alarms, the proposed system always offers a better performance over HD systems without collision detection. However, when there are some instances of false alarm, throughput would be less than a HD system for low density networks. Thus, in terms of throughput only, we see a trade-off between HD and FD modes.

Figure 3-21 (right) show the relationship between waiting time and the density of vehicles. As it is seen, the average waiting time for a message to be transmitted is considerably less in the proposed system, compared to that in a HD system without collision detection.

3.4.3 Full Duplex Impact on V2X Performance

<table>
<tr><th>System Model</th><th>Main Idea</th></tr>
<tr><td>


We consider a network environment where users (UEs) and Vehicles use the available uplink (UL) and downlink (DL) radio resources, Both UEs and Vehicles transmit data simultaneously. Vehicles and UEs use the same frequency bandwidth. A high density of vehicles is considered. Vehicles transmit towards vehicles, and one user transmits towards the BS, simultaneously on the same frequency, at each instant. V2V connections exist if a given SINR threshold is reached at each vehicle. The power and the SINR received by a Vehicle/UE depend on the distance between the transmitter and the receiver.
</td><td>
V2V transmissions are done using the Full Duplex (FD) Mechanism.

Full Duplex: a given frequency resource is used for DL and UL transmissions simultaneously.

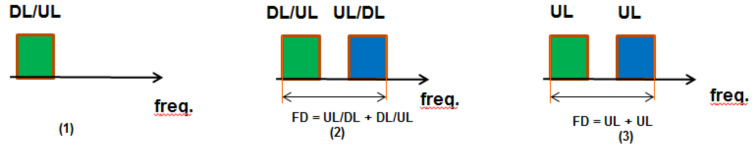
V2V case: FD can be used to allocate the same resources to vehicles, for receiving and transmitting data simultaneously.

However, there is an increase of interferences due to self-interference induced by FD mechanism. Therefore, SINR are lower than for a standard system.
</td></tr>
</table>

Use Cases	Main Benefits
All uses cases. The full duplex mechanism may be used to improve the performance (throughput, delay…) or to improve and optimize the frequency bandwidth allocation to UEs and Vehicles.	FD makes it possible - to improve the available frequency bandwidth allocated to UEs and vehicles, - to improve performance (throughput, delay, outage probability). - to optimize the use of the frequency bandwidth. These benefits can be implemented in V2V or V2X scenarios, in particular with high vehicle density. Consequences - A given frequency bandwidth can be allocated for UL and for DL (1) - Resource allocation may become more dynamical (2) - A wide frequency bandwidth can be allocated to a user (3)

Description of Technology Component (TC)

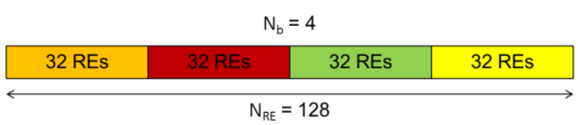
In FDD case, a transmitter uses a given frequency to transmit data, and simultaneously it can receive data on another frequency bandwidth. The Full Duplex mechanism allows a transmitter to receive and transmit data simultaneously, on the same frequency bandwidth. However, the FD mechanism induces self-interference that can dramatically affect performances. Indeed, due to this self-interference, the SINR is lower than in a half-duplex case and therefore the reachable throughput also. As a consequence, this mechanism must be used only with "advanced receivers" since these receivers are able to mitigate the self-interference. In half-duplex, there is a frequency bandwidth dedicated to UL transmissions, and another frequency bandwidth dedicated to DL transmissions. Since the FD mechanism makes it possible to use the same frequency bandwidth in UL and DL (1), the resource allocation may become more dynamic (2): Vehicles and UEs can use a UL resource, or a DL resource, to transmit and to receive data. Moreover, a wide frequency bandwidth can be allocated to a Vehicle/UE (3). Indeed, Vehicles and UEs can use the whole available frequency bandwidth UL+DL, to transmit or to receive data. Therefore, the frequency bandwidth use can be optimized.



3.5 Reliability Enhancement

Several use cases of connected automated driving build on the 5G URLLC service, which is capable of providing highly reliable communication links. There exists a fundamental trade-off between reliability, latency and throughput, suggesting that high reliability increases the demand in bandwidth and thus decreases the bandwidth efficiency, as elaborated in [SMP+14]. The bandwidth requirements can be balanced, however, if channel diversity can be made available and properly exploited in the signal transmission. The larger the degree of diversity utilized, the better the bandwidth efficiency (for a fixed reliability), or the better the reliability (for a fixed bandwidth), respectively. The utilization of channel diversity is therefore seen as the key for enhancing the reliability in radio communications, which is addressed by the first three TCs in this chapter (section 3.5.1 – 3.5.3). Further means for attaining high reliable communication at reasonable bandwidth costs are on-demand retransmissions of information, where retransmissions are requested only if previous transmissions have not been successful, yielding an overall reliability given by the product of the reliabilities of each transmission. In this respect, the TCs presented in section 3.5.2 and 3.5.3 apply retransmissions to make channel diversity from independent V2X communication links available, whereas the TC in section 3.5.4 uses a retransmission scheme for control information to improve the bandwidth efficiency of the control channel.

3.5.1 Fundamental Tradeoff between Latency and Reliability

System Model	Main Idea
 We consider coded transmission over a block fading channel model, where each block of symbols experiences the same fading coefficient. The maximum number of resource elements within a block is a parameter depending on how fast the channel is changing. The block fading model is also appropriate for frequency hopping, antenna switching, or precoder cycling.	It is known that there exists a trade-off between latency and reliability. The idea is to understand this trade-off from the theoretical perspective and optimize the channel coding and modulation parameters accordingly. The aim is to obtain general design guidelines for coded modulation schemes according to the channel fading characteristics, ensuring high reliability with a limited latency. The obtained design guidelines are then used to improve actual coded modulation schemes.
Use Cases	**Main Benefits**
The solution targets use cases requiring highly reliable communications, which may also entail strict latency constraints. Hence, it particularly applies to UC 4 & 5.	Understanding the fundamental diversity limits of block fading channels and obtaining design guidelines for coded modulation schemes supporting URLLC.

Description of Technology Component

According to Shannon's channel coding theorem, obtaining a vanishing error probability at the receiver is only possible if the message is transmitted with a rate *R,* smaller than the channel capacity which is the ultimate bound on the information rate on a given channel. However, this bound can only be achieved for asymptotically large codeword length and hence infinite delay. For finite length transmission (i.e. finite delays), one needs to lower the rate, or accept a certain decoding error probability, which forms a fundamental trade-off between reliability and latency. This trade-off has been a very important topic for researchers since Shannon's channel coding theorem, but recently there has been an increased interest in this topic. For example, [PPV10] shows bounds on the achievable rates for finite block lengths and gives tight approximations for these bounds. These results are further extended to the case with feedback in [PPV11] and to MIMO in [YDK+14]. In this project, we first derived optimal design parameters for higher order modulation using the tools from [PPV10], and then evaluated the performance for 5G NR channel codes.

If bit-interleaved coded modulation is considered, the rate can be formulated as $R=mR_c$, where m is the modulation order, indicating the number of bits per symbol (e.g., m=2 for QPSK) and R_c is the binary channel coding rate. Accordingly, the same rate R can be obtained by using different combinations of m and R_c. For example, QPSK with R_c=1/2 and 16-QAM with R_c=1/4 both results in R=1 bits/use, but their trade-off between latency and reliability may be different, making the combination of coding rate and modulation order a system design parameter to meet the desired tradeoff.

Main Results

Both the theoretical investigations and our simulation results using 5G NR polar codes reveal that higher-order modulation is required already for relatively small data rates in order to fully exploit the diversity of the block fading channel.

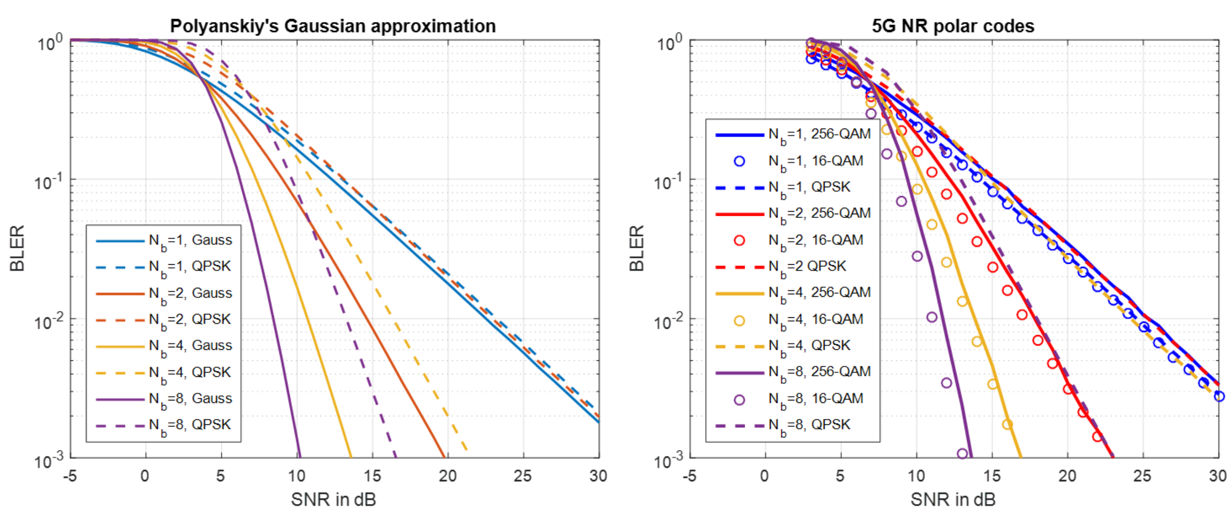
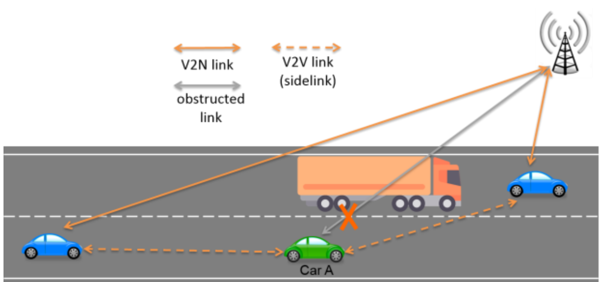


Figure 3-22: Block error rates for transmission of 192 info bits in 128 REs (R = 1.5 bit/use) over N_b Rayleigh fading blocks. Theoretical results (left) and 5G polar codes (right).

Figure 3-22 shows an example for R = 1.5 bit/use. The theoretical results based on the finite length approximation from [PPV10] demonstrate that Gaussian codebooks do not only provide a shaping gain compared to QPSK, but also lead to a significantly higher slope of the BLER curves. This is verified for practical higher-order modulation schemes and 5G NR polar codes. For the considered scenario, the best performance is achieved using 16-QAM with R_c=3/8. A proper choice of the coding and modulation scheme is essential to meet the high reliability requirements of URLLC services in fast time-varying V2X scenarios, which do not allow for channel-aware resource allocation and need to rely on diversity instead.

3.5.2 Enhancing V2N Reliability by Sidelink Cooperation

System Model	Main Idea
 Vehicles moving on a highway are connected to a common BS. All vehicles maintain a V2N connection to that BS as well as V2V links to the vehicles in the vicinity. The V2N link to car A may be blocked by a bypassing trailer. V2V links are modelled as independently Rayleigh fading. The BS multi-casts packets dedicated for car A to car A and its neighbors, allowing car A to request retransmission from its neighbors in case its V2N link is blocked.	1. If the V2N link to a target user gets blocked, reliable packet reception can be attained if retransmissions are carried out via independent radio links. 2. Neighboring cars can make these independent radio links available by forwarding packets dedicated to car A via the sidelink to that car A. 3. A larger degree of diversity provided by the independent V2V links can be utilized if neighboring cars cooperatively forward packets received from a multi-cast transmission from the BS. 4. The current work analyses the reliability gains attainable for an increasing number of cooperating cars and for one and two retransmissions via the sidelink.
Use Cases	**Main Benefits**
The solution targets use cases requiring highly reliable V2N communications, which may also entail strict latency constraints. Hence, it particularly applies to UC 4 & 5. Addressed challenges: a) Meeting latency and reliability requirements of future V2X services; b) Increase the reliability of sidelink comm.	1. High reliability at moderate costs of resources yields high bandwidth efficiency for URLLC services. 2. Works especially well at high-load, where many neighbors are available and bandwidth efficiency is a must.

Description of the technology component

Cooperative packet retransmission by multiple users via the sidelink enables to utilize the spatial diversity offered by the numerous V2V links in a highway scenario for improving the overall reliability of a V2N data transmission at moderate cost of transmission resources. Suitable means for utilizing the spatial diversity in this context are spatial diversity transmission schemes applied in a distributed fashion, such as distributed space-time block codes (STBCs) [LW03] or cyclic delay diversity (CDD) schemes [DK01]. Those schemes enable a constructive addition of signals that propagated via individual communication paths at the receiver, while the same time/frequency resources can be used for the redundant retransmission of identical data by different users. Additional resources need to be spent only for additional pilot symbols required to allow the receiver to estimate the channel constituted of the individual V2V links. Using distributed STBCs or CDD is thus an efficient solution in this scenario for a resource-sparing retransmission of data traffic attaining high reliability.

Illustrative Numerical Results

Detailed analysis and evaluation results can be found in [SS19]. The reliability is reflected by the error event, which occurs if car A cannot receive the packet after cooperative retransmissions, which may be either due to an outage of the compound channel (i.e. the effective channel gain lies below a certain target value), or due to the fact that neighboring cars did not transmit as they did not receive the multi-cast packet from the BS (the probability for a multi-cast packet loss is set to 5%). All V2V channels are assumed independently Rayleigh fading; firstly, with equal average power. Moreover, a total transmission power constraint for the cooperatively transmitting users is assumed.

Figure 3-23 (left) shows the error event for one and two retransmissions, respectively, and for the single frequency network (SFN) reference case. The SFN reference system shows a saturation behavior, as it cannot realize diversity gains from user cooperation. While the reliability for a single retransmission is poor, HARQ can improve it by roughly two orders of magnitude. The cooperative scheme, however, shows that the error event continuously scales with the number of cooperating users n, achieving one order of magnitude per user for the HARQ case. The curve for ARQ exhibits a slope that is less steep than that of HARQ, which reflects the reduced diversity order realized by ARQ compared to HARQ. Comparing to a single retransmission (rtx), 2 rtx HARQ provides a gain of one order of magnitude for n = 4 users, which increases to two orders of magnitude for n = 7 users.

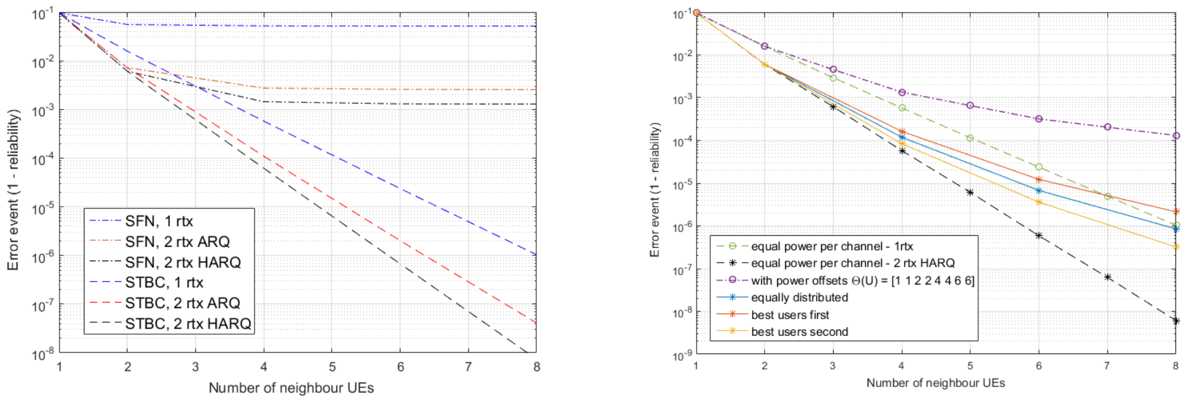
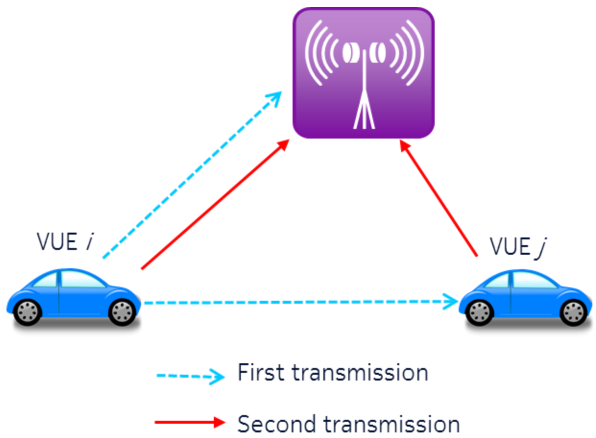


Figure 3-23 Improvement of the reliability by cooperative transmission of neighbor UEs (left) with equal average channel power (right) with power offsets.

Figure 3-23 (right) demonstrates the error event for a single retransmission as well as 2 retransmissions with HARQ considering different power offsets for the users. The vector of power offsets (= path loss) for the total set of users U (comprising all n users) is given by $\Theta(U) = [1; 1; 2; 2; 4; 4; 6; 6]$. Evaluation of these power offsets for a single retransmission (1 rtx) shows that these obviously cause clear performance degradations compared to the reference case of equal power per channel, yielding a loss of more than two orders of magnitude for $n = 8$ cooperating users. The cooperative HARQ scheme is evaluated based on two types of clustering strategies; one, where the n UEs are evenly distributed among the two subsets according to their power offsets, and second, where one subset contains the strong UEs (i.e. the n/2 UEs with smallest power offsets), and the other subset contains the weak UEs (i.e. the n/2 UEs with largest power offsets). Comparing the different cases of user clustering, it is observed that the best performance is attained if the strongest users transmit second. This can be attributed to the fact that the users in the second set have received the original packet with higher probability (as they were able to listen to the first retransmission), and hence their likelihood to retransmit is significantly increased. Since the strongest users have better channels than the others, the higher probability for transmission results in an improved reliability. Finally, we note that the performance degradation for two HARQ retransmissions with this user grouping, compared to the reference case of equal power per channel, amounts to significantly less than two orders of magnitude, exhibiting a clear advantage over a single retransmission also in this respect.

3.5.3 Sidelink Assisted Reliable Communication

System Model	Main Idea
 It is assumed that V-UE *i* and *j* have discovered each other and agreed as V-UE pairs. Due to the short distance between these two vehicles and better propagation channel conditions (comparing to Uu interface), V-UE *j* can be used as a diversity path for V-UE *i*. The received signals at BS can be combined together to achieve diversity gain both in time and spatial domain and increase the overall reliability. Figure above shows the case of UL, but similar concept can be applied to DL as well.	Diversity (time/frequency/space) plays an essential role to increase communication reliability and some schemes, e.g. PDCP layer duplication, have been specified in 5G NR already. In our study, we provide a method to achieve reliable Uu communication with the help of sidelink. In detail, with the assumption that the discovery phase is completed, V-UE *i* and V-UE *j* form as one group (allocated with unique group ID e.g. group RNTI). Once V-UE *i* has UL data to send, the allocated or configured resource information is decoded at both V-UEs in such a way that V-UE *j* can receive the data packet from UE *i* as well. In case the first transmission is not successful, gNB will allocate retransmission resource to V-UE *i* as the regular operation. The difference comparing to regular operation is that gNB will also allocate UL resource to UE *j* for forwarding the received packet from UE *i*. In this way gNB can combine the received packets from both V-UEs to enhance the overall reliability.
Use Cases	**Main Benefits**
Improved KPI: overall V2N/V2I reliability and latency (in case retransmission is needed) Applicable use case: UC 1, 4, 5	Sidelink acting as one diversity branch to increase the overall reliability.

Description of Technology Component

Assume that the two V-UEs have already discovered each other and formulated as one pair with the allocated group ID for example SL_RNTI (sidelink RNTI). The core of the proposed concept is that: taking the example shown in the figure in above table, assuming that V-UE *i* has UL data packet for transmission, with the same transmission both gNB and V-UE *j* will receive the same data packet from V-UE *i*. In case of a failed data detection, gNB can allocate resources for retransmission to both V-UE *i* and V-UE *j*. Therefore, both V-UE *i* and V-UE *j* can send the packet to gNB. Clearly the benefit is the reduced latency for retransmission in case more than one retransmission is needed and increased reliability which is one important performance indicator for URLLC. More detailed description of the signaling can be found in [5GCAR-D3.1].

Illustrative Numerical Results

System level simulation was carried out in order to investigate the benefits from the proposed concept. Taking the agreed highway scenario as described in [5GCAR-D3.1], in our simulation, 3 BSs are deployed along the highway. Traffic model is assumed to be periodic traffic with packet length of 160 bytes. ITU-Veh-A fading channel [3GPP-38885] is adopted in our simulation, system bandwidth is 10MHz at 2GHz center carrier frequency. Taking packet loss rate (i.e. the ratio of the packet cannot be delivered correctly after HARQ retransmission) as one example, Figure 3-24 illustrates the packet loss performance with different number of V-UEs. The comparison is between the case of with and without SL assistance, where the gain due to the SL assistance can be clearly seen.

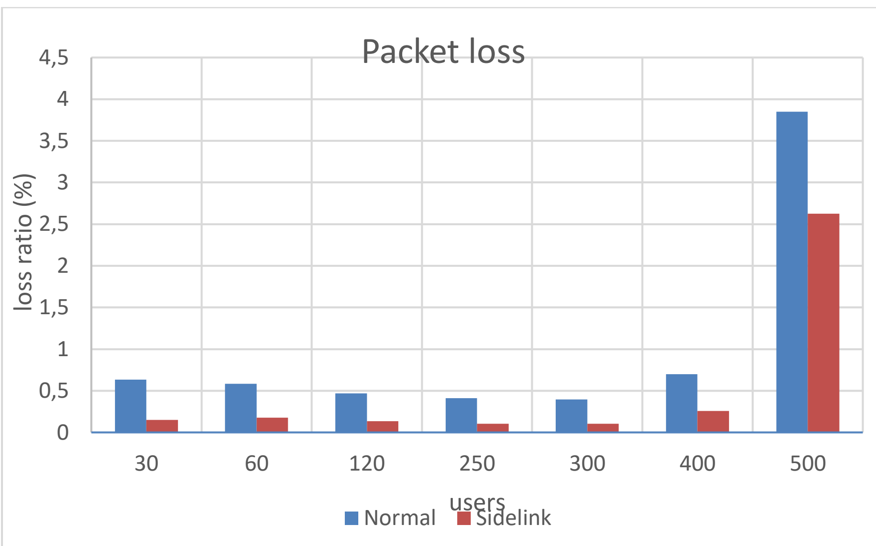
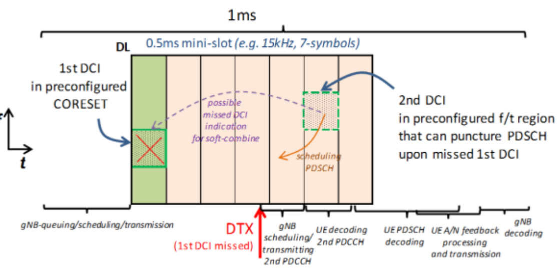


Figure 3-24 Performance of sidelink assisted reliable communication

3.5.4 Enhancing Control Channel Reliability by Using Repetitions

<table>
<tr><th>System Model</th><th>Main Idea</th></tr>
<tr><td>

We consider the scheduling and transmission of a URLLC message between two vehicles or a base station and a vehicle. The goal is to ensure the required reliability of control channel even for one-shot data transmission.</td><td>Relax BLER target of control transmission by transmitting the control message twice ('initial' and 'auxiliary' control transmission).

To support one-shot URLLC transmission, the auxiliary message punctures other data transmissions that occur at the same slot with the URLLC transmission.</td></tr>
<tr><th>Test Cases</th><th>Main Benefits</th></tr>
<tr><td>This technology component targets use cases requiring ultra-reliable V2X communications, with very low latency constraints. It particularly applies to UC 5.

Addressed challenges: a) Meeting simultaneous requirements on low latency and high reliability; b) Increase the reliability of sidelink unicast communications.</td><td>1. Less control resources needed. This reduces control channel blocking probability and control overhead.
2. Possible to relax data reliability target, leading to improved URLLC data throughput.
3. One-shot URLLC data transmission can be supported when inadequate control resources are available.</td></tr>
</table>

Description of Technology Component

URLLC data transmission may often be required to be one-shot, mainly to satisfy the stringent latency requirements; for example, a) in case of large queuing delay in high URLLC traffic load, b) to reduce URLLC preemption impact to eMBB, c) when there is large frame alignment delay in non-dynamic TDD, d) in case of last retransmission/repetition with no possibility of combining with previous transmissions, or e) to improve power consumption. The currently considered features on control channel design are either not enough (e.g. compact DCI [3GPP-38824]) or inefficient (overprovisioned control resources, e.g. higher aggregation level) to satisfy the performance requirements in that case.

The main idea is to relax BLER target of control transmission by transmitting the control message twice ('initial' and 'auxiliary' control transmission), where the auxiliary message punctures other data transmissions that occur at the same slot with the one-shot URLLC transmission. To relax overprovisioning of control resources due to the dual transmission, we can consider ACK/NACK feedback signaling for the auxiliary message to transmit it opportunistically only after initial message is missed. We examine two cases of puncturing: a) own URLLC data transmission; b) eMBB data transmission, in case URLLC/eMBB dynamic resource sharing is enabled. More details can be found in [3GPP-R1-1806958] and [3GPP-R1-1900680].

Benefits of opportunistic dual control

The reliability with the dual control approach when puncturing own URLLC data, without considering combining of the initial and auxiliary messages, can be given by:

$$R = R_{c1}R_{ACK}R_d + R_{c1}(1 - R_{ACK})R_{d*} + (1 - R_{c1})R_{DTX}R_{c2}R_d \tag{1}$$

where R_{c1}, R_{c2} and R_d denote the probability of successful initial control, auxiliary control and data transmission, respectively; R_{DTX} denotes the probability of receiver detecting DTX when initial control is missed. R_{ACK} is the probability of successful ACK for initial control, and R_{d*} is the probability of successful punctured data transmission. Comparing with a single control transmission approach which can achieve a BLER 10^{-5} target for a URLLC communication, we can observe that control repetition has the advantage that control (and possibly data) channel BLER target can be relaxed. Table A-4 in Annex A.6 analyzes these benefits in more detail for the DL case; however, similar observations apply also for sidelink control.

A direct result of the control channel BLER relaxation is that less control resources will be required. Comparing the average CCE usage per slot of the dual with the single control transmission approach (where reliability of control channel is guaranteed by always using a big chunk of control resources) we can expect a significant reduction when the first approach is used. In an example given in Annex A.3 for the DL channel, we can observe that a saving of about 75% on control resources is possible compared to the case of overprovisioning PDCCH.

Impact of puncturing

The puncturing of data transmission from auxiliary control will reduce the decodability of the former. The problem in case of puncturing the own one-shot URLLC data is even more delicate due to the also extremely strict BLER target of the data channel (e.g. <10^{-5}). Below, link level simulation results evaluate the puncturing impact in DL, showing that small auxiliary DCI can be a viable solution. We also investigate the case of puncturing eMBB data instead which results into insignificant impact. Further details and observations on simulations can be found in Annex A.6.

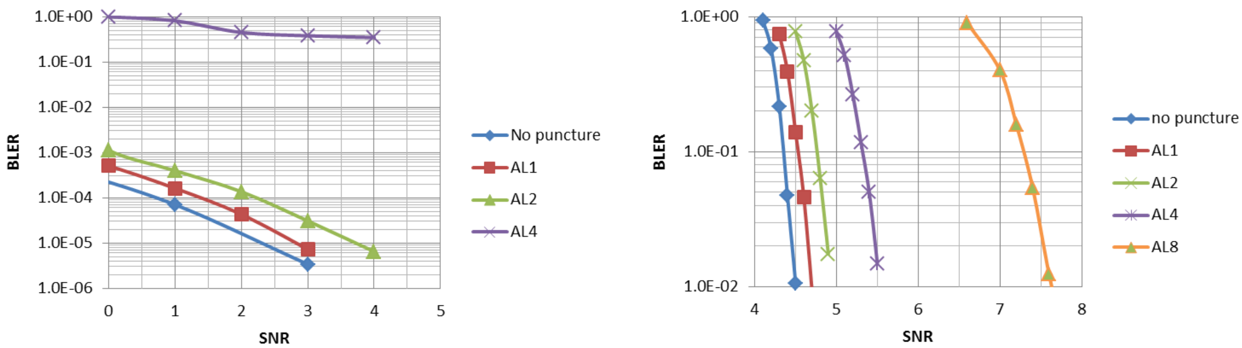


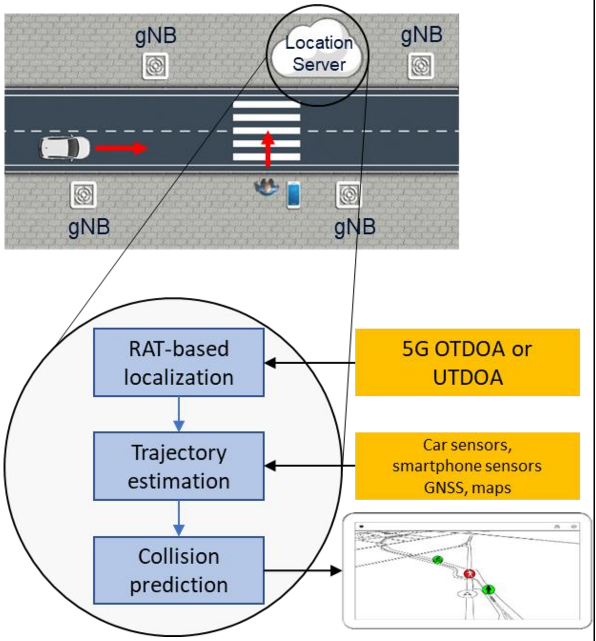
Figure 3-25 Impact of auxiliary control puncturing: left) own URLLC data; right) eMBB data.

3.6 Positioning

One of the key objectives of 5GCAR is to introduce features in the New Radio air interface that enable highly accurate and ubiquitous real-time positioning and tracking of road users which is a crucial requirement and enabler for many V2X use cases. Due to the importance of the topic 5GCAR has delivered a separate report [5GCAR-D3.2] where all details of the respective Technology Components can be found. Aim of this section is to give a summary of the investigated methods and an update of the achieved results.

While positioning in LTE is based on time measurements only, most 5GCAR approaches integrate enhanced time measurements with angle measurements. This becomes possible through smaller antenna array sizes in the frequency range above 6 GHz. In [5GCAR-D3.2] we have shown that the desired accuracy below one meter is in principle achievable. By rule of thumb this corresponds to an improvement of one order of magnitude with respect to the reference cases LTE and GPS.

3.6.1 Trajectory Prediction with Channel Bias Compensation and Tracking

<table>
<tr><th>System Model</th><th>Main Idea</th></tr>
<tr><td>
</td><td>

- Compensation of the impact of NLOS and unresolvable multipath propagation in RAT-based localization through estimation of channel bias distribution parameters
- Improvement of initial localization accuracy through sensor fusion and trajectory estimation with adaptive Particle Filters and soft map-matching
- Prediction of future road user trajectories with physical- and maneuver-based models, as well as prediction of collisions
- Release of warning messages according to an optimized collision probability threshold.

</td></tr>
<tr><th>Use Cases</th><th>Main Benefits</th></tr>
<tr><td>

- Applicable use cases: UC1: lane merge, UC3: VRU protection (integrated in 5GCAR demonstration already), UC5: remote driving
- Main research challenges: positioning accuracy, efficient collision prediction.

</td><td>

- Enhanced safety for Vulnerable Road Users (VRU) through reliable real-time localization and collision prediction
- Mobile radio network serves as virtual eye for the vehicle driver, complementing existing on-board equipment.

</td></tr>
</table>

Description of Technology Component

A detailed description of the technology component can be found in [5GCAR-D3.2]. It serves as representative example for 5G positioning methods in the 5GCAR VRU protection demonstrator, where two road users, a vehicle and a VRU, are localized and tracked in real-time. Vice versa, measurements from the demonstrator have been used to optimize the algorithms and to tune parameters and assumptions. It consists of three modules that can be applied independent from each other.

- RAT-based localization. This is an enhanced time-based positioning method. Positioning Reference Signals (PRS) sent in uplink or downlink are measured by the receiver and evaluated by a cloud service called Location Server, in 3GPP also referred to as Location Management Function (LMF). Our method can partly compensate Non-Line-of-Sight (NLOS) and multipath propagation through estimation of the statistical parameters of the channel bias [PLH16].

- Trajectory estimation. We track the UE position and optionally other state variables like speed and turn rate over time. The estimation of the current position of the road user is based on a state transition model, e.g. the constant turn rate and acceleration model, and a measurement model. We have implemented and evaluated two methods based on Unscented Kalman Filter (UKF) and Particle Filter (PF) to perform trajectory estimation with sensor fusion. For the latter, a novel soft map-matching technique is applied on top of a PF. The main benefit of our method is the possibility of detecting reliably critical situations, like vehicles skidding off the road. Moreover, we can reduce the positioning error by 45% with respect to prior art approaches. Important results have been published in [MMS+18].
- Collision prediction. We pairwise compare anticipated future trajectories of road users or anticipated occupancy areas to which road users will move within a certain time window. The collision probability between two road users is the probability that these occupancy areas overlap. A warning message is released in case the collision probability exceeds a certain threshold. Time window and threshold are important parameters to tune the metrics described in the following paragraph.

Key result

Figure 3-26 shows the most important evaluation results of the collision prediction module. The presented metrics are defined as follows

- False alarm rate: Probability of an erroneous warning message
- Precision: Ratio of correct warning messages
- Recall: Ratio of correctly predicted crashes
- F1-Score: Combination of precision and recall for the joint optimization of both metrics

$$\text{F1-Score} = 2\,\frac{\text{Precision}\cdot\text{Recall}}{\text{Precision}+\text{Recall}}$$

In the first row we assume that all five considered future trajectories (inertial trajectory, i.e. according to the constant turn rate and acceleration model, two variations of the acceleration, two variations of the turn rate) can appear with the same probability (20%), while in the second row the inertial trajectory has the probability 80% and the variations 5% each. The first case reflects situations that are tentatively difficult to predict like driving in a dense urban environment, whereas the second case reflects situations that are tentatively easy to predict like driving on a highway. We also show results for different collision probability thresholds (20%, 50% and 80%). The system sends a warning message if the estimated collision probability exceeds the threshold.

A first observation is that with increasing threshold we minimize the false alarm rate and maximize the precision. However, this comes along with missed detection of crashes, thus the recall (and the F1-score) decreases. A second important observation is that the scenario with assumption of a high probability for the inertial trajectory (second row) gives in normal driving conditions more reasonable results. However, this setting has difficulties to reliably detect unusual maneuvers like an emergency breaking. Finally, we can see that reasonable time windows for collision prediction range in the order of a few seconds depending on the threshold and the considered scenario.

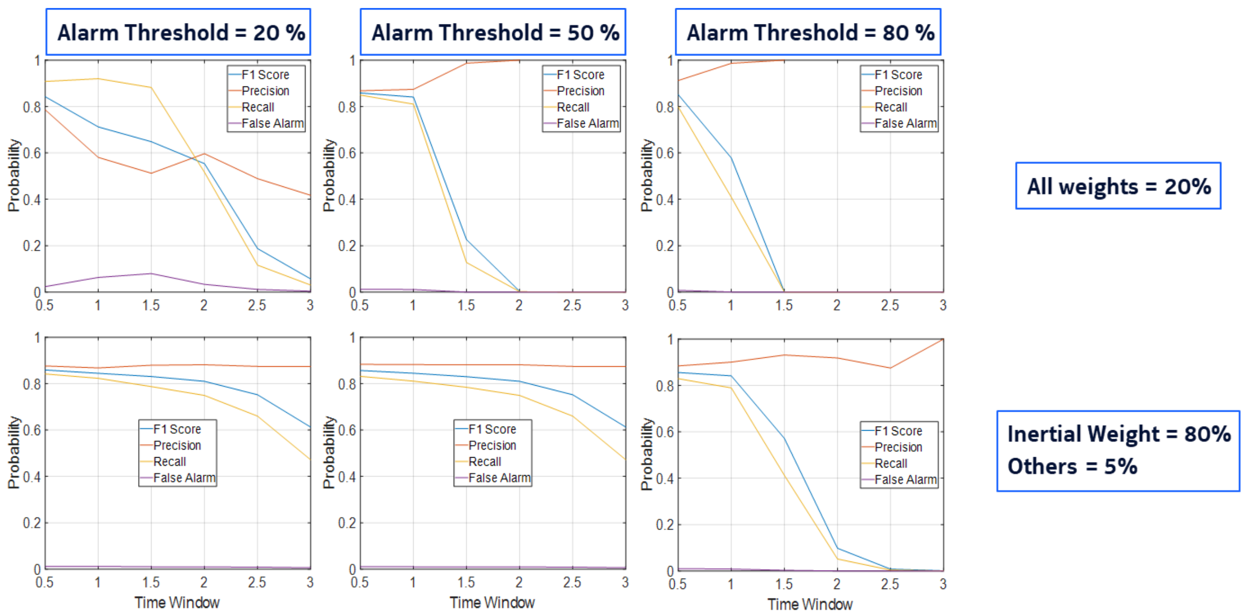


Figure 3-26 Evaluation of collision prediction for different threshold probabilities (20%, 50%, 80%) and different weights of potential future trajectories of road users.

3.6.2 Tracking of a Vehicle's Position and Orientation with a Single Base Station in the Downlink

System Model	Main Idea
• Single vehicle - User Equipment (UE) • mmWave Base Station (BS) • The environment comprises of reflecting surfaces and small objects causing multipath • The locations of these surfaces and objects, the UE's 2D position, 1D heading, and 1D clock bias are unknown.	The UE receives downlink mmWave signals, which are used to determine the channel parameters of each multipath component, characterized by a complex gain, a 1D delay, a 2D angle of arrival, and a 2D angle of departure. These channel parameter estimates are then used to solve for the UE state (position, heading, clock bias), as well as to build up a map of the environment.

Use Cases	Main Benefits
• This TC targets use cases requiring highly accurate positioning in 3D. These include UC1, UC3, and UC5. • This TC addresses the challenge “Support for accurate and ubiquitous real-time positioning”	• Determination of the UE position and heading with a single BS without a priori synchronization from a downlink transmission • Generation of a map of the environment, useful for other UEs to determine their position and heading • Distinguishing sources as being either reflecting surfaces or small objects. • Determination of UE position is possible even in absence of LOS.

Description of Technology Component

A technique utilizing only downlink mmWave signals from a single BS are used at the UE to jointly estimate the vehicle’s position and orientation, its clock bias and the channel parameters (locations and orientations of the reflectors). The reflectors are parameterized as Virtual Anchors (VA) and scattering points (SPs). As described in Figure 3-27, the proposed technique (circled in orange) consists of three stages:

1. Channel estimation: A search-free beam-space tensor-ESPRIT algorithm is developed for estimating the directions of departure and arrival, as well as the time of flight and channel gains of the individual paths. The proposed approach is based on higher-order singular value decomposition and it is a generalization of the beam-space ESPRIT method. Furthermore, the parameters associated to each path are automatically associated.

2. Data association: Since the paths are not yet tied to the VAs and SPs, a data association step must follow. We consider a simple technique based on the global nearest neighbor assignment which provides hard decisions regarding the associations of measurements. These assignments are only definitive after some time steps, after which the UE can confirm the nature of each source (VA or SP).

3. Positioning and mapping: We aim to compute the marginal posteriors of the UE position and orientations, the VA and SP positions, and the clock bias. It is achieved by executing belief propagation on a factor graph representation of all the parameters. When dynamic objects appear (moving cars, people, etc.), they will be added to the map, and then removed after they exit. They can be regarded as clutter for the proposed algorithm. Of course, performance may be affected.

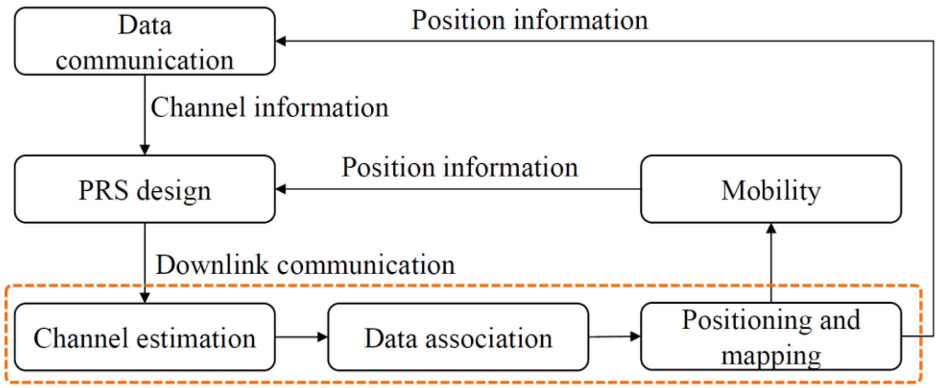


Figure 3-27 The stages of the proposed 5G mmWave downlink positioning technique. The vehicle estimates channel parameters from a dedicated PRS (including precoding and combining), which it associates to prior map information and then uses to refine the vehicle position, heading, and clock bias.

Key result

A Fisher information analysis was performed, and the following conclusions were obtained:

- The multipath channel and the vehicle's clock bias can be estimated, albeit with some performance penalty compared to a perfectly synchronized scenario.
- In the absence of multipath components, localization of an unsynchronized UE using a single BS is impossible.
- Mapping of the environment in terms of reflecting surfaces and scattering points is possible, even in the presence of clutter.

We observed a number of other interesting facts. In all cases, having more paths is beneficial assuming they are resolvable. In practice, if the number of paths grows too large, paths will not be resolvable, and performance will degrade. Thankfully mmWave channels have fewer paths with non-negligible energy compared to their microwave counterpart. The best performance is achieved when the both LOS and NLOS paths are available, and when the clock bias and VA positions are known (referred to as "map"), while the worst performance is achieved when only NLOS paths are available, and neither the clock bias nor the VA positions are known. Provided enough paths are available, the system state is always identifiable in spite of the fact that the UE has not a synchronized clock. With an unknown clock bias, one NLOS path is needed when LOS is present. When LOS is not present, at least three NLOS paths are needed, or only two in case map information is available (i.e., the position of the VAs). These results are corroborated by Figure 3-28, which clearly confirms that the clock bias can be estimated even with one-way transmission as long as the scenario provides enough diversity in terms of NLOS paths.

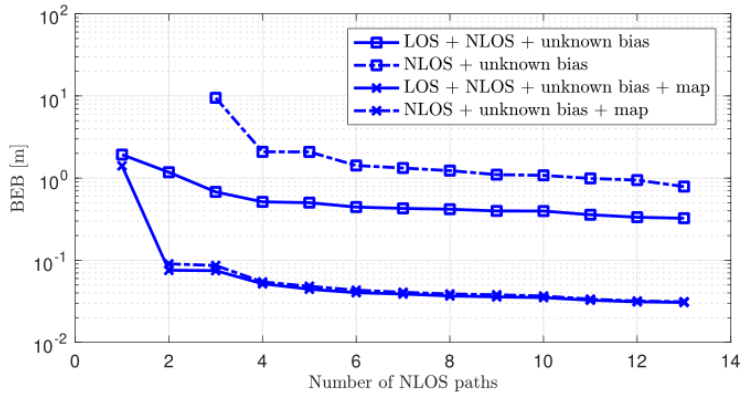


Figure 3-28 Bias Error Bound (BEB) as a function of the number of NLOS paths for 4 combinations: with and without a LOS path, with and without knowledge of the map (VA positions).

3.6.3 Beam-based V2C Positioning

System Model	Main Idea
• BSs/TRPs equipped with 2D antenna array at rooftop/roadside • 2D AoD measurements obtained at V-UE • LoS links	• Apply network-assisted UE-centric approach • Exploit angular information obtained using 3D beamforming • Investigate NR-specific technology with respect to positioning accuracy
Use Cases	**Main Benefits**
• Solution builds on V2N communication and addresses high positioning accuracy < 1m → UC 3, 4 & 5. • Challenge: support for accurate and ubiquitous real-time positioning	• Understanding the impact of the number of references TRPs and the geometric setting of the selected reference TRPs on the positioning accuracy

Description of Technology Component

This technique focuses on UE-based approaches for the V2X positioning and investigate the potential of NR-specific technology, namely angle estimation capability provided by 3D beamforming with respect to positioning accuracy. A UE-based approach allows the vehicle to estimate its own position based on the radio measurements as well as locally available information such as on-board motion sensors. This facilitate the position tracking process. Compared to the network-based approach where the location server placed in the core network calculating the UE positions, the UE-based approach avoids communicating measurement information to the location server, thus conserves network traffic overhead and reduces latency as well.

The first step of the UE-based approach can be realized by estimating the position through the TOA (Time of Arrival) and/or TDOA (Time Difference of Arrival). A method for combining multiple radio signals, e.g. in aggregated carrier components or multiple radio interfaces can be done in such way that reference symbols transmitted therein are used for a joint estimation, as proposed in [XSM19, XDL18]. As shown, such approaches can achieve a much higher accuracy compared to estimation per carrier or radio interface, providing thus a more accurate information as input to the next stage of the positioning procedure.

In the considered scenario, uniform rectangular panel array on the base station side are assumed. The angular information in both the horizontal and the elevation plane can be obtained by a vehicular UE via downlink channel estimation.

For the LOS path from the anchor base station a, let θ_a denote the estimated AOD in the horizontal plane and ϕ_a denote the estimated AOD in the elevation plane. Given the knowledge of the anchor base station's 3D coordinates (x_a, y_a, z_a) , the UE's 3D position can be determined using simple linear regression. Since each anchor base station provides two measurements, namely θ_a and ϕ_a, at least two anchor base stations are required to estimate a UE's 3D coordinates. However, for a vehicular UE whose height z assumed to be known by itself, the 2D position in the x-y plane can be obtained given a LOS path from a single base station.

For a positioning system whose dynamics can be described as a state space model, Bayesian filtering is a statistically optimal solution [AMG+02]. Given that the system is non-linear and non-Gaussian, we choose to apply particle filtering which approximates the posterior probability density function using Monte Carlo method [AMG+02].

Main results

Figure 3-29 showed that with AOD measurements in the horizontal and the elevation plane from multiple TRPs, a V-UE of moderate velocity can be localized. Compared to a simple estimator using Linear Regression (LR), Bayesian tracking technique such as particle filter (PF) improves accuracy significantly when only sub-optimal angle estimations are available. It is also observed that although the positioning accuracy improves in general as the number of reference anchor points increases, the geometric setting of the selected anchor TRPs plays an important role. This motivates the UE-based positioning methods since a UE may dynamically select anchor TRPs which contribute better to UE positioning from the specific UE's perspective.

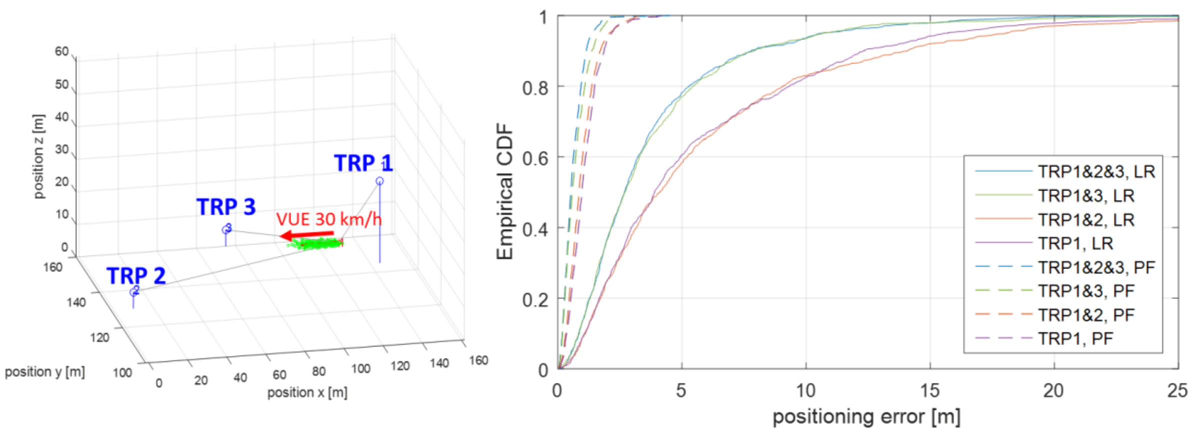


Figure 3-29 Scenario and empirical CDF of the positioning performance

3.6.4 Data-aided Beam-based C2V Positioning

System Model	Main Idea
• It is assumed an up-link mmW transmission model where channel is LOS-dominant. Both at the transmitter and receiver side, beamforming is applied to provide sufficient SNR for data transmission. • At the receiver (gNB), the location-orientation of the transmitter is estimated based on pilot and data symbols. • The communication is based on OFDM. Pilot symbols are known, whereas data reference symbols are provided by the communication chain. An uncertainty to the data symbols is computed based on the SNR.	The main idea of the UL position-rotation estimation is to jointly use the data and pilot symbols for a quasi-continuous estimation of the location and orientation of the device. To implement this idea, a graphical model connecting pilot-based positioning and data-aided positioning is developed. The challenge is to exploit the synergy between a) Data and pilot symbols for position estimation b) Location information to channel parameter estimation and prediction.
Use cases	**Main Benefits**
• This TC targets use cases requiring highly accurate positioning in 3D, low-latency and low impact on data communications. These include UC1 and UC3	• Determination of the UE position and heading with a single BS • Quasi-continuous estimation of the location and orientation using data • Estimate channel information as

• This TC addresses the challenge “simultaneous positioning and communication”	Rx gain, Tx gain and delay to use in location-aware channel prediction model.

The technology component is a Bayesian inference algorithm that uses the uplink pilot and data symbols to estimate the location and orientation of the UE in LOS channel condition. One of key aspect is the location-based parameterization of the channel, which provides the advantage of inferring directly the position and rotation from the received signal.

The positioning task is implemented with a two-step approach:

1) pilot based positioning using full-beam scanning procedure: uplink pilot reference symbols are received at the gNB by multiple beams, scanning the whole area of interests. The gNB processes the received signal using pilot-based method and computes an estimate of the UE location and orientation.
2) data-based positioning using location-based beamforming: uplink data are received using a beam pointing to UE estimate direction. The I-Q samples of the data streams are then estimated and used as reference symbol symbols. The gNB re-processes the received data signal to estimate of the UE location and orientation by leveraging prior information captured from pilot transmission.

Figure 3-30 illustrates a possible implementation of the two phases during a radio frame. More specifically, phase 1 is implemented during the beam sweeping procedure at the gNB for the UL receive beam selection. The reference signal used is the SRS. Phase 2 is implemented during the data up-link slots. Note that only one beam is used at the gNB, which helps increasing the SNR and limiting the search space in the angular domain. Figure 3-31 illustrates a snapshot of the positioning method, where the posterior distribution of the UE location is iteratively refined.

Simulation results, which are reported in [5GCAR-D3.2], indicates an improvement of over 50 % of accuracy along with faster location update. More specifically, a significant gain can be achieved when the pilot-based positioning is relatively accurate. In other words, when a pilot-based positioning can provide sufficiently reliable position information.

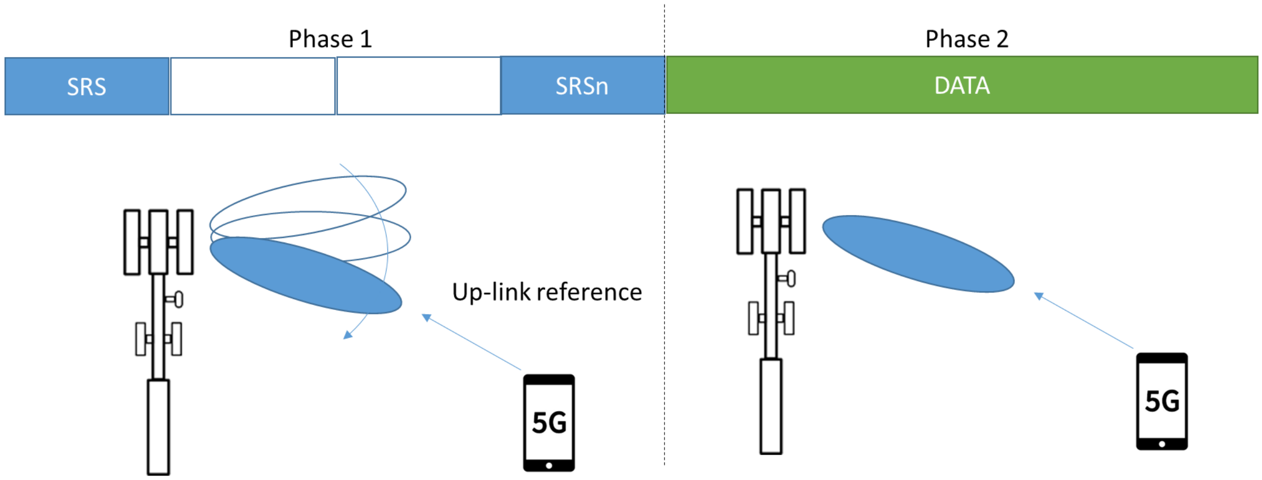


Figure 3-30 Possible implementation of data-aided positioning

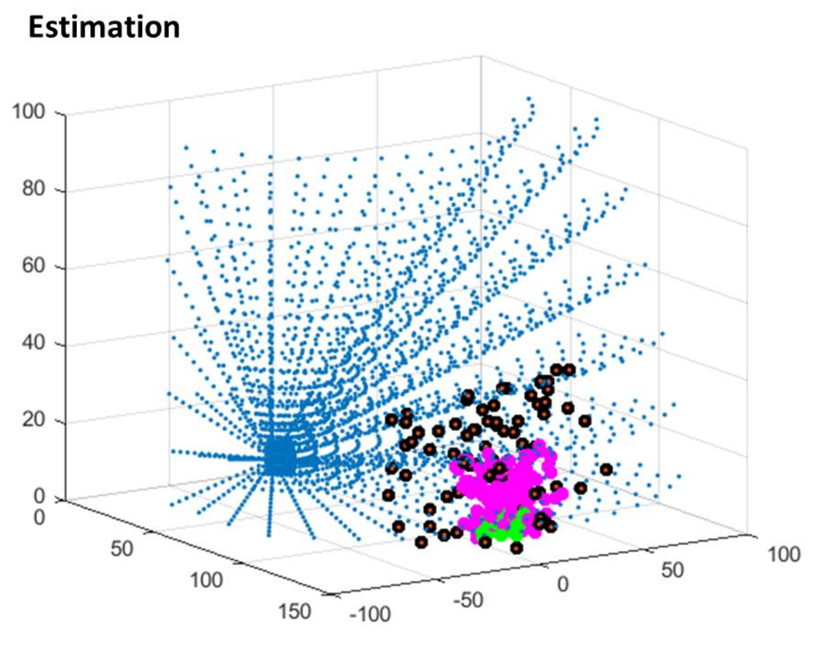
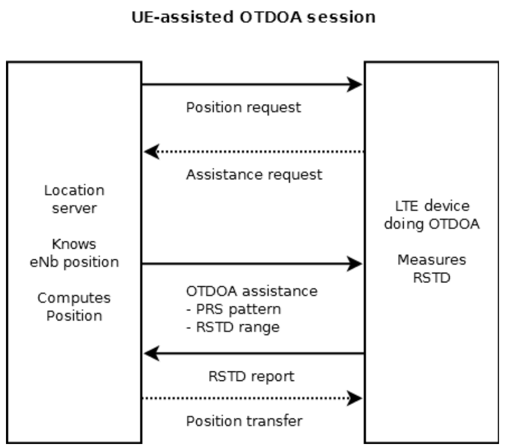


Figure 3-31 Illustration of a 3D estimation process

3.6.5 Enhanced Assistance Messaging Scheme for GNSS and OTDOA Positioning

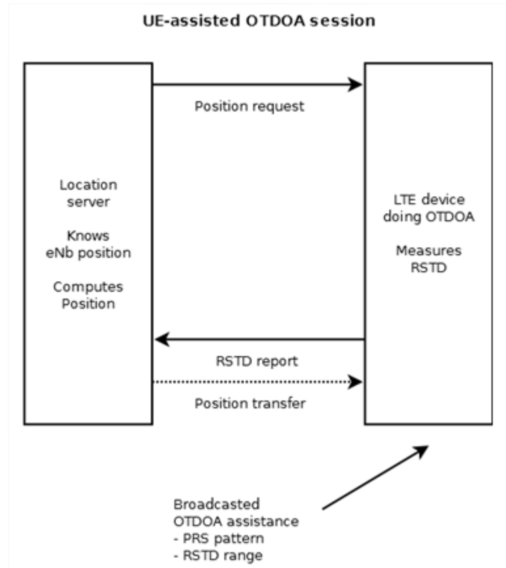
System Model



Conventional positioning session:

The location server requests the UE to provide the positioning technologies it supports. UE answers the server request by providing its capabilities. Location server provides assistance information to the UE which can be e.g. OTDOA assistance. Location server then requests the location information. UE answers the server requests and provide either the measurements and/or the position.

Main Idea



Proposed positioning session:

Introduce new mechanism in legacy Positioning Protocol (LPP) to transmit assistance messages in order to improve GNSS and OTDOA positioning. The main idea is to broadcast assistance per cell a) via new System Information Block (SIB) messages or b) by introducing unsolicited messages at the NAS level.

Test Cases

This technology component targets use cases requiring highly accurate, low latency positioning with low impact on data communications. It particularly applies to UC 3, 4 and 5.

Addressed challenge: Support for accurate and ubiquitous real-time positioning.

Main Benefits

- Reduce positioning delay and power consumption at UE device by reducing number of transmitted messages.
- Increased system resource efficiency from per cell sharing of assistance information

Allow new usages and use cases by allowing UE-based positioning and reducing positioning delay

Description of Technology Component

In this contribution, considering the LTE positioning mechanisms as baseline, we introduce new mechanisms to transmit assistance messages in order to improve GNSS and OTDOA positioning in cellular radio technologies. The main idea is to broadcast messages per cell. In [D3.2] we have described the LTE conventional mechanism and highlighted its drawbacks. Then we explained a how the broadcasting scheme can be implemented: new System Information Block (SIB) messages, which can be updated and reacquired by the UE whenever there is change on the vehicular network topology, can be introduced to carry such assistance information. We proposed two new SIBs for each case of GNSS and OTDOA positioning, provided details on their content, and summarized the key benefits of the proposed assistance messaging scheme. Here we discuss a mechanism to only allow authorized users to make use of those broadcasted SIBs. We also discuss the motivation and some details on a second option regarding unsolicited assistance reception at the control plane level or at the user plane level. This option involves unicast transmissions compared to SIB-based approach; however, it also avoids unnecessary handshakes through the LPP. Some analysis on the expected benefits is provided in [5GCAR-D3.2].

Encryption scheme for base station position

In the case of OTDOA, an operator may be reluctant to broadcast the position of its base station as well as the pattern location. Besides it may want to monetize the services that can be derived from this information rather than providing free usage to all UEs. A mechanism to only allow authorized users to make use of those broadcasted SIBs is illustrated below.

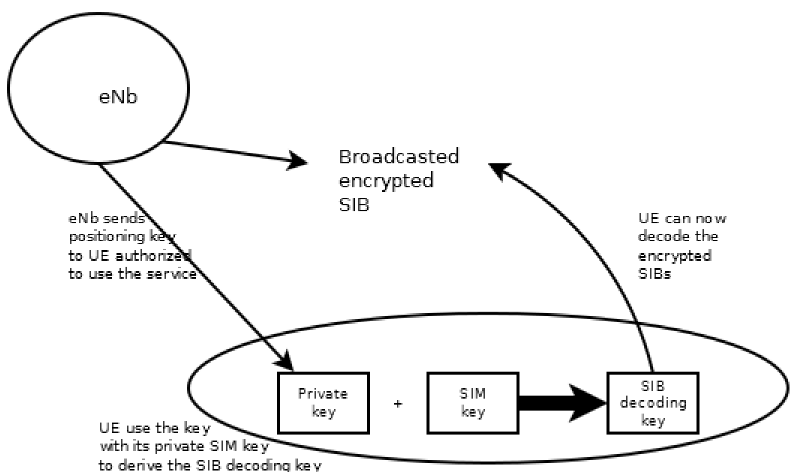


Figure 3-32 Encryption mechanism associated to the SIB broadcasting

It works as follows:

- Base station broadcasts one or several SIB to all the UEs in the cell. The SIBs have been encrypted using a secret key.
- Therefore, a UE needs this secret key to be able to decode it.
- When a user is authorized to use the service, the base station will send to the UE a public positioning key that is specific to the UE.

- This key cannot be used directly to decode the broadcasted SIB. It is indeed specific to the UE and depends on private keys stored on the UE SIM.
- To be able to retrieve the positioning private decoding key, the UE needs to use the public key, plus information stored on its SIM to derive it.

This scheme is actually quite common in security and there are many ways to combine public and private keys.

Unsolicited message at NAS level

The SIB broadcasting of positioning assistance data requires many additional system information messages and may cause resource shortage for the SI messages. If this is seen as problematic, an alternative option would be to send occasionally unsolicited assistance using NAS as a transport layer. A mechanism to do this would be to introduce a new NAS message type for the generic message container [3GPP-36.335, Table 9.9.3.42.1]. For instance, message 00000011 could be used to send unsolicited assistance messages to the UE where the 4 messages content could be transmitted as previously described.

3.6.6 Multi-Array 5G V2V Relative Positioning

In this work we consider Tx and Rx vehicles equipped with multiple antenna arrays, referred to as panels in 5G New Radio (NR) standardization, which are distributed around the vehicle to support 5G NR side link (V2V) communication between vehicles. Our goal is to leverage these arrays and the side link to also perform V2V relative positioning using e.g. position reference signals.

System Model	Main Idea
• Vehicles equipped with conformal antenna arrays at the edges of their bumpers • OFDMA access to shared channel • Transmission through fixed beamforming vectors -> No AOD estimation • Asynchronous Tx-Rx clocks • LOS links	• Derivation of the performance bounds of V2V relative positioning • Comparison with 5G NR V2X requirements [3GPP-22186] • Evaluation of the relative significance of channel measurements (AOA, TDOA)

Use Cases	Main Benefits
• Accurate V2V relative positioning for UC1 (lane merge)	• Determination of the achievable V2V relative positioning accuracy and the range of distances for which 5G NR V2X requirements can be met • Understanding the significance of angular measurements compared to that of delay measurements with potential applications to reference signal design

Key results

The main outcomes can be summarized as follows [KCS+18]:

- Comparing low (3.5 GHz) and high (28 GHz) carrier frequency configurations, we concluded that the latter can provide better positioning accuracy pertaining mainly to its higher angular resolution, as a result of the larger number of antennas that can be packed in the same physical area.
- In the overtaking scenario, angular measurements are sufficient and the 5G NR V2X requirements can be easily met for a wide range of distances.
- TDOA measurements can drastically improve the lateral positioning accuracy in the platooning scenario, as they provide valuable Fisher information on the unknown orientation of the Tx vehicle. With known Tx vehicle orientation, AOA measurements are sufficient for accurate position estimation.

4 3GPP V2X Standardization Status

The intention of this section is to summarize the status of standardization related to V2X in 3GPP and to link 5GCAR proposed solutions, described in the previous section, with the ongoing standardization in 3GPP. To this end, contributions to 3GPP study and work items related to vehicular communications directly (NR V2X) or indirectly (NR URLLC and NR Positioning) are captured. It is noted that status and assessment of V2X channel modelling in 3GPP standardization has been captured already in [5GCAR-D3.2].

4.1 V2X / URLLC

3GPP standard was first expanded to the automotive industry in 2016 to support V2V services with enhancements on additional V2X operation scenarios in 2017. This standardization work was included as V2X phase 1 service in Rel-14 LTE, focusing on basic road-safety service. Later on, within Rel-15 LTE, advanced use cases for V2X were targeted (with stricter requirements [3GPP-22886, 3GPP-22186]) and enhancement of 3GPP support for V2X services (eV2X services) was envisioned. Both LTE and NR are considered as candidate RATs to support eV2X. V2X phase 2 in Rel-15 LTE introduced some enhanced features in that direction. On the other hand, NR V2X is intended, as V2X phase 3, to complement and support interworking with LTE V2X for eV2X services, while including the possibility to independently support basic safety use cases as well.

NR RAT was first introduced in Rel-15 and is expected to have higher system capacity and better coverage than LTE. Nevertheless, the advanced V2X use cases beyond the ones supported by Rel-15 LTE V2X have more stringent requirements. As a consequence, an enhanced NR system and new NR sidelink need to be defined. NR V2X is designed to anticipate services with low latency and high reliability requirements, in a flexible manner. A feasibility study on NR V2X [3GPP-RP-181480] was recently concluded successfully and several technical solutions were identified [3GPP-38885]. The study covered aspects including:

- NR sidelink design
  - Support of sidelink unicast/groupcast/broadcast
  - Physical layer structures and procedures
  - Synchronization mechanism
  - Resource allocation mechanism
  - L2/L3 protocols
- Uu enhancements for advanced V2X use case
- Uu-based sidelink resource allocation/configuration by LTE or by NR
- RAT and interface selection

- QoS management
- Non-cochannel coexistence between NR and LTE sidelink

Based on the NR V2X feasibility study, a new 3GPP work item has started which is expected to address the aforementioned aspects and specify radio solutions in Rel-16 NR that are necessary to support eV2X services [3GPP-RP-190766]. The work in 5GCAR project inspired contributions to the NR V2X study item regarding sequences and algorithms for synchronization for the V2V sidelink ([3GPP-R1-1900025, 3GPP-R1-1901539]) as well as reference signals design for direct V2X communication ([3GPP-R1-1901228, 3GPP-R1-1903175, 3GPP-R1-1903163]). Promotion of the aforementioned solutions will be continued in the work item phase of NR V2X.

Before the NR V2X development, the basic support for URLLC services was introduced in Rel-15 NR, which included TTI structures for low latency, as well as methods for improved reliability. The motivation to support URLLC services came from a broad spectrum of use cases with tight latency and reliability requirements, envisioned to be enabled by NR. Later on, in parallel to V2X study item, a URLLC study was conducted to evaluate Rel-15 NR URLLC feasibility for further key use cases, including transport industry and especially the remote driving use case [3GPP-RP-182089]. This study item concluded that it is beneficial to support a set of enhancements to Rel-15 URLLC solutions (eURLLC) [3GPP-38824]; as a result, another new 3GPP work item has started to specify such enhancements [3GPP-RP-190726]. The work in 5GCAR project stimulated several contributions to the URLLC study item, promoting solutions for eMBB/URLLC multiplexing in DL ([3GPP-R1-1718708, 3GPP-R1-1808973]) and UL ([3GPP-R1-1806959, 3GPP-R1-1900683, 3GPP-R1-1902129]), as well as increased control channel reliability by repetition ([3GPP-R1-1806958, 3GPP-R1-1900680]). The aforementioned solutions regarding eMBB/URLLC multiplexing in UL are within the scope of the ongoing work item phase of eURLLC and are already being promoted there. The other solutions are planned to be promoted again when within the scope of a future V2X related work item.

4.2 Positioning

3GPP opened a Rel-16 study item for positioning support in NR in the second half of 2018 [3GPP-38855], which is now being continued as work item in 2019.

The performance requirements defined in [3GPP-38855] for commercial use cases are more relaxed than the requirements for the 5GCAR use cases. In outdoor deployment scenarios the objectives are a horizontal positioning error of less than 10 m, and a vertical positioning error of less than 3m each for 80% of the UEs.

5GCAR relevant evaluation scenarios are

- Scenario 2. Urban micro (UMi) street canyon for frequency range (FR)1 and FR2 at inter-site distance (ISD) 200 m
- Scenario 3. Urban macro (UMa) (ISD 500 m) for FR1 only (macro cell only deployment scenario)

3GPP agreed to consider the following radio access technology (RAT)-dependent positioning technologies in the work item

- Downlink-based solutions
  - NR should support DL time difference of arrival (DL-TDOA) in FR1 and FR2.
  - NR should support DL angle of departure (DL-AoD) with at least beam sweeping at least at the gNB in FR1 and FR2.
- Uplink-based solutions
  - NR should support UL time difference of arrival (UL-TDOA) in FR1 and FR2.
  - NR should support UL angle of arrival (UL-AoA) based positioning techniques in FR1 and FR2
- Downlink and uplink-based solutions
  - Round-trip time (RTT) with one or more neighboring gNBs for NR DL and UL positioning should be supported for FR1 and FR2.
  - Enhanced cell ID (E-CID) based positioning

The work in 5GCAR has inspired several contributions to the study item, in particular [3GPP-R1-1811029, 3GPP-R1-1813143, 3GPP-R1-1901022, 3GPP-R1-1901847] addressing the design of Positioning Reference Signals (PRS) required for DL-TDOA which has been agreed as one of the solutions listed in [3GPP-38855].

5 Summary

It is envisioned that V2X communications will play an important role to support the emerging applications from automated driving. V2X communication can bring improvement in the areas of traffic safety, traffic efficiency and also end-user experience in terms of infotainment. Cellular-based V2X communications enables more advanced applications including, among others, the ones identified in 5GCAR. As the outcome from 5GCAR use case studies, the key performance indicators related to wireless communication are reduced end-to-end communication latency (below 5 ms), high reliability (99.999%) and positioning accuracy (down to 5 cm) on top of regular capacity requirement. From overall 5G V2X system design point of view, one of the key areas to achieve the required performance is the 5GCAR radio air interface design.

Leveraging the latest technology development especially the fast moving 5G new radio in 3GPP, we have made further progress by studying advanced and future-oriented technology concepts inspired by the identified use cases and research challenges. The proposed technology components can be applied to both Uu interface (e.g. PHY design, RRM, multi-antenna and diversity, mmW beamforming) and sidelink interface (e.g. sidelink essential design, RRM and interference management, full duplex communication). On top of the regular radio interface design, V2X channel modeling and 5G radio assisted positioning techniques have been reported in [5GCAR-D3.2]. In brief, the following technology component clusters have been explored within 5GCAR:

- Multi-antenna techniques

  Efficient usage of the available multiple antennas to improve system performance such as network capacity is important, especially considering the bands around 3.5 GHz and in the mmW spectrum, which offer the high potential to apply massive MIMO. Predictor antenna, beam management for both unicast and multicast/broadcast communications and related feedback design, optimized antenna design for V2V communications are the main solutions proposed by this TCC.

- Resource allocation and management

  How can we efficiently allocate resources (all dimensions e.g. time, frequency, space, code and power) to vehicular UEs and also conventional mobile UEs so that their respective service requirements are satisfied is the issue studied within this TCC. The proposed solutions cover both infrastructure-based and sidelink-based resource usage.

- Sidelink design

  The 5GCAR sidelink-based V2X technology components enable the delivery of V2X services independently of the infrastructure nodes and take advantage of network assistance under infrastructure coverage. Solutions to the key problems of synchronization signal design, reference signals design and a network-assisted discovery are proposed.

- Full duplex

  Full duplex communication can offer benefits at least in terms of increased system capacity and reduced latency. With the help of natural capability of simultaneous transmission and reception, cognitive resource usage and collision detection/avoidance are studied for V2V communications.

- Reliability enhancement

  As mentioned many times, reliability is essential, especially for safety-related applications. An analysis of fundamental trade-off between reliability, latency and throughput is provided, which suggests that high reliability increases the demand in bandwidth and thus decreases the spectral efficiency. The utilization of channel diversity, on-demand retransmission, and improved control channel reliability are addressed to improve the reliability for both control channel and data channel.

- Positioning

  As one of the key objectives, highly accurate and ubiquitous real-time positioning and tracking of road users is a crucial requirement and enabler for many V2X use cases. Concerning positioning, six TCs are proposed with the one integrated into 5GCAR VRU protection demonstration which is a good example of development of an innovation, from algorithm design to validation via implementation.

In summary, the proposed TCs can be applied to improve the identified KPIs in terms of capacity, latency, reliability and positioning accuracy for future autonomous driving. As evidence, some contributions at the 3GPP have already been accepted (URLLC, V2X and positioning WI) for further study as discussed in Chapter 4. Moreover, thanks to the close cooperation with the demonstration work, the TCs related to positioning and sidelink design are implemented for the final 5GCAR demonstration of VRU protection and see through.

We believe that as time goes, the importance of 5GCAR outcome will become more visible.

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Annex

A Additional Details on Certain Technology Components

A.1 Predictor Antenna for Massive MIMO (M-MIMO) Adaptive BF (see Section 3.1.2)

We recall that the MMIMO antenna array (described in [5GCAR-D3.2]) is composed of 64 elements mapped onto 16 columns and 4 lines.

Three BF schemes are studied:

- GoB with 64 beams; in this scheme, a two-dimensional Discrete Fourier Transform (DFT) beamforming is used, with 4 horizontal beams times 16 vertical beams;
- GoB with 1024 beams; in this scheme, a two-dimensional Discrete Fourier Transform (DFT) beamforming is used, with 4x4=16 horizontal beams times 16x4=64 vertical beams;
- Maximum ratio transmission (MRT) BF (as in [5GCAR-D3.1].

The three prediction schemes are compared:

- Ideal prediction;
- Without prediction (with outdated channel);
- With the predictor antenna.

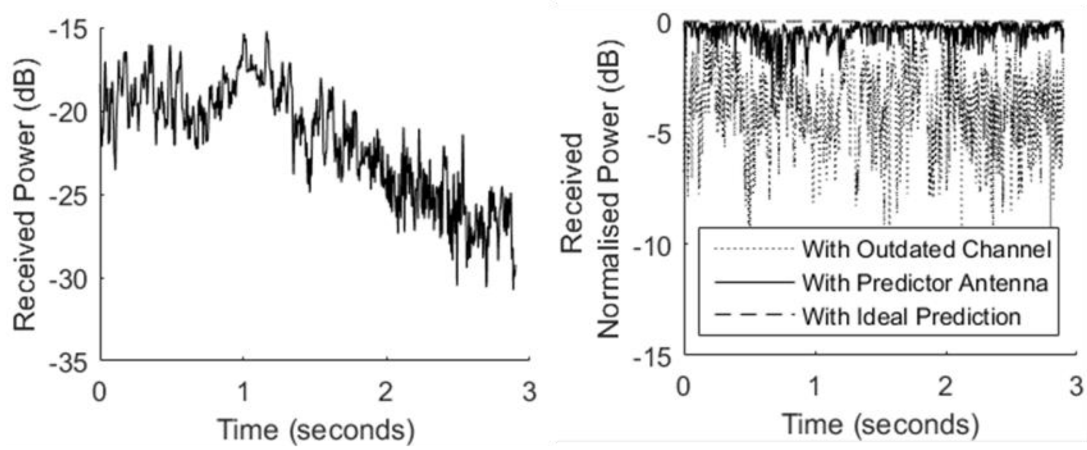
The simulation methodology is explained in detail in [5GCAR-D3.1] [5GCAR-D3.2][PWB+18].

Figure A-1-a), Figure A-2-a) and Figure A-3-a) below illustrate the received power when ideal prediction is used as a function of the time, for GoBG BF with 64 beams, GoB BF with 1024 beams and MRT Bf, respectively.

Figure A-1-b), Figure A-2-b) and Figure A-3-b) below illustrate the received normalized power as a function of the time (for the three prediction schemes), for GoB BF with 64 beams, GoB BF with 1024 beams and MRT Bf, respectively.

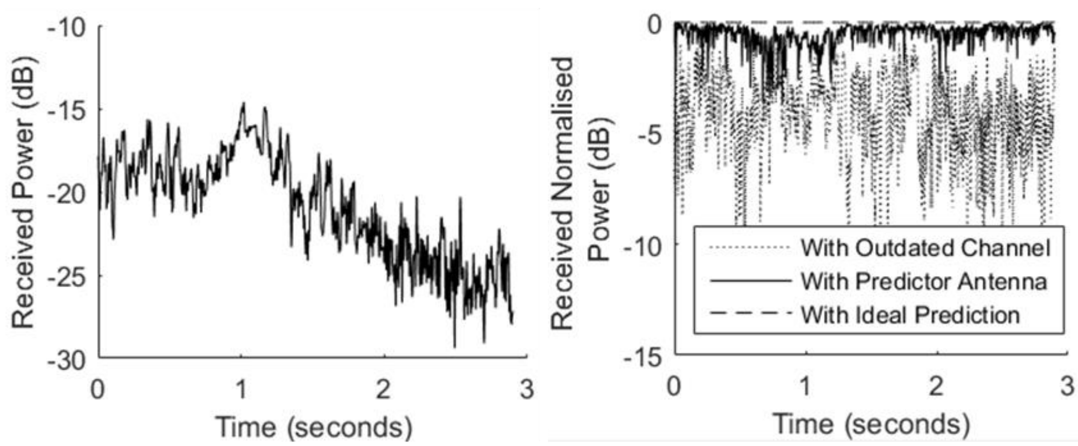
One can notice that GoB BF without prediction is more robust to speed than MRT BF without prediction, due to the fact that GoB BF is less “precise”.

Nevertheless, GoB BF performance also benefits from the predictor antenna-based prediction.



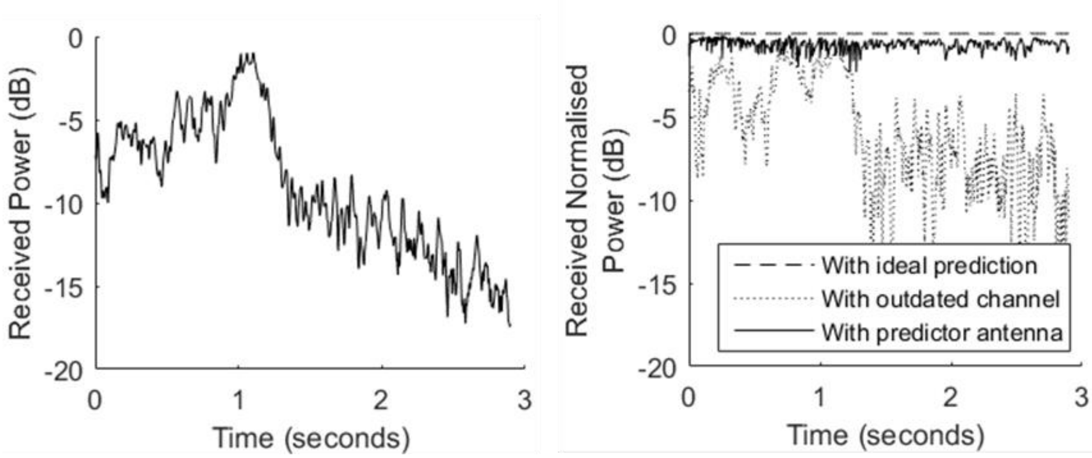
a)Received power with ideal prediction **b) Normalised received power for different prediction schemes**

Figure A-1 Performance for GoB BF with 64 beams



a)Received power with ideal prediction **b) Normalised received power for different prediction schemes**

Figure A-2 Performance for GoB BF with 1024 beams



a)Received power with ideal prediction

b) Normalised received power for different prediction schemes

Figure A-3 Performance for MRT BF

A.2 Beam-domain Broadcasting for V2N/V2I Links (see Section 3.1.5)

The performance of the beam-domain multicast scheme was analyzed through system-level evaluations assuming the 3GPP specified highway deployment scenario [3GPP-36885, 5GCAR-D3.1] comprising a 2 km long 6-lane road configuration. 3-sector BSs of 25 m in height and with inter-site distance of 200 m were assumed to be deployed single-sided along the highway and with distance of 35 m from the road. The key simulation assumptions regarding BS and UE deployments are captured in Table A-1. For BS antenna setup, 64-element rectangular antenna arrays (one per sector) were assumed to be deployed in 2-by-6 grid of beam (GoB) configuration. Analog beamforming with Time Division Duplexing (TDD) scheme and subcarrier spacing of 60 kHz were assumed. Moreover, simulation assumptions regarding the user deployment, mobility and traffic models are shown in Table A-2.

The performance of the TC was analyzed by comparing the achievable average cell throughput in two different cases, namely

- Case A: All V-UEs being served in unicast mode
- Case B: V-UEs being served both in unicast and multicast mode. Group common messages are multicasted to a subset of V-UEs while other UEs are served in unicast.

As target UEs for the multicast traffic, a subset of V-UEs within a geographical region, covering the area of right-facing lanes with +/- 50m horizontal distance with respect to positions of the roadside BSs, were considered. As the downlink beam for multicasting, a beam corresponding to the median beam index out of the sorted list of indexes of the best beams reported by the V-

UEs in the multicast area of the highway, (based on reference signal received power (RSRP) measurements) was used.

Table A-1 Deployment scenario for BSs and UEs

Parameter	Value
Deployment scenario	Highway
BS antenna height Inter-site distance	25 m 200 m
Number of BS antenna elements (TX/RX)	64/64
BS antenna gain	8 dB, radiation pattern according to 3GPP TR 36.814
Maximum BS transmit power	49 dBm
BS noise figure	7 dB
BS carrier center frequency	28 GHz
BS carrier bandwidth	20 MHz
UE type	Vehicle UE
Vehicle antenna height	1.5 m
Number of vehicle antenna elements (TX/RX)	2/2
Vehicle antenna gain	0 dB, isotropic
Maximum UE transmit power	23 dBm
Vehicle noise figure	13 dB
Distribution of antennas Polarization	Co-located Co-polarized (vertical)

Table A-2 User deployment, mobility and data traffic model

Parameter	Value
Scenario	Highway scenario comprising 3 lanes in each direction, with a lane width of 4 m. Highway length of 2 km.
Spatial distribution on V-UEs	Vehicles dropped in the roads according to a spatial Poisson process with an average inter-vehicle distance of 2.5s x vehicle speed. Average vehicle speeds of 30 km/h and 120 km/h considered.
Distribution of V-UE speeds	Vehicles move along the lanes of the highway at up to 250 km/h
V-UE position update rate	Vehicle position is updated every 100 ms of the simulation
Data traffic model	Unicast: Full-buffer traffic Multicast: Poisson traffic with rate 1/λ=100/200/500 and packet size of 1500 bytes or full-buffer

Figure A-4 shows the average downlink throughput per cell in case of 30 km/h average V-UE speed with different levels of offered load of multicast traffic for the Case B (represented by the four left-most bars) in comparison to the unicast-only reference Case A (represented by the right-most bar). The different subfigures (left, middle, right) show performance in cases of scheduling multicast PDSCH (Physical Downlink Shared CHannel) with fixed modulation order and coding rate of QPSK R=3/4, 16-QAM R=3/4 and 64-QAM R=3/4, respectively, while applying link adaptation for unicast data.

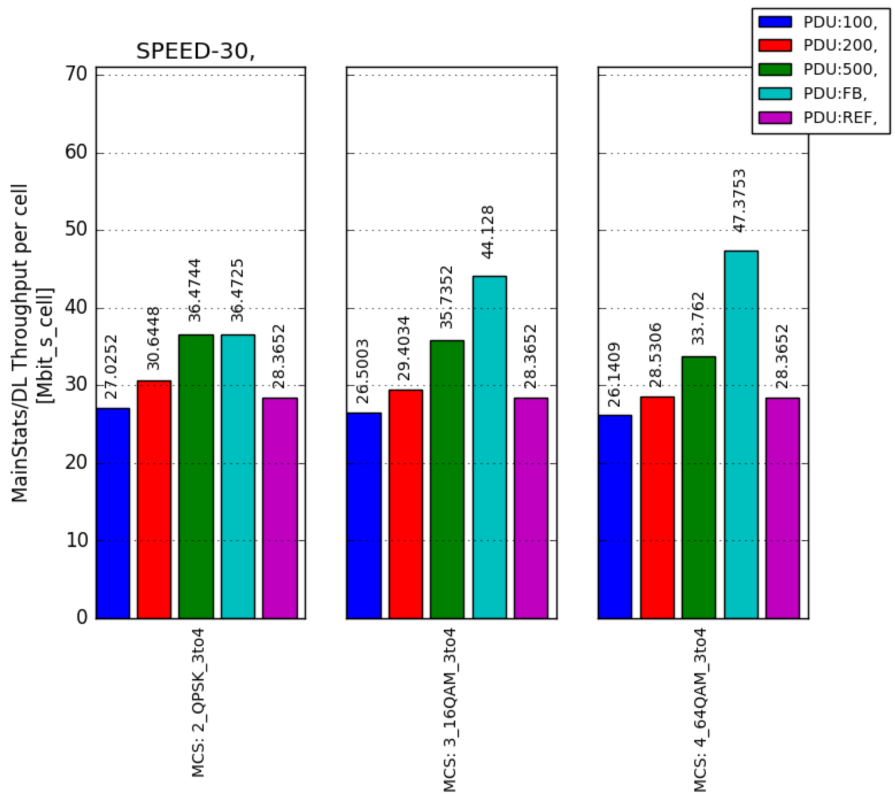


Figure A-4 Performance of the beam-domain multicasting scheme in comparison to unicast-only transmission mode in terms of average cell throughput with different offered loads of group-common data. Average V-UE speed of 30 km/h (with average spatial density of 580 V-UEs on the highway).

The results indicate that with a given fixed modulation and coding scheme (MCS) the beam-domain multicast scheme provides gain in terms of improved downlink cell throughput compared to the unicast-only transmission (the performance of the reference Case A shown by the right-most bar with legend ‘REF’), with the level of gain increasing as a function of the offered load of multicast traffic. In case of packet arrival rate of 1/λ=200, gains are 8.0%, 3.6% and 0.6% with R=3/4 QPSK, R=3/4 16-QAM, and R=3/4 64-QAM, respectively. With increased packet arrival rate of 1/λ=500, gains become larger and are 28.6%, 26.0% and 19.0% with

QPSK, 16-QAM, and 64-QAM, respectively. In case of full buffer multicast traffic, the corresponding gains are 28.6%, 55.6% and 67.0%.

Figure A-5 shows corresponding results in case of 120 km/h average V-UE speed. In this case, only marginal performance gain can be observed in case of full buffer traffic when multicast PDSCH data is scheduled with R=3/4 16-QAM or 64-QAM. With other offered load levels or with R=3/4 QPSK the performance is degraded compared to the unicast-only Case A. This change in the relative performance trend between the 30 km/h and 120 km/h cases is dominantly due to lower number of multicast V-UEs that results from a sparser spatial distribution of V-UEs (average inter V-UE distances being approximately 20.8 m and 83.3 m, respectively, for 30 km/h and 120 km/h scenarios).

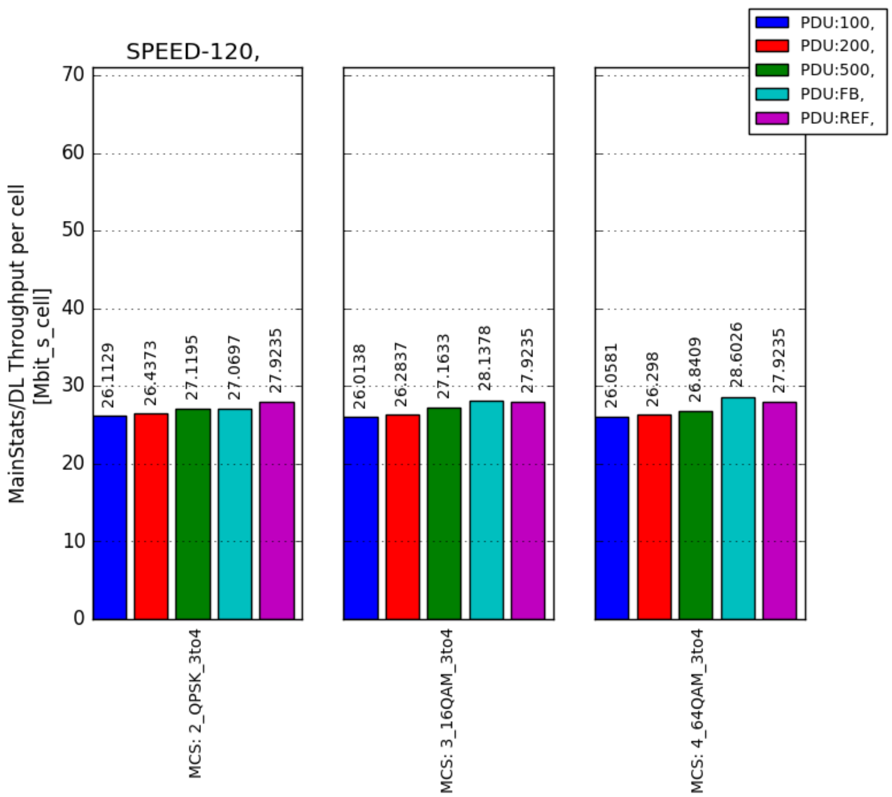


Figure A-5 Performance of the beam-domain multicasting scheme in comparison to unicast-only transmission mode in terms of average cell throughput with different offered loads of group-common data. Average V-UE speed of 120 km/h (with average spatial density of 145 V-UEs on the highway).

To confirm the impact of the multicast group size on the relative performance gain, the 120 km/h case was evaluated also under assumption of the higher spatial density of 20.8 m average inter V-UE distance. The simulation results are shown in Figure A-6. In case of packet arrival rate of 1/λ=200, gains are 6.4%, 2.6% and 0.5% with R=3/4 QPSK, R=3/4 16-QAM, and R=3/4 64-QAM, respectively. With increased packet arrival rate of 1/λ=500, gains are 23.9%, 21.7% and

16.2% with QPSK, 16-QAM, and 64-QAM, respectively. In case of full buffer multicast traffic, the corresponding gains are 23.7%, 45.5% and 53.6%.

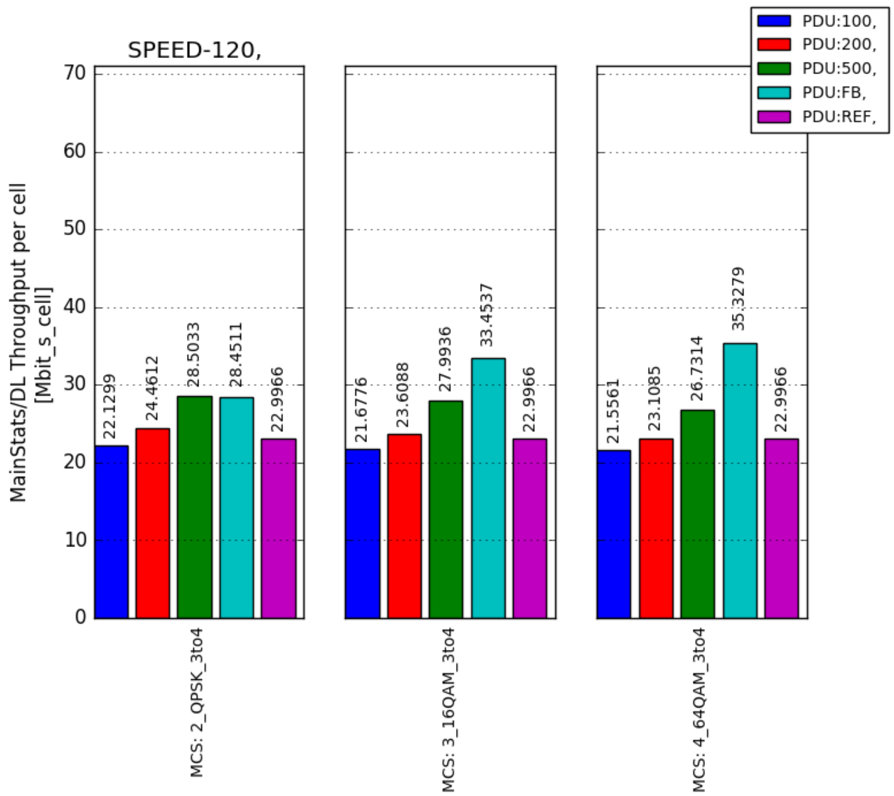


Figure A-6 Performance of the beam-domain multicasting scheme in comparison to unicast-only transmission mode in terms of average cell throughput with different offered loads of group-common data. Average V-UE speed of 120 km/h (with average spatial density of 580 V-UEs on the highway).

Overall, the obtained results indicate that the beam-domain multicast scheme can increase the spectral efficiency of the network-to-vehicle links in the highway deployment scenario and consequently improve the DL cell throughput. Performance improvement is achievable especially when the system is in high load state and the level of gain compared to the unicast-only mode increases with the offered load of group common data.

A.3 Efficient Preemption-based Multiplexing of Services (see Section 3.2.1)

RACH-like channel for SR transmission

Upon packet arrival for transmission at UE, one resource can be randomly selected and indicated to the gNB, and then the gNB can use the index of the detected resource to address the UE in the DL indication. The sequence pool size can be selected according to a target collision rate and a smaller pool is possible when a higher collision rate is acceptable. Such approach can provide significant benefits on signaling overhead as explained below.

For the case of dedicated SR, when a configured resource is not used (all UEs have no data to transmit), it is just wasted. What is more, when a resource occasion is shared by two or more UEs who transmit simultaneously, collision happens. It is understood that channel waste and collision can be traded but cannot be achieved simultaneously, for instance, when the number of channel resources is infinite, collisions can be completely avoided but the number of wasted channel resources is infinite too. In Figure A-7, we show the curve of collision probability versus channel usage. For URLLC type services, a very high reliability will request a very low collision probability which in turn result in a very low channel usage; for instance, 10^{-5} collision probability corresponds to ~0.43% channel usage which means 99.57% channel resources are not used and just wasted (channel waste = 100% - channel usage).

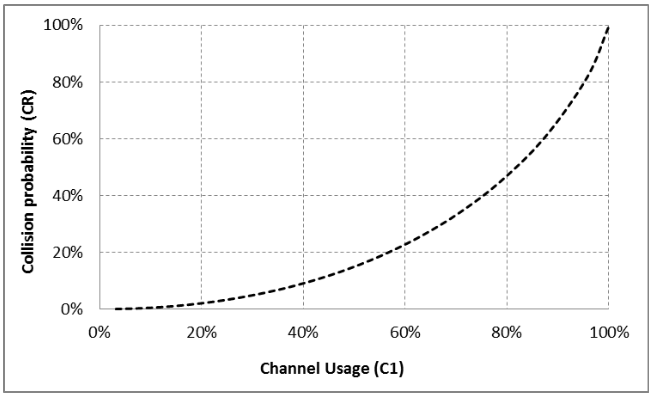


Figure A-7 Proposed UL cancelation/continuation indication.

More generally, the probability that at least one URLLC UE transmits on specific resource can be given by:

$$U = 1 - \left((1-a) + a\frac{K-1}{K}\right)^N \quad \text{(A.1)}$$

where U denotes the resource usage, N is the number of active URLLC UEs, a stands for the URLLC packet arrival rate, and K is the amount of required resources. As an example, assuming a packet arrival rate of 0.001 (e.g. 7000 transmission occasions within 1 second and 7 packets per second per UE), 100 active URLLC UEs and a target collision rate of 10^{-5} that corresponds to 0.43% resource usage (as discussed above), we can derive that a minimum of 23 resources are enough to ensure that at least one UE transmits on specific resource with the required resource usage (instead of 100 with the dedicated SR approach).

Combined Continue/Cancel UL CI design

Generally, two options for the UL cancellation indication exist. First, UL CI can be designed to *indicate cancel*, i.e. to ensure that eMBB UE is aware of a scheduled interrupting URLLC transmission. In that case, missing the indication will lead to collision between the two transmissions which is a big problem especially for achieving the latency and reliability requirement of the URLLC communication. But the advantage is that UL CI is signaled only when interrupting URLLC transmission has been scheduled. Second, UL CI can be designed to *indicate continue*, i.e. to ensure eMBB UE that no interrupting URLLC transmission occurs. In that case UL CI has to be always transmitted when eMBB is scheduled, leading to significant DL control signaling overhead. However, the advantage of such approach is that if the indication is missed, the worst that can happen is for eMBB transmission to wrongly be cancelled, leading to some overall spectral efficiency impact for eMBB service.

Normally, an AL is selected for a DCI according to the channel quality and a UE needs to blindly detect which AL is used. For the UL CI, only UEs with bad channel quality have the reliability concern and it is not difficult for UEs with good channel quality to achieve the required reliability with a low AL. Therefore, it is proposed to use a combined indication of cancelation and continuation, different UEs take different actions once it is lost, i.e., UEs with bad channel quality cancel the transmission while UEs with good channel quality continue the scheduled transmission. The way how the proposed UL CI is processed is illustrated in Figure A-8.

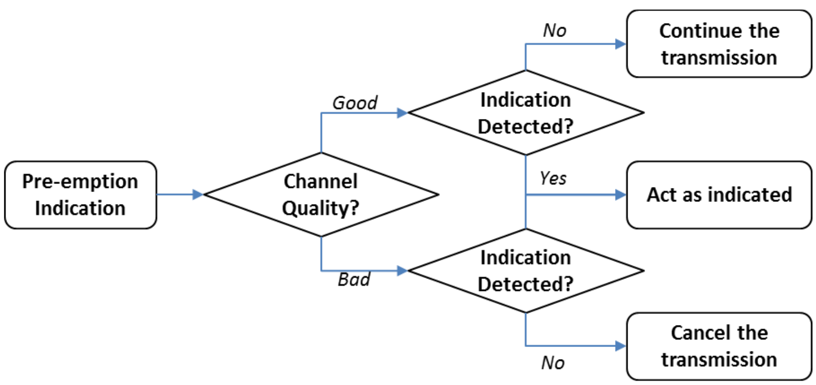


Figure A-8 Proposed UL cancelation/continuation indication.

A single configurable AL could be used for UL CI for reduced blind detection. The key point is to select a proper AL so that UEs with good channel quality can receive it with high reliability (e.g. BLER of 10^{-5} or 10^{-6}) and UEs with bad channel quality can receive it with bigger BLER but still acceptable. If it is lost by a UE with good channel quality, interference from this UE may cause the URLLC transmission fail but it is acceptable as the probability is negligible. If it is lost by a UE with bad channel quality, there will be no interference from this UE as it will cancel the transmission.

It can be considered to use the AL of the DCI carrying the UL Grant message to implicitly indicate the UE the channel quality, for example, AL higher than *N* can be classified as bad channel quality otherwise good channel quality. Considering the DCI payload size is variable, *N* can be configured for each UE separately.

In figure below, we obtained LLS results of Rel-15 NR PDCCH with 1 OS CORESET, to evaluate its BLER performance versus SNR, for various DCI sizes and ALs.

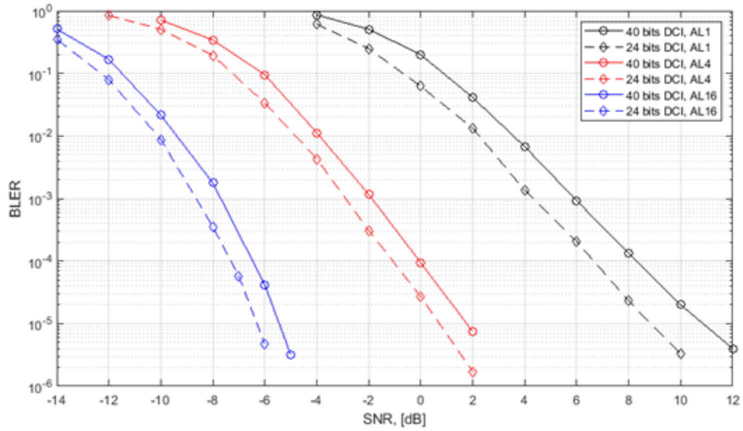


Figure A-9 PDCCH BLER.

Given the above and considering SSL results of DL geometry distribution (e.g. see [3GPP-R1-1812153]), the corresponding AL distribution with 1% BLER target can be estimated as in Table A-3.

Table A-3 AL distribution for target PDCCH BLER of 1% (DCI size = 24 bits)

	AL16	AL8	AL4	AL2	AL1
SNR range, [dB]	-9 ~ -7	-7 ~ -5	-5 ~ -2	-2 ~ 3	> 3
AL distribution	0%	0%	1%	6%	93%

For the particular set of results presented in Section 3.2.1, it is assumed the cancel indication must achieve 10^{-5} reliability and AL16 is needed, while the continue indication can use AL4 with 1% BLER at -5 dB SNR. The combined indication proposed is assumed to also use AL4, but it is only transmitted when a URLLC interruption is to happen or when a UE with bad channel quality is monitoring this UL CI. A UE with a bad channel quality is implicitly indicated by using AL4 or higher for the UL Grant. The PDCCH overhead of UL CI is related to how often interruptions happen and the average overhead in CCEs is compared in Table 3-2 in Section 3.2.1 for all three options.

A.4 Decentralized Pilot-to-Data Power Ratio Configuration in Multi-Cell Multi-User MIMO Systems (see Section 3.2.2)

Description of the Technology Component

We model the vehicular network as a MU-MIMO system, in which the mobile stations (MS) -- that is vehicular user equipment, V-UEs -- transmit orthogonal pilot sequences to facilitate channel state acquisition at the multi-antenna receiver of their serving BS. The pilot sequences are constructed such that they remain orthogonal when the number of spatially multiplexed V-

UEs is equal to or less than the length of the pilot sequence. To obtain some insights, we initially assume a frequency flat (narrow band) channel, within which the subcarriers can be considered having the same channel coefficient in the frequency domain. This is a realistic assumption considering, for example, a 3GPP LTE system based on Orthogonal Frequency-Division Multiplexing (OFDM), in which a physical channel (realized by a physical resource block) consists of 12 subcarriers corresponding to 180 kHz channel bandwidth, while the coherence bandwidth even in relatively large outdoor cells can be assumed to be at least 300 kHz [SFG09].

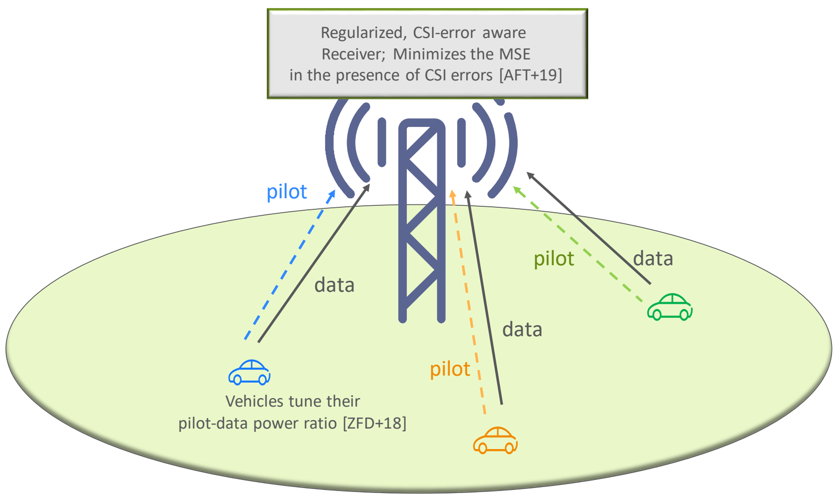


Figure A-10 The technology component *Decentralized pilot-to-data power ratio configuration in MU-MIMO systems* is an interplay between the pilot-to-data power ratio setting [ZFD+18] and the CSI-error aware MU-MIMO receiver. Regularization refers to taking into account the CSI-errors in the MSE minimization [AFT+19].

We assume that the BS uses either the least squares (LS) or the minimum mean squared error (MMSE) channel estimator to obtain an estimate of the uplink channel at the receiver. The proposed technology component helps V-UEs to continuously tune their data and pilot power levels by means of a decentralized algorithm executed by each V-UE based on concepts from non-cooperative game theory. The key tenet of the proposed algorithm, called the “Best Pilot-to-Data Power Ratio” (BPA) algorithm, is that vehicles iteratively update their data and pilot power levels such that they minimize the mean squared error of their own transmitted data symbols. In [ZFD+16] it was shown that when every vehicle follows the MSE minimization strategy, this game converges to a Nash equilibrium. In a single cell system, the Nash equilibrium pilot and data power allocation is close to a globally optimal power allocation. In highly mobile multi-cell systems, the V-UEs transmit pilot signals to help the serving BS to continuously maintain a valid channel estimate that is used as input to the multi-antenna receiver [MSF+17], [ZFD+18].

In this environment, the multi-antenna receiver at the serving BS has an erroneous channel estimate due to mobility, and a constrained power budget at each V-UE, which must be shared between transmitting pilot sequences and uplink data symbols. Due to the constrained sum-power budget, and the consequent limited power budget to the pilot signals, the pilot-based channel estimation suffers from channel estimation errors. To make the BS receiver robust with respect to channel estimation errors, we propose a novel multi-antenna receiver design, which uses the individual instantaneous (erroneous) channel estimates of each user as well as the second order statistics of each user to minimize the MSE of the uplink received data symbols. We refer to this new receiver structure as CSI-error aware regularized receiver [AFT+19].

Illustrative Numerical Results

The combined effect in terms of the MSE of the uplink received data symbols of the two intertwined technology components -- a novel and robust MU-MIMO receiver design [AFT+19] and the proposed decentralized pilot-to-data power ratio (PDPR) setting [MSF+17], [ZFD+18] -- is illustrated in the Figure A-11 below. The proposed receiver minimizes the MSE of the uplink received data symbols by using the instantaneous channel estimates of the desired and interfering users. In contrast to the state-of-the-art receiver developed in [FMT15], the proposed receiver, thus, makes use of all channel estimates as an input to the MU-MIMO receiver. As the figure below shows, this CSI-error aware receiver (red curve) has lower MSE performance than the state-of- the-art receiver. To fully take advantage of the potential of this receiver, the pilot-to-data power ratio must be tuned at the transmitter (mobile station) side such that the MSE is minimized.

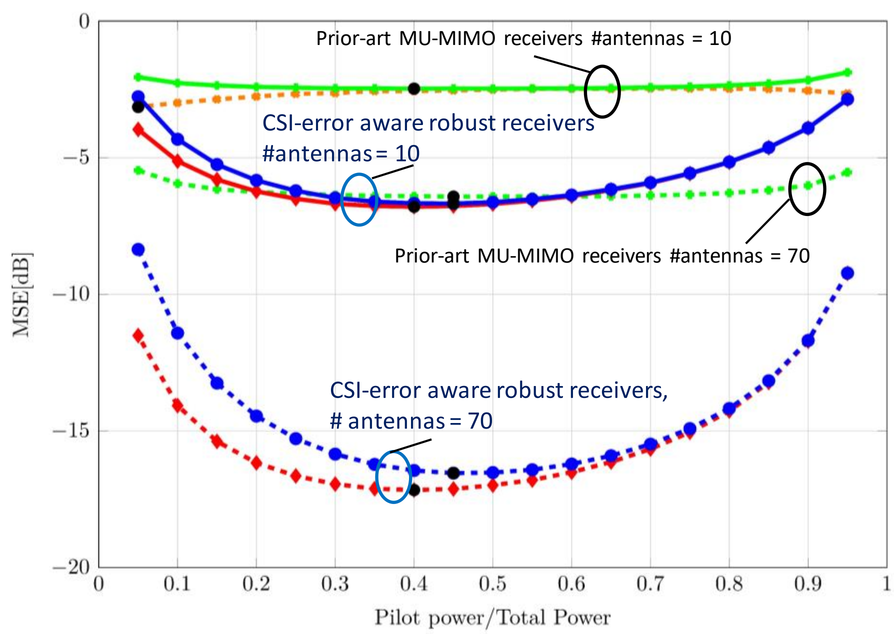


Figure A-11 Performance of the proposed CSI-aware robust MU-MIMO receivers as compared with prior-art MU-MIMO receivers. The gain of the robust receivers over prior-art receivers, in terms of MSE, increases as the number of antennas increases (from 10 to 70).

A.5 Power Control and Scheduling to Mitigate Adjacent Channel Interference in Vehicle-to-Vehicle Communication (see Section 3.2.4)

Illustrative Numerical Results

Figure A-12 shows the ACI over frequency slot, for a typical Single Carrier Frequency Division Multiple Access (SC-FDMA) transmitter. The black curve shows the ACI mask proposed by 3GPP [3GPP-36942].

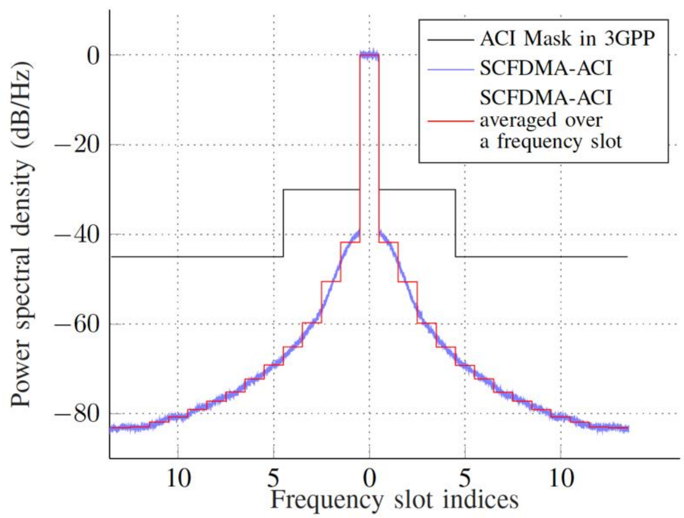


Figure A-12 Different ACI models.

In Figure A-13, we compare the performance of various scheduling schemes, by varying *F* (number of frequency slots), *T* (number of timeslots), and *N* (number of V-UEs). The performance metric used is the average number of connected V-UEs per V-UE. The red and magenta curves show the performance of joint scheduling and power control scheme, where the magenta curves correspond to a low computational complex computational method using a column generation procedure. The blue and green curves correspond to optimal scheduling, where the blue curves show the performance after applying a sensitivity reduction technique. The violet curves show the performance of low computational complex heuristic scheduling algorithm. For all the details, please refer to [HSB+17].

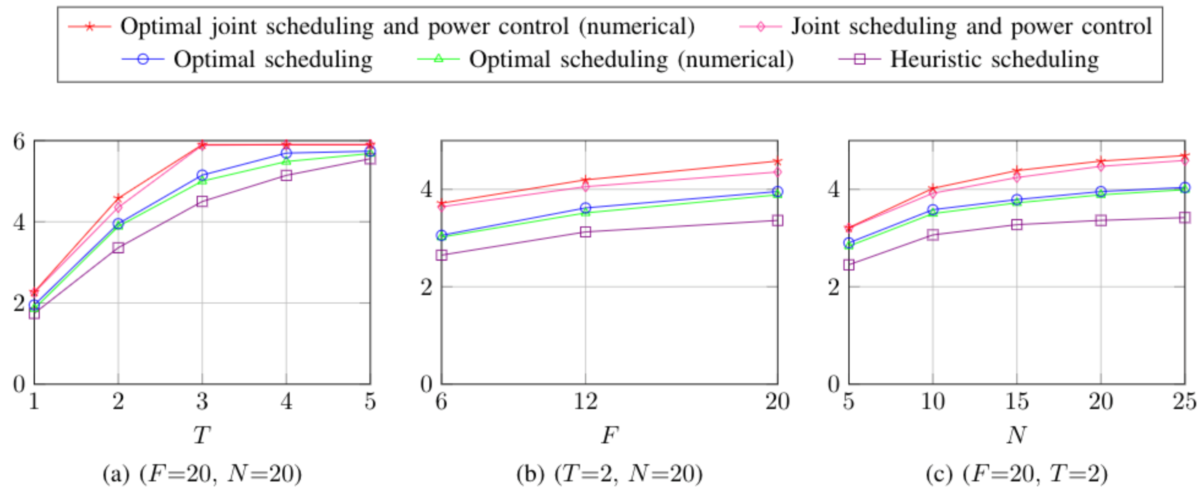


Figure A-13 Performance of different algorithms

A.6 Enhancing Control Channel Reliability by Using Repetitions (see Section 3.5.4)

Overview of benefits

Considering the DL case, here we compare our proposed approach (i.e. dual DCI) with the conventional case of having a single DCI. One-shot data transmission is assumed and with single DCI the URLLC target can be achieved with a combination of channels' error probabilities such as $\mathrm{P}_c = 1 \cdot 10^{-6}$ and $\mathrm{P}_d = 9 \cdot 10^{-6}$ (considering that generally PDCCH has stricter target than PDSCH). In Table A-4 below, we denote the maximum possible PDSCH/PDCCH (i.e. data/control channel) BLER targets and the possible benefits from having dual control. Note that for the DTX-to-ACK error probability target ($\mathrm{P}_{\mathrm{DTX}}$), the optimal case of 0 corresponds also to the case where second DCI is always repeated (in time or frequency). Also note that in the numerical evaluation below the minimal influence of ACK reliability has not been considered.

Table A-4 BLER targets of Dual-DCI versus Single-DCI

One-shot Tx target BLER $=10^{-5}$	$\mathrm{P}_{\mathrm{DTX}}$	PDSCH Target BLER	1st PDCCH Target BLER	2nd PDCCH Target BLER	Benefit
Single DCI	-	$9*10^{-6}$	$1*10^{-6}$	-	-
Dual DCI	0	$9*10^{-6}$	**$1*10^{-3}$**	**$1*10^{-3}$**	Relax PDCCH target, - Achieve SNR targets with lower AL - Less control resource
	10^{-2}	$9*10^{-6}$	**$9*10^{-5}$**	**$9*10^{-5}$**	

	0	**9.9*10^{-6}**	**3*10^{-4}**	**3*10^{-4}**	Additionally, Relax PDSCH target - Higher throughput (coding rate ↑)
	10^{-2}	**9.9*10^{-6}**	**~10^{-5}**	**~10^{-5}**	

Numerical example for overhead reduction evaluation

Applying higher AL to increase reliability of control channel essentially means high provisioning of the control channel with highly inefficient use of the spectral resources. Here, we provide a numerical example for the DL case to compare higher AL approach with our proposed opportunistic dual DCI. By deducing the results from [3GPP-R1-1716620] and assuming asymmetric repetition for the dual DCI (i.e. DCI is only repeated with a high BLER target if initial DCI is missed), it is expected that a ~75% saving of CCEs in average can be achieved as depicted in Table A-5 below.

Table A-5 BLER targets of Dual-DCI versus Single-DCI

Assumptions: [3GPP-R1-1716620]						
HARQ	DCI Transmission	PDCCH BLER	Coding Rate	AL	Total PDCCH resources (CCE)	PDCCH resources saving (%)
Optional Dual DCI (asymmetric)	1st	4*10^{-4}	1/15	8	8.28	**~75%**
	2nd	<10^{-6}	1/36	32		
Higher AL	-	<10^{-6}	1/18	32	~33	

Simulations for puncturing impact evaluation

It is expected that the puncturing of data channel will reduce its ‘decodability’, i.e. increase the BLER for a specific SNR. The problem in case of puncturing own URLLC data is even more delicate since the BLER target of URLLC data channel will be extremely strict. On the other hand, the dual DCI approach may also relax a bit the BLER target. Moreover, the URLLC UE knows exactly, at RE-level, which data resources have been punctured, after detecting the control repetition. We performed link level simulations for the DL case to evaluate the puncturing impact of the second DCI on URLLC PDSCH. Table A-6 below summarizes the LLS assumptions.

Table A-6 LLS assumptions; puncturing URLLC PDSCH

Parameter	Value
URLLC TB size	32 bytes

Bandwidth	20 MHz
Sub-carrier Spacing	30 kHz
CRC	16 bits
URLLC PDSCH Modulation	QPSK
Channel Coding	Turbo code, 3 iterations
Code Rate	1/3
Preemption size	6 / 12 / 24 … REGs (AL 1/2/4 …)
URLLC Slot size	14 OFDM symbols
URLLC CORESET size	2 OFDM symbols
DL antennas configuration	1Tx, 2 Rx
Equalization	MMSE
Channel model	Flat frequency, low mobility
Channel Estimation	Practical (averaging)

Observations from Figure 3-25 in Section 3.5.4 which illustrates the achieved BLER versus SNR:

- A small 2nd DCI, of AL1 or AL2 punctures about 17.5% or 35%, respectively, the small (yet robust) URLLC data transmission and the PDSCH can still be decoded with a marginal impact of <1dB for AL1 and ~2dB for AL2 at the 10^{-5} BLER target.
    - Especially for AL1 preemption, where the impact on BLER seems to be only about half an order of magnitude, this loss could be completely reversible from the relaxed PDSCH BLER target due to dual DCI.
- For AL4 or greater preemption, the PDSCH is undecodable.
- However, we should note that PDCCH of AL 1 can achieve very low BLER only at quite high SNR even for compact DCI. This may raise some coverage issues.
- Therefore, in that case, it is more feasible to use a 2nd DCI with more relaxed BLER target than the 1st DCI.

We also performed link level simulations for the case URLLC 2nd DCI punctures eMBB data instead, to evaluate the puncturing impact on eMBB PDSCH. Table A-7 below provides the additional simulation assumptions.

Table A-7 LLS assumptions; puncturing eMBB PDSCH

Parameter	Value
eMBB TB size	~2,1 kbytes or ~1.5 kbytes
eMBB SCS	15 kHz
eMBB PDSCH Modulation	16 QAM
Code Rate	1/2 or 1/3
Preemption size	6 / 12 / 24 / 48 … REGs (AL 1/2/4/8 …) equally distributed over even number of

	symbols at URLLC numerology
eMBB Slot size	14 OFDM symbols
eMBB CORESET size	2 OFDM symbols
DL antennas configuration	1Tx, 4 Rx

Figure A-14 illustrates the achieved BLER versus SNR for a less and a more robust eMBB PDSCH transmission, respectively.

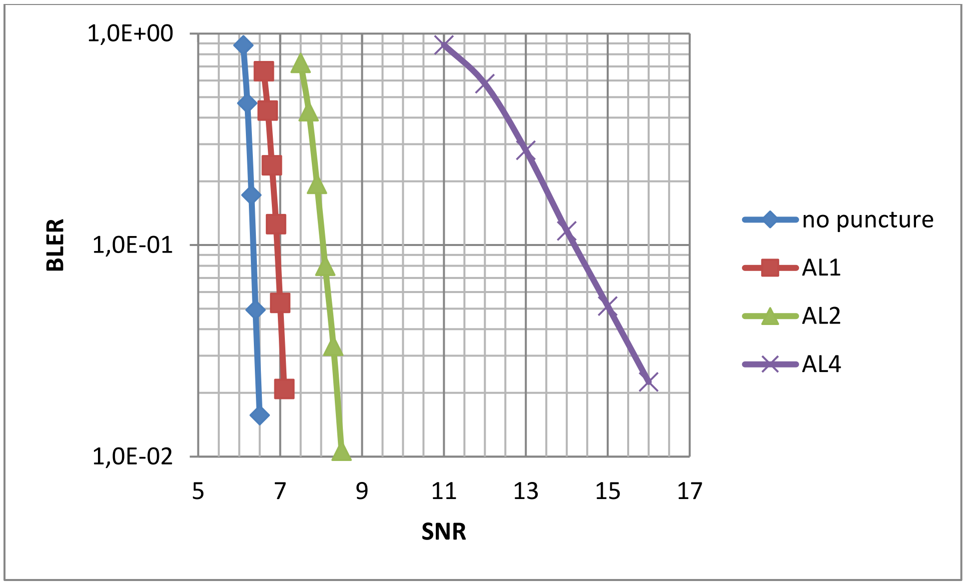


Figure A-14 eMBB PDSCH performance with/without 2nd DCI puncturing. 16 QAM, ½ code rate.

Observations:

- For 16QAM and ½ code rate eMBB transmission of a ~2.1kbytes packet, a small 2nd PDCCH puncture of AL1 or AL2 has a small effect (<1.5dB) at 10^{-1} BLER target.
    - Note: it is assumed here that preemption location is also known to eMBB UE, e.g. via DL PI, and punctured REs' LLRs are nulled at demodulation.
- An AL4 2nd DCI, punctures about 3.5% of eMBB PDSCH REs and impacts the performance more severely. However, the PDSCH can be still decoded for UEs experiencing fairly good channel or for UEs not at cell edge.
    - Note: no CBG operation is considered here. When a CB within a TB cannot be decoded, the TB is wholly discarded. Average performance can be even better by considering several CBGs configured within the TB.
- For AL8 or greater preemption, the PDSCH TB (as a whole) is undecodable.
- For more robust code rate of 1/3, the puncturing effect is less severe. eMBB transmission can even handle a 2nd DCI puncture of AL8 size, i.e. TB is decodable for

UEs >3dB away from eMBB coverage limit (assuming this is fine tuned to the no puncture case of 10^{-1} BLER) even with ~7% puncture.

- Therefore, in that case, even the exemplary -5 SNR target can be achieved with the 2nd DCI BLER targets we calculated in Table A-5 (e.g. by AL8 PDCCH as evaluated by [3GPP-R1-1720998]). Thus, it is possible in that case to achieve the URLLC reliability target even for UEs at coverage edge.

B 5G CAR Technology Components Use Case Support and Self-assessment

In this section, we provide a comprehensive view on the technology components introduced in 5GCAR, on how they individually support the key performance indicators most relevant to automotive applications, and an initial set of recommendations on how to integrate them in order to support the requirements introduced by the use cases defined in [5GCAR-D2.1].

B.1 Use Case Support

The technical components and system enablers defined in 5GCAR have been designed with the intent of supporting next generation automotive applications, which are a wide domain including diverse and complex use case classes. In 5GCAR, five use cases are considered, selected because of the way they cover different types of requirements and different paradigms of V2X communications. These use cases provide a comprehensive and relevant representation of Day-2 vehicular applications; however, their practical implementation will be deeply influenced by the local road configuration, regional driving patterns, local regulations, and by the business models chosen by the involved actors. These factors introduce a variability of scenarios not only from the economic standpoint but will also have an impact on their technical realization.

In 5GCAR, we hence developed our solutions in form of technical components, which are modules designed to address a specific challenge imposed by V2X communication. Hence, in order to address a specific scenario, a potential implementer needs to select the optimal subset of components to implement, based on their specific requirements.

B.2 Technology Component Overview and Self-assessment

The research work conducted in 5GCAR resulted in the definition of a collection of technology components belonging to seven major categories, as illustrated in Table B-1.

Table B-1 Classification of 5GCAR technology components

Category	References
Multi antenna techniques	Section 3.1.1 – Section 3.1.8
Resource allocation and management	Section 3.2.1 – Section 3.2.8
Sidelink design	Section 3.3.1 – Section 3.3.3
Full duplex	Section 3.4.1 – Section 3.4.3
Reliability enhancement	Section 3.5.1 – Section 3.5.4
Positioning	Section 3.6.1 – Section 3.6.6
Architecture	[5GCAR-D4.2, Section 3.1 – Section 3.14]

In Table B-2, we present a comprehensive view of all the technology components, including their description, a reference to the document wherein their formal definition and evaluation are treated in detail, and an assessment of the technical solution provided by each of them. Furthermore, we provide the reader with insights about potential drawbacks of each technology component, with the purpose of helping a potential implementer to choose the right building blocks to support the requirements of their use cases.

Table B-2: comparative analysis of benefits and disadvantages of 5GCAR technology components

Name of technical component	Reference	Technical component description	Pros	Cons
Sensitivity Analysis of the Predictor Antenna System	Section 3.1.1	This TC investigates the effectiveness of coupling compensation in predictor antenna systems.	The predictor antenna system enables CSIT at the transmitter also at high speed, which enables closed loop adaptive MIMO communications also at high speed. Coupling compensation is in general effective to mitigate antenna coupling degradations.	The predictor antenna system requires more hardware in its simplest form, but the predictor antenna can also be used for open loop communication, so compared to a two antenna receiver the extra complexity is on the signal processing side.
Predictor Antenna for Massive MIMO Adaptive Beamforming	Section 3.1.2	This TC makes massive MIMO adaptive beamforming schemes work for very high velocities.	The energy efficiency and the spectral efficiency of network-to-vehicle links is increased, and the network capacity is increased.	Requires an additional antenna on the roof of the car.
Genetic-Algorithm Based Beam Refinement for Initial Access in Millimeter-Wave Mobile Networks	Section 3.1.3	This TC proposes a machine learning based approach for beam refinement that is shown to be effective in maximizing the throughput for a given latency constraint.	Beam refinement with a global search approach with very few required iterations compared to exhaustive search, and that is robust also to mobility.	Iterative machine learning approach with no proof of guaranteed performance.
Rate Adaptation in Predictor Antenna Systems	Section 3.1.4	This TC proposed a rate adaptation scheme for predictor antenna systems.	The rate adaptation scheme maximizes the throughput in predictor antenna systems that cannot implement spatial interpolation of the channel	The performance is substantially better than a predictor antenna system without spatial interpolation, but inferior to a system with

			samples, which is much less complex than a predictor antenna system employing spatial interpolation both from a transceiver and a signal processing perspective.	optimal spatial interpolation.
Beam-Domain Broadcasting for V2N/V2I links	Section 3.1.5	This TC applies SC-PTM principle -based multicasting in beam-domain for mm-wave V2N/V2I radio links for delivering group common messages to a set of V-UEs within a geographical area.	The spectral efficiency of network-to-vehicle and infrastructure-to-vehicle links is increased and the network capacity is increased.	For optimized performance constant beam tracking for V-UEs of multicast group is required.
Beam-based Broadcast Schemes for V2X Applications	Section 3.1.6	Intelligent selection of the beam scanning scheme for V2X broadcast, which depends on the targeted performance metric.	Allows flexible configuration to achieve tradeoff between latency and overhead.	Defensive design by considering the worst user in coverage; No ACK/NACK scheme for the case of packet loss.
Beamformed Multi-Cast with HARQ feedback and retransmission	Section 3.1.7	Exploit redundant information of neighbouring beams for beam slot bundling. Low-overhead UE ACK/NACK schemes to trigger retransmissions for enhancing the reliability of broadcast/multicast service.	Allows usage of high-order MCS and significantly higher data rates in the medium and high SNR ranges compared to SoTA. The ACK/NACK scheme enhances reliability of the broadcast/multicast service.	Performance depends on correlation of neighboring beams.
LOS MIMO Design for V2V	Section 3.1.8	Exploit multiple solutions of the optimum antenna separation product for ULA antenna placement in car bumpers in a LOS MIMO V2V link, over a range of distances between the Tx and Rx vehicles, maximizing degrees	In contrast to design for fixed distances between the Tx and Rx, larger antenna separations are preferred for the design over a range of distances between the Tx	Though an antenna separation may be optimum at several distances, i.e. achieves the maximum degrees of freedom, at other distances the LOS MIMO

		of freedom of V2V link.	and Rx ULAs.	channel may be rank deficient.
Efficient Preemption-based Multiplexing of Services	Section 3.2.1	This TC introduces enhancements to the ability of sharing dynamically resources between eMBB and URLLC traffic. For DL case, enhancements regard HARQ feedback design and scheduling design for retransmission. For UL case, enhancements regard design for the UL cancellation indication and a RACH-like channel for SR transmission.	Maintain high data rate eMBB service despite preemption from sporadic URLLC transmissions while at the same time ensure URLLC latency and reliability requirements.	Requires additional specification effort to introduce to e.g. 3GPP standard.
Decentralized Pilot-to-Data Power Ratio Configuration in Multi-Cell Multi-User MIMO Systems	Section 3.2.2	Combination of a novel MU-MIMO receiver that is robust to CSI errors and a decentralized pilot and data power control algorithm to minimize the MSE.	Near optimal system-level spectral efficiency can be achieved by allocating proper uplink transmit power levels.	In multicell systems the global optimum in terms of (weighted) sum MSE may not be reached within coherence time in highly mobile scenarios.
Joint Optimization of Link Adaptation and HARQ Retransmissions for URLLC Services in a High-Mobility Scenario	Section 3.2.3	This TC jointly optimizes the selection of the modulation and coding scheme and the waiting time before re-transmission, based on average SNR knowledge.	The spectral efficiency of network-to-vehicle URLLC links is increased, and the network capacity is increased.	This TC has been assessed successfully under a constant noise power. Its robustness to bursty inter-cell interference needs to be checked.
Power Control and Scheduling to Mitigate Adjacent Channel Interference in Vehicle-to-Vehicle Communication	Section 3.2.4	Adjacent channel interference can be a severe problem for broadcast sidelink V2V communication. The TC provides a centralized solution for the joint power control and scheduling problem. The TC requires knowledge of the actual pathloss and shadow fading of the V2V links and the statistics of the small-scale fading.	The TC provides optimum scheduling and power control in the sense that the number of connected vehicles is maximized. This constitutes a significant performance gain compared to ACI-unaware scheduling and	The main disadvantage is the required complexity for computing the optimum solution, which is exponential in the number of scheduled vehicles.

			power control schemes.	
Sidelink Resource Allocation with Network Assistance using Multiple Antennas	Section 3.2.5	Exploit multi-antenna techniques (beamforming, MIMO) to orthogonalize transmissions at PHY level, and report nulling sets to sidelink scheduler (BS).	Increase in system capacity, as sidelink scheduler (BS) can take advantage of UEs' interference suppression capabilities to reuse resources more aggressively.	Additional reporting overhead on the Uplink (nulling sets).
Distributed RRM for Direct V2X Communication	Section 3.2.6	Cooperation between a group of 2 or more users for sidelink resource reservation in out of coverage scenarios.	Improves reliability and enables traffic prioritization in cases in cases of loaded channel and limited resources	Additional overhead introduced by sharing information about the whole group resources and the results of the sensing mechanism compared to the cases where each UE broadcasts only its own resources
Radio resource management in 5G-enabled vehicular networks	Section 3.2.7	A two-stage RRM framework for D2D-based V2X communication, where semi-persistent RB and power allocation is conducted for the V-UEs in the first stage and flexible resource allocation methods are applied to the C-UEs on a dynamic basis in the second stage.	The respective requirements of V-UEs (i.e., high reliability and low latency) and C-UEs (i.e., high data rate) can be satisfied simultaneously.	The needed channel information at the BS cannot be supported by the current LTE/NR standards.
V2V Resource Allocation and MAC Capacity	Section 3.2.8	This TC provides a resource allocation scheme that uses a hybrid of periodic scheduling and slotted aloha to maximize system capacity while keeping low delays.	Signaling is minimized, as network is not directly involved in MAC decisions. Latency is bounded and low, even for non-periodic messages. Network capacity is increased.	Network coverage is required for direct V2V communication.

Synchronization for the V2V Sidelink: Sequences and Algorithms	Section 3.3.1	Synchronization sequences provide information on synchronization source type, assisting the Rx user to select the highest priority synchronization source.	Synchronization source type info provided to sidelink users via synchronization sequences; highly-reliable “one-shot” sequence detection for fast and reliable link establishment	Due to larger number of sync sequences, decoding complexity is slightly increased.
Reference Signals Design for Direct V2X Communication	Section 3.3.2	Obtaining channel state information is crucial for signal detection and demodulation at the receiver and is important for advanced signal processing schemes at the transmitter. This TC provides design guidelines and a concrete structure for reference (a.k.a pilot) signals for the above purpose, in the context of direct device-to-device communication.	Achieving high channel estimation quality at very high vehicle speeds. At the same time the design allows for flexible reference signal patterns depending on, e.g., speed or numerology, to improve resource utilization efficiency.	Coexistence of multiple reference signal patterns in the same resource pool may lead to interference from data symbols of one transmissions to reference signal symbols of another transmission. However, only very limited impact has been observed.
Code-expanded Random Access for Reliable V2X Discovery	Section 3.3.3	This TC aims to minimize the signaling overhead required for V2X discovery based on a flexible structure of discovery signatures. Based on principles of code-expanded random access, the TC aims to improve the utilization of the scarce radio resources and allows the V2X discovery entity to obtain full knowledge of the proximity relations and timely discover sidelink-capable pairs.	The proposed V2X discovery scheme achieves significant performance gains in terms of minimum required time slots for discovering all potential sidelink pairs. Unlike beacon-based discovery that suffers from uncontrolled collisions, a proper discovery signature design was shown to improve the resource efficiency especially in the high traffic load regime.	Due to false positives introduced by the discovery signature design, the resource efficiency gains remain limited in the case of a low number of vehicles. The false positives can be mitigated by optimizing the signature properties (i.e., number of hash functions) but the computation time will be traded off.

Cognitive Full Duplex Communication in V2X networks	Section 3.4.1	A Cognitive method for opportunistic use of 5G resources for a Full Duplex D2D communication between two vehicles	A high speed D2D communication between two vehicles, desirable for real-time voice or video applications. No need for any dedicated BW, Sharing unused channels of a cellular network	No direct means of sensing of primary users' presence, may experience many interruptions in dense and congested cells
Full Duplex Collision Detection in V2X Networks	Section 3.4.2	Application of FD capability for detection and avoidance of collisions between CAM messages broadcasts.	Detection of collision of CAM messages and avoiding them. Increasing the success rate of CAM messages delivery and providing priority for emergency messages.	Requires FD capability of OBUs, which may increase the costs. A tiny decrease in throughput would happen due to false alarms.
Full Duplex Impact on V2X Performance	Section 3.4.3	The Full Duplex mechanism allows a transmitter to receive and transmit data simultaneously, on the same frequency bandwidth. However, FD mechanism induces self-interference that could dramatically affect performances.	FD is a response to the scarcity of radio resources. It improves the available frequency bandwidth allocated to UEs and vehicles. Judiciously used, it improves performance (throughput, delay, outage probability), and it optimizes the use of the frequency bandwidth	FD mechanism must be used only with "advanced receivers" since these receivers are able to mitigate the self-interference.
Fundamental Tradeoff Between Latency and Reliability	Section 3.5.1	Transmission over fading channels requires a proper choice of the modulation and coding scheme in order to exploit the diversity gains required for high reliability.	The combination of higher-order modulation with low-rate channel codes can achieve full diversity for block fading channels.	Slightly higher receiver complexity compared to conventional modulation and coding schemes designed for AWGN channels.

Enhancing V2N Reliability by Sidelink Cooperation	Section 3.5.2	V2N communication is assisted by cars in vicinity that cooperatively relay data packets.	High reliability improvements that scale with the number of cooperating UEs; URLLC facilitated with reduced costs in bandwidth.	Requires additional signaling and resource reservation in SL for cooperative retransmissions.
Sidelink Assisted Reliable Communication	Section 3.5.3	Taking full advantage of spatial diversity, two replicas of the same data packet are sent from the original UE and the assisted UE with the help of sidelink in case the first transmission is not success.	Enhanced reliability with increased diversity and reduced blocking probability (better support applications with high reliability requirements)	Potential unnecessary transmission and assisting UE management
Enhancing Control Channel Reliability by Using Repetitions	Section 3.5.4	Transmitting the control message twice (‘initial’ and ‘auxiliary’ control transmission) relaxes the BLER target of control transmission. The auxiliary message punctures other data transmissions that occur at the same slot with the URLLC transmission. Feedback signaling for the auxiliary message can be also considered to transmit it opportunistically only after initial message is missed.	Improve URLLC reliability. Reduced control channel blocking probability (thus, improved URLLC availability) and control overhead. One-shot URLLC data transmission can be supported when control resources are limited.	The puncturing of data transmission from auxiliary control will reduce its decodability. Increased blind decoding capability requirement for UE. ACK in UL whenever initial control message is detected, in case feedback signaling is considered.
Trajectory Prediction with Channel Bias Compensation and Tracking	Section 3.6.1	Enhanced time-based 5G positioning method combined with sensor fusion to localize and to track road users	The radio network serves as virtual eye for the car driver and complements onboard equipment like cameras and radar.	Pedestrians who don’t use the application cannot be detected. Too many false alarms may annoy car drivers.
Tracking of a Vehicle’s Position and Orientation with a Single Base Station in the Downlink	Section 3.6.2	The UE receives downlink mmWave signals, which are used to determine the geometric channel parameters of each multipath component. These channel parameter	Accurate positioning and mapping, fully exploiting all properties of 5G signals. Enables positioning even in	Additional overhead for synchronization. High computational complexity for mapping.

		estimates are then used to solve for the UE state (position, heading, clock bias), as well as to build up a map of the environment.	the absence of LOS.	
Beam-based V2C positioning	Section 3.6.3	High accuracy 3D positioning using 5G technologies.	LOS-based positioning requiring single eNB only can achieve positioning accuracy <1m for UEs close to eNB. Significant gains compared to SotA schemes.	UEs far away from eNB require additional support: - V2V cooperation - additional eNBs
Data-aided Beam-based C2V Positioning	Section 3.6.4	This component is based on UL and single-base station connectivity. It exploits both data and pilot symbols for positioning.	It can provide up-to 50% of improvement over pilot-based positioning as well as provide a “quasi-continous” localization of the UE	The benefits of using data for positioning requires that data symbols are received with high-SNR. Thus, availability can be a challenge.
Enhanced Assistance Messaging Scheme for GNSS and OTDOA Positioning	Section 3.6.5	This TC introduces a new mechanism in legacy Positioning Protocol (LPP) to broadcast assistance messages per cell a) via new System Information Block (SIB) messages or b) by introducing unsolicited messages at the NAS level.	Reduce positioning delay and power consumption at UE by reducing number of transmitted messages. Increase system resource efficiency from per cell sharing of assistance information. Allow new usages and use cases by allowing UE-based positioning and reducing positioning delay	SIB broadcasting of positioning assistance data requires many additional system information messages and may cause resource shortage for the SI messages. In case of OTDOA, an encryption scheme is needed for base station position due to broadcasting.
Multi-Array 5G V2V Relative Positioning	Section 3.6.6	Achievable V2V relative positioning accuracy for asynchronous vehicles equipped with multiple arrays.	Understanding the relative significance of angular and temporal measurements and determination of distances	More than one antenna arrays are required on each car to ensure the relative position is identifiable in

			for which 5G NR V2X requirements can be met.	asynchronous mode.
RSU enabled Smart Zone (SM-Zone)	[5GCAR-D4.2, Section 3.1]	This TC considers an integration of a functional architecture and a deployment architecture based on using RSUs for a flexible and effective support of V2X communications. The integration provides smart radio access service areas, referred to as Smart Zones (SM-Zones), which are local to targeted individual roads (covering just road areas) for serving V2X communications of UEs on roads, over either SL or Uu via either UE-type RSU or Base Station (BS)-type RSU. There are various enhancements on RAN level functions and procedures, focusing on RSUs and UEs for resolving inherent problems of broadcast-based SL, as adopted in LTE and NR, as well as for improving reliability, latency, efficiency and capacity in serving V2X.	This TC allows for keeping V2X communications truly local to individual roads with enhanced reliability and latency as well as adaptability, resource efficiency and multi-operator support.	This comes with the cost of deployment of RSUs along targeted individual roads, mounted on roadside lamps for instance.
Fast application-aware setup of unicast SL	[5GCAR-D4.2, Section 3.2]	This TC proposes an adaptive operation for setting up a needed unicast communication session over SL wherein the network-assisted L1 unicast SL is preferred whenever possible or otherwise L1 broadcast SL is applied. This TC also proposes that the UE which initiates the setup of the unicast SL may proactively allocate SL resources for the other involved UE for faster and more reliable SL transmissions.	This TC allows for selecting the most preferable unicast SL option as well speeding up the setup of the unicast SL needed for some cooperative driving use cases.	The application domain is limited to the use of SL.
SL and Uu multi-connectivity	[5GCAR-D4.2,	This TC provides an optimized solution for facilitating a SL and Uu multi-connectivity in which SL is established as the primary end-	This TC allows for improving reliability and/or data rate of local V2X communications	The application domain is limited to the use of SL. The secondary Uu connection

	Section 3.3]	to-end (E2E) connection between a pair of involved or impacted UEs (direct communication). In addition, a secondary connection between the impacted UEs is also established and routed via a serving base station (BS). That is, the uplink (UL) transmission from one impacted UE is mapped onto the downlink (DL) transmission to the other impacted UE so that the E2E communications between the impacted UE is realized over Uu interface via the serving BS. The secondary Uu connection is being used for assisting or enhancing data transmissions over the primary SL connection, e.g., with data duplication or split, respectively.	primarily over SL.	may inherently suffer from the multi-operator issue due to the national roaming restriction which can be resolved based on using V2X credential.
Location aware scheduling	[5GCAR-D4.2, Section 3.4]	The TC takes additional V2X service information into consideration when mapping a certain service to a certain QoS. In particular, the focus is on using location information, with regards to both vehicle location information (e.g., expected or planned trajectory) and service location information (e.g., area of relevance of a certain message) in order to optimize the message transfer accordingly.	Enable a dynamic adaptation of QoS parameters taking into consideration additional V2X service information instead of using static QoS mapping for services that might be sub-optimal and bring to an inefficient utilization of network resources	Integration or interoperability with network schedulers which work on different time scales (hundreds of ms) compared to message transfer optimization that can take up to tens of minutes (or even more depending on message size).
Infrastructure as a Service (IaaS) for vehicular domain	[5GCAR-D4.2, Section 3.5]	Interface AF(application function)-NEF (Network Exposure Function) will grant access of information (channel quality info, UE Location, Cell-ID, Cell Load, Average Network Latency, target Cell-ID (before handover execution)). These informations are issued from 3GPP functional entities (gNB, UDR (Unified Data Repository), GMLC (Gateway Mobile Location Center)).	Redeploy/deploy application components taking into account network conditions. Adapt/secure vehicular application behavior to network condition.	Defining Network architecture to offer infrastructure as a service could be seen as a complication compared to embedding the application inside architecture as an internal component (without defining proper interfaces)

		Interface/API could be set between NEF and Business Support System and/or Operating Support System for service (re)orchestration purpose.		and compared to just plugging/deploying the application at MEC level in a uniform way.
Redundant mode PC5 and Uu	[5GCAR-D4.2, Section 3.6]	In order to increase the system reliability, the Uu (UE to basestation) and PC5 (sidelink) are simultaneously used, transmitting two redundant replicas of the same messages	Reliability is increased, which is beneficial for applications with ultra-high requirements on this respect	Higher consumption of resources (which Implies the TC shall be used for specific use cases only) and increased complexity to manage message duplication and deduplication.
Evolution of infrastructure-based communication for localised V2X traffic	[5GCAR-D4.2, Section 3.7]	Formation of local end-to-end (E2E) radio data paths over the Uu interface, proposed to enable the fast and guaranteed transmission of localized data traffic among the involved devices, satisfying their QoS requirements and the features of the V2X services	Allows the realization of V2V services that more demanding in terms of latency and reliability requirements (e.g., cooperative manoeuvres, sensor data exchange, cooperative perception, see-through).	Extend BS's functionality by introducing routing capabilities. Additional solution is needed to be considered in the case of V2V communications of vehicles that belong to different mobile network oerators.
Use case-aware multi-RAT, multi-link connectivity	[5GCAR-D4.2, Section 3.8]	Based on use-case specific QoS requirements and network conditions, multi-connection would be a solution when a single link cannot deliver the use-case required QoS.	Use case-aware multi-RAT, multi-link connectivity would improve data rate, reliability, and latency via exploiting diversity/multiplexing gain among different available link/RATs. As a result, use-case availability (the probability that a use-case is declared as available) is increased.	Lower efficiency due to higher resource consumption (in case of exploiting diversity gain), necessity of cooperation between different RATs and more complex vehicles' transceivers to enable multi-link/RAT connectivity.

Multi operator solutions for V2X communications	[5GCAR-D4.2, Section 3.9]	The TeC aims at reducing delays and limited reliability of a multi operator environment by simplifying it to single operator based on regional split among the operators. Additionally, UE pre-registration and enhancements in the transition areas are proposed to reduce the transition delays. This solution can be applied in any type of cross border communication, such as the border crossing and the delays due to UE roaming.	Delays are reduced in the transition area since the UE is pre-registered and it is not needed to have increased service interruptions. Enhancements in the transition area, when the UE listens to broadcast channels of other operators facilitate the reception of emergency messages.	The solution if it applied in national level it requires agreements among the operations for splitting the area into single operator areas (in cross country cases there are no drawbacks with the pre-registration though).
V2X service negotiation	[5GCAR-D4.2, Section 3.10]	The TC is introduced to enhance network awareness about service requirements (spatial or time information, information about receiver/vehicle status, such as its location, speed, intended trajectory, etc.), which is usually referred to QoS only. The TC also consider information that the service might benefit from, e.g., network capability in fulfilling QoS in a certain area, network capability for message transfer within a certain deadline.	Support a more dynamic network-service negotiation, extending current QoS-based negotiation procedures. Facilitate the introduction of V2X-specific network features.	Network-service information exchange may require ad-hoc agreements. Network-service information exchange may be service-specific, with consequent high implementation effort. The way information exposed by the service are threated could be operator specific with consequent difficulties in offering same negotiation capabilities across operators.
Edge computing in millimetre Wave Cellular V2X networks	[5GCAR-D4.2, Section 3.11]	Vehicles need high computation capabilities as well as long battery lifetimes to execute computation-sensitive tasks during use-cases such as cooperative perception. This TC helps addressing the aforementioned problem via offloading computing tasks to an access node (which is equipped with edge computing capabilities) using high-rate	Faster computation due to higher computing capabilities at the edge, as well as lower energy consumption at the vehicles/UEs (due to offloading computing tasks) enabling low cost smart	Additional complexity to ensure delivery of computation results to the vehicle/UE while it is still under the coverage of the access node, which is hard to guarantee because of high blockage probability of

		millimetre wave connection.	vehicles with higher battery lifetime.	millimeter wave.
Dynamic selection of PC5 and Uu communication modes	[5GCAR-D4.2, Section 3.12]	Enable 5G systems to select, combine and dynamically switch the best communication interface (PC5, Uu) in order to support the QoS requirements of demanding services.	The dynamic selection of the appropriate interface for the V2X services that can be realised with both communication interfaces could provide several benefits: increase flexibility of communication networks and V2X services, better coordination of available Uu and Sidelink resources utilizing all communication interfaces, increase throughput via link aggregation, reduce latency via optimal link selection, increase reliability via link redundancy, maintain and guarantee the expected QoS by selecting (or switching to) the appropriate interface(s) and communication link(s).	Increases the complexity of the user equipment by introducing the capability to dynamically select the most appropriate mode.
Security and privacy enablers	[5GCAR-D4.2, Section 3.13]	This TC relies on symmetric encryption, using ephemeral symmetric keys derived from shared secret keys valid during short periods of time. Those shared secret keys are downloaded from a central entity in back office (called "key manager") over a connection requiring strong authentication (using a pseudonym certificate on the vehicle's side). The trust relationship is built upon the fact	Reduced latency and CPU processing compared to a security scheme where all messages are individually signed and verified using public key algorithms. Reduced cost for OEMs because the number of pseudonym certificates required per vehicles will be	A new "key manager" server (or multiple ones) needs to be deployed and operated in the back-office.

		that both sender and receiver can derive the same encryption key (i.e. both knows the shared secret key over a given period).	much lower.	
5G core network evolution for edge computing-based mobility	[5GCAR-D4.2, Section 3.14]	During their journeys, vehicles will likely be involved in a handover procedure involving two base stations (origin and destination) connected to different MEC servers (local data centers). For delay sensitive applications, the application-layer latency due to this occurrence shall be minimized, by predicting such handovers, and pre-migrating the applications and their internal state, from the origin MEC server to the destination MEC server state, for it to be ready upon handover completion.	Reduced application-layer latency due to inter-MEC handovers	Requires integration between MEC servers and core network functions, and further infrastructure deployment (links between local data centers)