Fifth Generation Communication Automotive Research and Innovation

# Deliverable D3.1
# Intermediate 5G V2X Radio

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# Executive Summary

The radio interface for V2X communication plays an increasing essential role for supporting the emerging new use cases targeting to support fully autonomous driving in all kinds of environments. Taking the direct input from WP2 in terms of use cases and requirements, the objective of Vehicle to Anything (V2X) air interface study is to design a flexible 5G V2X radio interface, enabling Ultra-Reliable and Low Latency Communications (URLLC) between road infrastructure, vehicles and other road users. In addition, we propose a set of positioning related solutions.

Moving forward from the most recent technology developments, including the V2X solutions specified by the 3GPP, and at the same time keeping in mind the research challenges resulting from 5GCAR use cases especially considering the simultaneous stringent requirements in terms of end-to-end communication latency (below 5 ms), reliability (99.999%) and positioning accuracy (down to 5 cm), this deliverable summarizes the intermediate outcome of 5GCAR project on the technology components designed for the V2X radio interface including positioning as communication enablers. The proposed technology components in this deliverable have a broad coverage and are classified into infrastructure-based, sidelink-based and positioning-based groups.

With respect to infrastructure-based technologies, the design of the physical layer interface considers both cm- and Millimetre Wave (mmWave) frequency bands. Realistic multi-antenna channel estimation and prediction schemes, mmWave broadcast and beamforming schemes, multi-beam/multi-node multi-vehicle communication techniques for at least diversity, and interference control are among the key technology components under. Dynamic multiplexing of different traffic types and radio frame design are investigated as well.

The 5GCAR sidelink-based V2X technology components include a network assisted reliable discovery mechanism, synchronization and reference signals design, adjacent channel interference mitigation and radio resource management, power control and scheduling mechanisms. The 5GCAR sidelink can be used to enhance the reliability of cellular communication and can take advantage of full duplex capability at vehicles.

Concerning positioning, a combination with sophisticated tracking algorithms like the Particle Filter and radio-based positioning is required to improve the accuracy. Positioning algorithm is investigated for the case with a single base station and antenna arrays both at the base station and terminal. Possible extensions of positioning protocol for future standardization are studied as well.

As the next step, 5GCAR project will further develop these and in some cases new technology components, investigate the applicability and performance, and integrate selected technology components into a unified system concept, and thereby contribute to the outcome of the 5GCAR project.

# 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 |
| **AOA** | Angle of Arrival |
| **AOD** | Angle of Departure |
| **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 |
| **CDF** | Cumulative Distribution Function |
| **CPE** | Common Phase Error |
| **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 |
| **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 |
| **E2E** | End-to-end |
| **eMBB** | enhanced Mobile Broadband |
| **ETSI** | European Telecommunications Standards Institute |
| **EVM** | Error Vector Magnitude |
| **GA** | Genetic Algorithm |
| **gNB** | Next Generation NodeB |
| **GNSS** | Global Navigation Satellite System |
| **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 |
| **LOS** | Line of Sight |
| **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** | Millimetre 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 |
| **PDCCH** | Physical Downlink Control Channel |
| **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 |
| **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 |
| **SC-PTM** | Single-Cell Point-To-Multipoint |
| **SC-FDMA** | Single Carrier Frequency Division Multiple Access |
| **SINR** | Signal-to-Interference and Noise Ratio |
| **SIR** | Signal-to-Interference Ratio |
| **SNR** | Signal-to-Noise Ratio |
| **SRS** | Sounding Reference Signal |
| **SUs** | Secondary Users |
| **TB** | Transport Block |
| **TBCC** | Tail-biting Convolutional Coding |
| **TDD** | Time Division Duplex |
| **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 |
| **URLLC** | Ultra-Reliable and Low-Latency Communications |
| **UTDOA** | Uplink Time Difference of |

| | |
|---|---|
| | Arrival |
| **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

The 5GCAR project aims to contribute to 5G network design, and specifically to design V2X technology components for V2X use case classes identified in the project. The requirements on reliability, latency, data rates, spectral and energy efficiency cannot be fully supported by today's wireless networks and V2X solutions and call for novel and innovative approaches, including the design of a new radio interface.

The radio interface of 5G communication systems in general, and 5G V2X communication systems, in particular, is designed to meet stringent end-to-end (E2E) latency, reliability, data rate, spectral efficiency and energy efficiency requirements imposed by a broad range of mobile broadband, ultra-reliable low-latency communication (URLLC) and machine type communication services. The use case classes (UCC) identified in the 5GCAR project [5GCAR D2.1] include cooperative manoeuvre, cooperative perception, cooperative safety, intelligent autonomous navigation and remote driving, which impose a broad range of challenging requirements on the 5GCAR radio interface. Indeed, the support of diverse use cases (UC), such as lane merge, see-through, accurate positioning assisted vulnerable road user (VRU) protection, high-definition local map acquisition and remote driving for automated parking, require that the 5G radio interface is capable of supporting high date rates with low latency and ultra-high reliability simultaneously. 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 V2X communication, including the radio interface (i.e. sidelink) between user equipment (UE) (incl. both vehicle UEs and other UEs) and the radio interface (Uu interface) between UEs and various infrastructure nodes such as cellular base stations.

To meet the 5G V2X requirements, as also described in the 5GCAR project, including the requirements on E2E latencies (below 5 ms), ultra-high reliability (99.999%), high density of connected vehicles and positioning accuracy (down to 5 cm), the 5GCAR radio interface design involves a rich set of technology components that can be combined and deployed jointly such that these requirements can be met. Specifically, the 5GCAR radio interface technology components include 10 infrastructure-based and 9 sidelink-based technology components that can be deployed in various combinations to facilitate the 5GCAR use case classes. In addition, 5 technology components are specifically designed to enable accurate positioning and the various services built around such underlying positioning services.

## 1.1 Objective of the Document

The objective of the present document is to give an overview of the radio interface technology components developed in the 5GCAR project in the first year. 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. Based on these challenges, the main objective is to describe the radio interface components together with preliminary, illustrative numerical results that help to obtain some first insights into the main idea and potential of each technical component. Finally, the objective is to discuss the next steps for the 5GCAR radio interface design.

## 1.2 Structure of the Document

The document is organized as follows. The next chapter reviews the key challenges that are imposed by the use case classes and use cases identified in 5GCAR. Chapter 3 is devoted to radio interface design and it is further divided into five subsections:

- Section 3.1, covers the state of art discussion for V2X communications.
- Section 3.2, contains the main infrastructure-based V2X technology components.
- Similar in Section 3.3, sidelink-based V2X technology components are described.
- Section 3.4, discusses the main positioning related technology components.
- Section 3.5 summarize the main outcome and the latest V2X standardization status is discussed.

A summary of the deliverable, key conclusions and next step are given in Chapter 4. In addition, Annex A discusses evaluation methodologies that are applicable to obtain numerical insights and test the applicability of the proposed technology components in relevant use cases. Moreover, Annex B provides further details of different technology components including initial simulation results.

# 2 Use Case Review and Radio Related Research Challenges

The design of the radio interface plays a crucial role in meeting the requirements specified in Deliverable D2.1 [5GCAR-D2.1] of the 5GCAR project. A short summary related different use cases is included in Table 2-1.

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

| | UC1: Lane merge | UC2: See-through | UC3: Network assisted VRU protection | UC4: High Definition (HD) local map acquisition | UC5: Remote driving |
|---|---|---|---|---|---|
| **Communication range** | >350 m | 50 to 100 m | >70 m | >1 km | Several kms |
| **Data rate per vehicle** | 0.350 to 6.4 Mbps | 15 to 29 Mbps | 0.128 Mbps | 0.96 to 1.92 Mbps | 6.4 to 29 Mbps |
| **Reliability** | 99,9% | 99% | 99.99% | 99.99% | 99.999% |
| **E2E Latency** | <30ms depending on vehicle speed | <50ms | <60ms | <30ms | 5-30ms including application layer latency |
| **Positioning** | | ~10m | 10-50 cm | 5-50cm | 5 to 50cm |
| **Communication types** | Vehicle to vehicle (V2V), Vehicle to Infrastructure (V2I), Vehicle to Network (V2N) | V2V, V2I, V2N | V2P, V2I, V2N | V2I, V2N | V2I, V2N |

Indeed, supporting unicast, multicast and broadcast communications between vehicles, vulnerable road users and infrastructure nodes in a spectral and energy efficient manner in the broad spectrum of 5GCAR use case classes imposes challenges on the radio interface.

To meet the requirements identified in D2.1, this document identifies the main challenges for the radio interface design as summarized in the Table 2-2. The careful identification of these challenges helps the design and evaluation of radio interface technology components and identify the bottlenecks in terms of performance over the radio interface.

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

| Challenge | Description (Why is it a challenge ?) | Comments |
|---|---|---|
| Providing high quality links for **V2N and V2I uplink** communications | In highly mobile environments, channel estimation and data reception is problematic. | Due to short coherence time and limited coherence bandwidth, both channel estimation and data equalization are challenging. |
| 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. |
| **Adjacent Channel Interference (ACI) mitigation** for V2V communication | ACI is especially difficult to mitigate when a large number of vehicles communicate with each other (e.g. in a convoy). | |
| **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. |
| Meeting the **latency and reliability** requirements of future V2X services simultaneously. | In highly mobile environments, channel estimation and data reception are problematic. | Future V2X services require user plane latency below 10 ms while providing 0.99999 reliability. |
| Providing **highly reliable V2V communications for high-speed vehicles.** | High Doppler shift, large delay spread, pilot contamination effects represent difficult challenges for direct V2V communications (oncoming traffic). | This challenge is present in several 5GCAR use cases and is especially severe in mmWave bands. |
| 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. |
| **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 the limited resources in unlicensed bands, there is a strong motivation to reuse cellular resources for V2X services. |
| 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. |
| **Increase the reliability** of sidelink unicast or multicast communications | 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 |

In the sequel, we discuss the main challenges listed in the Table above in detail. It is important to note that these challenges cannot be met by deploying existing technologies or technologies that are currently or will be under standardization (Rel.16), but need innovative solutions, that can partially be based on existing standards and research results. Providing reliable and low latency radio links for fast moving vehicles typically requires high quality channel estimation, adaptive and robust beam management and efficient adjacent channel interference mitigation. In addition, to meet the expected requirements on delivering large data volumes, resource sharing and coexistence between mobile broadband and URLLC V2X services also imposes challenges. Also, facilitating the reliable and timely discovery of peer entities in various 5GCAR use case classes impose requirements that are hardly met by existing technologies.

## 2.1 Meeting Low Latency and High Reliability Requirements in V2X Communication Scenarios

In the current 3GPP standardization efforts, as indicated in [3GPP17-38913], there are explicit requirements and design targets related to latency and reliability of future V2X services. Taking the example of a data packet of 300 bytes, the requirements are as follows:

- Reliability = $1\text{-}10^{-5}$, and user plane latency = 3-10 ms, for message relayed by Base Station (BS) as well as for direct communication via sidelink and communication range of (e.g., a few meters);

Meeting these requirements simultaneously in highly mobile vehicular scenarios is a major challenge. For future 5G V2X services, providing highly reliable communication for vehicles that move at very high speeds [5GCAR-D2.1] is expected to be a major requirement. This requires overcoming the challenges created by the dynamics of the V2X wireless environment, including high Doppler and delay spread due to moving transmitters, moving receivers, and moving scatters. This highly dynamic environment has large impacts on the direct device-to-device (sidelink-based) V2X communication where the transmitting and receiving antennas are placed at lower elevation than that of the BSs in cellular networks.

Furthermore, the high frequency bands that are tentatively considered for 5G V2X [5GCAR-D2.2], e.g. the mmWave band, can exacerbate the detrimental impact caused by Doppler spread, frequency error, and phase noise [ZZG+16]. Some of these sources of errors, e.g., the phase noise, were not a big issue in existing V2X communication technologies such as Long Term Evolution (LTE) V2X (3GPP Rel-14/15) wherein the targeted spectrum was under 6 GHz (e.g. the Intelligent Transport System (ITS) band at 5.9 GHz). On top of that, the uncoordinated nature of the direct D2D communication leads to pilot contamination due to overlapping transmissions from different nodes.

## 2.2 Mitigating Interference between V2X and Mobile Broadband Communications

Dynamic resource sharing between eMBB and URLLC services can be beneficial for some V2X use case classes. In the 3GPP technical specification [3GPP-22186], V2X use cases are defined for 3GPP 5G scenarios, which include comfort driving-related URLLC V2X (e.g. automated driving) and non-safety-related high data rate V2X scenarios (e.g. mobile entertainment). A well-known way of multiplexing eMBB and URLLC traffic is to use orthogonal frequency and/or time resources. Unfortunately, this is inefficient in terms of resource usage for sporadic URLLC transmissions (e.g. see [3GPP-R1-1610188]), such as event-triggered traffic. Hence, there is a need for dynamic sharing of resources (frequency and time) for eMBB and URLLC in V2X communications.

The dynamic multiplexing of eMBB and URLLC services can be realized by, for example, using a pre-emption-based mechanism where the URLLC transmission is ensured virtually zero latency and interference-free scheduling using the resource of an ongoing eMBB transmission. However, pre-emption corrupts the eMBB transmission since the eMBB decoder receives its scheduled information punctured; especially if eMBB receiver cannot be aware of the puncturing regions to try and decode the impacted messages or, at least, improve its soft combining with a retransmission. Hence, a main challenge for this technology component is to maintain high data rate service despite pre-emption.

Furthermore, various V2X services in 5GCAR scenarios require the exchange of large amount of data among vehicles. Examples of such services include the see-through use case identified by 5GCAR [5GCAR-D2.1] and the extended sensor sharing use case identified by 3GPP [3GPPRP-172502]. To support such services, the aggregated system bandwidth can be a promising enabler for high data-rate transmissions. For the unlicensed spectrum at 5.9 GHz, only 30 MHz of ITS spectrum are currently available for V2X safety use cases. Also, there could be a need for sharing LTE-PC5, New Radio (NR)-PC5, and Dedicated Short-Range Communications (DSRC). Therefore, to enable further increased aggregated sidelink bandwidth, licensed bands can be considered. For instance, a sidelink bandwidth up to 100 MHz could be possible if licensed bands, e.g., 3.5GHz, are used for V2X use cases.

As a typical scenario, V2X communications (including V2V, V2P (Vehicle to Pedestrian), and V2I) in licensed bands can be considered as a D2D underlay that coexists with cellular UL transmissions. In this case, intra-cell interference resulted from resource reuse between conventional cellular UE (C-UE) and vehicular UEs (V-UEs) may be problematic for the whole system. Moreover, it should be noted that the service requirements of V-UEs and C-UEs are quite different in terms of ITS requirements. For typical V2X services, there are stringent latency and reliability requirements. Also, the latency requirement is usually modelled as hard deadlines, i.e., the transmitted message is considered useless when its latency exceeds the deadline and there is no additional benefit when the latency is less than the deadline. On the other hand, for typical cellular infotainment traffic, the latency requirement is much less strict, and the system usually strives for high data rate subject to some level of fairness.

When the V2X/D2D underlay is placed in licensed spectrum and the transmitting vehicles are in the coverage of the BS, it is possible and efficient for the BS to coordinate transmissions and allocate resources to C-UEs and V-UEs in a centralized manner. However, how to efficiently mitigate the intra-cell interference resulting from resource reuse and satisfy the distinct service requirements of both V-UEs and conventional C-UEs is challenging. Additionally, the high mobility of vehicles brings more difficulties to the channel information acquisition needed at the BS. Hence, Radio Resource Management (RRM) becomes a crucial design aspect to render D2D as an eligible candidate for the provision of direct V2X communications.

## 2.3 Adaptive and Robust Beam Management in mmWave Spectrum Bands

Several V2X applications impose a requirement to deliver a common message to a set of vehicles over the V2I communication link. Among the different advanced V2X use cases identified in 5GCAR [5GCAR-D2.1], these include for example *Network Assisted Vulnerable Pedestrian Protection* (UC3) and *High Definition Local Map Acquisition* (UC4) falling under the use case classes of *Cooperative Safety* (UCC3) and *Autonomous Navigation* (UCC4), respectively. In such scenarios, the downlink (DL) transport mode based on multicast / broadcast improves the resource efficiency of the V2I/N links significantly compared to that of unicast distribution. Relying on the broadcasting feature, the common data of interest can be transmitted only once to the concerned vehicles instead of addressing every vehicle separately by sending the same message over multiple dedicated V-UE specific channels. The multicast / broadcast transmission mode can be envisioned to enhance the downlink capacity in the context of downlink re-distribution of the received Cooperative Awareness Messages (CAMs) and/or Decentralized Environmental Notification Messages (DENMs) messages which are characterized by modest packet sizes. Even higher gains can be expected scenarios, where vehicles receive high data rate V2I transmissions supporting applications such as high definition map acquisition and Gbps infotainment.

On the other hand, utilization of mmWave bands holds a great potential in realizing the high data rates required by these advanced V2X applications, due to the large spectral channels available. On the other hand, beamforming associated to the operation on mmWave frequencies necessitates adequate alignment of transmit and receive beams which impose a challenge in highly dynamic environments typical for V2X communication.

Beam-domain broadcasting (section 3.2.4) is targeting scenarios where V-UEs communicate at mmWave with infrastructure nodes such as next generation NodeB (gNB) or Road Side Unit (RSU) that are equipped with a large antenna array, and investigates adaptive and robust beam management techniques for V2I broadcasting / multicasting.

## 2.4 Providing High-quality Uplink for V2N and V2I Communications

V2X applications beyond road safety services, including platooning, automated driving and broadband infotainment services impose stringent latency, rigorous reliability, high data rate and large communication range requirements [CVG+16], [VSB+16], [CHS+17]. Such advanced V2X applications benefit from maintaining communication links with advanced infrastructure nodes, such as cellular BSs and RSUs equipped with a massive number of antennas and associated advanced transceiver and spatial multiplexing capabilities. The technology component described in Section 3.2.3 is designed for scenarios, in which vehicles communicate with the cellular infrastructure to receive high bit-rate V2N services. This technology component is especially applicable in use cases in which the infrastructure node is equipped with a larger number of antennas [SLY+16], [CHS+17]. These scenarios includeV2X communications for advanced driver assistance systems, fully automated driving, traffic efficiency, and Gbps infotainment applications, requiring high rate and low latency Internet access. In particular, several of the 5GCAR use cases identified in the 5GCAR problem space impose high bit rate requirements on the V2V and/or the V2I communication links, e.g. the intelligent autonomous navigation and remote driving use case classes [5GCAR-D2.1]

In multicell MU-MIMO networks, state of the art research has shown that controlling the power of the pilot as well as the data channels has a large impact on the system performance [Mar06], [GGF+14], [FMT16]. Efficient, scalable and fast converging power control algorithms, especially those that can account for the inherent trade-off between the power used for pilot and data signals are not available in the literature. The problem of near optimal pilot and data power control is especially challenging in the presence of fast fading channels with short coherence time and narrow coherence bandwidth, such as in high frequency bands, [VH15], [VCH17].

## 2.5 Mitigating Adjacent Channel Interference for V2V Communications (non-coverage mode)

Traffic safety applications typically use V2V broadcast communication to convey safety related messages. However, these applications require low latency and high reliability, therefore, setting stringent conditions upon V2V broadcast communication. One major limiting factor in V2V and V2I communication is ACI when these communication links use a dedicated spectrum (i.e., overlay spectrum) and all V-UE transmitters are scheduled in non-overlapping Resource Blocks (RBs) [HSS+16]. Section 3.3.1 studies various methods to overcome the impact of ACI by using proper scheduling and power control. Efficient and fast converging scheduling and power control algorithms are crucial for V2V and V2I broadcast communication. The technology component discussed in Section 3.3.1 is especially applicable in use cases where a large number of V-UEs are communicating with each other in a convoy (e.g., a one-directional highway, when all V-UEs are moving in the same direction) as well as when V-UEs are communicating with infrastructure. It can also be extended to any V2V and V2I broadcast communication scenario, including traffic efficiency and driver assistance systems.

## 2.6 Facilitating Highly Reliable and Timely Peer Device Discovery for V2V Communications

V2X discovery constitutes a necessary condition for the establishment of the direct communication path between vehicles located in close proximity with each other as well as for the realization of the sidelink message exchange. Several use case classes (UCC) and their respective use cases (UC) as identified in [5GCAR-D2.1], involve a V2X discovery process prior to the actual data transmission. In particular, in *lane merge* (UC1) scenarios which fall under the cooperative manoeuvre UCC, vehicles need to first be discovered by each other before they merge smoothly into the main lane without collisions and with minimum impact on the ongoing traffic flow. RSUs may also be involved in the discovery process to provide an additional assistance for the establishment of the communication among the different vehicles. In addition, in *vulnerable pedestrian protection* (UC3) scenarios which fall under the cooperative safety UCC, a successful discovery process among vehicles and road side users allows for a reliable and timely detection of the presence of vulnerable users, e.g., pedestrians, motorcycles, bicycles. After the discovery step, the local information can be processed for generation of alerts to the vehicle drivers when there is a high probability of potential accidents.

In both use cases (UC1 & UC3), V2X discovery is event-triggered, thus posing important design challenges for achieving highly-reliable and timely establishment of the discovery process. In addition, conventional discovery schemes may not be sufficient to address the stringent requirements in terms of latency, reliability and spectral efficiency that 5GCAR use cases introduce [5GCAR-D2.1]. Traditional localization-based vehicle discovery methods introduce high signalling overhead in high-mobility scenarios, since vehicles have to frequently report their current location to the eNodeB to maintain connectivity. In such schemes, vehicles should remain always connected or frequently alternate between idle and connected mode which leads to high power consumption. On the other hand, vehicle discovery schemes relying on beacon transmissions often lead to underutilization of the scarce radio resources. Beacon frames consist of primary and secondary synchronization signals followed by information bits. In massive deployment scenarios (as the ones envisioned in 5GCAR use cases) that entail a high density of connected vehicles, such contention-based vehicle discovery schemes suffer from uncontrolled collisions in the transmission of beacons which may compromise the reliability performance.

Thus, besides the need for adaptive resource allocation to optimize the utilization of resources required for information acquisition in the V2X discovery process, an appropriate technical component needs to rigorously consider the stringent requirements in terms of latency and reliability for a successful link establishment. The V2X discovery problem becomes especially challenging in highly dense scenarios, where the presence of numerous communicating units may lead to severe scalability problems. As discussed later in Section 3.3.6, our technology component “Code-expanded Random Access for Reliable V2X Discovery” is expected to address these issues.

## 2.7 Accurate and Ubiquitous Real-time Positioning

As shown in Table 2-1 the majority of V2X use cases identified in [5GCAR-D21] require knowledge of the current position of a road user on a certain level of accuracy ranging from a few centimetres (for UC5, remote driving) to several meters (for UC2, see-through).

Generally, we can consider the need for accurate positioning from two different perspectives. First, accurate positioning is an enabler for some of the challenges discussed in the previous sections. It is helpful for a robust and adaptive beam management in mmWave bands, especially for the timely prediction of handovers of moving road users. It is also useful for interference mitigation and proximity detection.

Second, the positioning procedure itself is a challenge for the radio interface design. An obvious requirement is the presence of a sufficiently large set of PRS in the downlink, uplink, and sidelink. These PRS should be configurable with respect to occupied bandwidth, time periodicity, power setting including PRS muting, as well as correlation properties for reliable TOA measurements.

Apart from TOA measurements, some of the positioning methods described in Section 3.4 are also based on accurate estimation of AOA and AOD of uplink or downlink beams in frequency bands above 6GHz. This fact leads to additional design requirements for the PRS. They should illuminate the scene in different angles with a variety of beamformers and a variety of combiners. Specific beamforming codebooks and procedures may be required, which are not supported in 4G today. The need of centimetre-level accuracy and the possibility for precise angular estimation places more strict requirements on synchronization and antenna calibration than for communication purposes. Furthermore, it is important to understand the synergies between positioning and communications, as channel estimation during communication can support positioning methods, just as position information can support beam management and handover prediction.

# 3 V2X Radio Interface Design

In this Chapter, after the short discussion of current V2X communication technologies, the V2X radio technical components developed in 5GCAR project are presented. For each technology component, the description starts with one table to summarize the main concept, followed by the detailed description. The simulation assumptions developed within 5GCAR project are included in Annex A which includes two parts:

- Simulation assumptions for system-level simulations, including the deployment scenarios, user deployment and mobility, antenna models, traffic models, channel models, and performance metrics.
- And a suggested list of parameters to be included for link-level evaluation.

When available, the initial performance evaluation of various technology components is included in Annex B.

## 3.1 State of Art for V2X Communications

The concept of V2X communication, including V2V, V2P, V2I, and V2N) services has been maturing for almost two decades. The first large scale services based on connections between vehicles and infrastructure nodes offered electronic toll collection and low-rate communication services between vehicle-mounted on-board units and peer vehicles or RSU. These services drove the standardization of Institute of Electric and Electronics Engineers (IEEE) 802.11p, which aimed at providing DSRC capabilities. Initially, the supported data rate was limited to 0.5 Mb/s, which was later enhanced up to 54 Mb/s [Vin12, LDT+17].

Recognizing the increasing demand for vehicular communications, in 2015, 3GPP launched an activity aiming at developing a technology that is from the start integrated into cellular systems and can offer ubiquitous vehicle connections over a wide geographic area. Indeed, the release 14 (Rel-14) of LTE includes a full set of technical components for vehicle-to-everything (V2X) services. These technical components, including radio interface and medium access control layer support, protocols and management functionalities together enable V2X communications. 3GPP-based V2X communications can be readily utilized for safety and non-safety (e.g., infotainment) purposes. Thus, the V2X support provided by 3GPP Rel-14 makes LTE a suitable technology for meeting the requirements of the European Telecommunications Standards Institute (ETSI) for delivering safety messages such as cooperative awareness messages (CAM) and DENM [SLY+16, CHS+17].

To expand the LTE platform to meet the evolving requirements of the automotive industry, the initial set of technical components provided by Rel-14 are currently being enhanced in Rel-15 and expected to further mature in Rel-16 of the 3GPP NR initiative. These enhancements are driven by the 25 use cases identified for advanced V2X services by the 3GPP Services and Architecture (SA1) working group, that are categorized as vehicles platooning, extended sensors, advanced autonomous driving, and remote driving [3GPP-V2X, CHS+17].

Main technical challenges for providing the 3GPP SA1 use cases and corresponding requirements by the Rel-15 and Rel-16 NR relate to the design of the new V2V broadcast, multicast and unicast sidelink. Coexistence of multiple unicast (multicast) and broadcast sidelink transmissions with the ongoing cellular DL and uplink creates new challenges for synchronization and time alignment between multiple transmissions and users. Moreover, network-assisted resource allocation needs to assign physical resources to users for the V2V sidelink, while at the same time avoiding high overhead for reference signals, as well as signalling overhead and information exchange between mobile users and the cellular network. Reference signal (RS) design further needs to support all PHY layer sidelink procedures at a reasonable overhead.

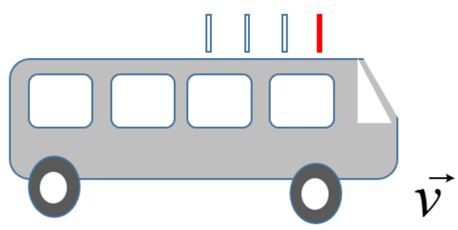
In parallel with the 3GPP Rel-15 work on LTE sidelink interface enhancements, the research community has been exploring the possibility of using mmWave frequency bands for V2X communications, as a natural extension and part of 5G cellular networks. The authors of [CVG+16], for example, argue that the current technologies for vehicular communications such as DSRC and 4G cellular systems will be insufficient for future connected vehicles that wish to share large amount of raw sensor data acquired by cameras and LiDARs. In that work it is proposed that a vehicle should have multiple mmWave transceivers to mitigate blockage and have tight spatial packing in vehicular environments. In line with the research results in mmWave communications, the 3GPP has also been studying evaluation methodology and channel models for sidelink in the above 6 GHz bands, to prepare for V2X services support by NR.

Although using mmWave for vehicular communications is part of the 5G connected vehicle solutions, communicating in mmWave presents some challenges due to unfavourable propagation characteristics including large path loss and LOS blockage probability and to the potentially large Doppler shift and spread. However, in [VCH17] it is shown that the Doppler spread is not necessarily large when directional beams are employed, allowing the Doppler shift effects to be handled more easily. On the other hand, directional transmission and reception introduces some channel state information (CSI) acquisition and beam alignment overhead. Indeed, obtaining accurate CSI at transmitting and receiving vehicles, as well as at infrastructure nodes, such as cellular base stations in high mobility vehicular environments is a challenging task. To this end, implementations combining analogue and digital components have been recently proposed for mmWave transceivers, also known as hybrid precoding techniques. In [LKJ+17], the authors study the spectrum and power allocation problem in device-to-device (sidelink) enabled vehicular networks, where the CSI of the vehicular links is reported to the BS periodically. In this setting, the sum throughput of all V2I links is maximized while guaranteeing the reliability of each V2V link with the delayed CSI feed-back. That work also proposes a low-complexity algorithm to find the optimal spectrum sharing strategy among V2I and V2V links and properly adjust the transmit powers. However, in these works the power setting to the pilot and data signals taking into account a sum power constraint and the negative effects of pilot contamination are not captured.

Today, localization relies mostly on Global Navigation Satellite Systems (GNSS), like the Global Positioning System (GPS), which can be complemented by onboard equipment of vehicles such as cameras, radar and other sensors [MTM12]. GPS works well in open areas with unhindered line-of-sight (LOS) links to a sufficient number of satellites. However, accurate GPS localization is challenged in tunnels, under bridges, in parking garages [KH06], while inappropriate weather conditions and obstacles, as other cars and buildings, can limit performance of other onboard equipment and hence the related location methods [MT06]. Alternatively, the radio access network can be utilized for obtaining localization. LTE supports the observed time difference of arrival (OTDOA) measurements of positioning reference signals (PRS) sent out from the base station and also UTDOA measurement based on Sounding Reference Signal (SRS). The tracked user reports the OTDOA/ Uplink Time Difference of Arrival (UTDOA) measurements to a network entity called Location Server. However, the localization accuracy is mainly limited by the non-line-of-sight (NLOS) propagation conditions of the PRS/SRS between base stations and tracked user, leading to a bias in the OTDOA/UTDOA measurements. This effect can be compensated partially by advanced methods like the Blind Learning Algorithm for channel bias Distribution Estimation (BLADE) [PLH16]. Nevertheless, even for perfectly synchronized base stations, the achievable localization accuracy can hardly fulfil the stringent performance requirements throughout all propagation conditions and deployment scenarios. In addition, map matching can be used to identify the actual road on which the user is moving. During the last years, many solutions for map matching have been proposed: probabilistic approaches [PSS01], fuzzy logic [QNO07], some advanced techniques [SRA+14] and particle filters with weights modified according to position and velocity in the map topology [PTA11].

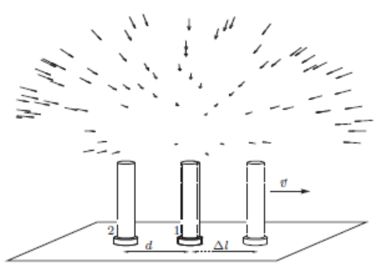
## 3.2 Infrastructure-Based V2X Technical Components

### 3.2.1 Sensitivity Analysis of the Predictor Antenna System

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


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

*The predictor antenna system*



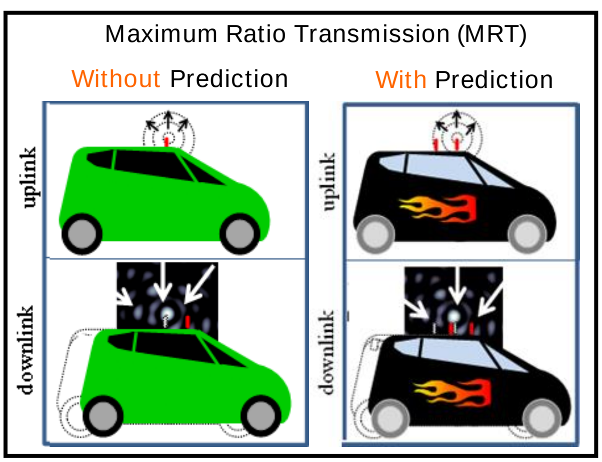
*A sample scenario for the analysis, in which two monopoles above a perfect electric conductor (PEC) plane move with speed of v in an isotropic environment.*
</td><td>
1. The predictor antenna concept is used to obtain channel state information at the transmitter side (CSIT), which is the key for robust V2I links, with multi-antenna systems for high speed vehicles. 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.<br>
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.<br>
3. We quantify the adverse effect of velocities, different from the target velocity, on prediction performance.<br>
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.
</td></tr>
<tr><th>Test Cases</th><th>Main Benefits</th></tr>
<tr><td>
1. The formula for calculation of the covariance matrix is defined in a Rayleigh multipath environment.<br>
2. We arbitrarily choose two classical types of two-element lossless thin wire antennas with separation *d* above an infinite PEC plane: (1) quarter-wavelength monopoles, and (2) horizontal half-wavelength dipoles
</td><td>
1. We clarified that the pattern deformation in the presence of coupling reduces these systems’ performance.<br>
2. The impact of accuracy of the self-impedances on the open-circuit decoupling method is negligible.
</td></tr>
</table>

### Description of Technology Component

Using predictor antenna systems for wireless moving relays and base stations on top of vehicles like buses, trains etc. has been shown to be a very promising approach for collecting channel state information to such fast moving nodes [SGA+12]. However, in practice a predictor system can be optimized only for a specified velocity, i.e., any deviation from the intended velocity results in a reduced prediction performance. On the other hand, it has been shown that coupling between different ports of a multiport antenna system used as a part of a predictor system may also reduce the prediction performance [JAM+14]. In [JAM+14] different decoupling methods were briefly reviewed and it was concluded that the open-circuit method is the most effective one to compensate for the coupling.

In this work, by integrating position and velocity vectors in the channel covariance matrix as seen at the antenna ports in a rich Rayleigh multipath environment, we quantify the impact of antenna coupling on prediction performance. Moreover, practically these predictor systems are designed for a certain target velocity. We further quantify the adverse effect of velocities, different from the target velocity, on prediction performance. 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. Illustrative results and conclusions are shown in Appendix B.1.

## 3.2.2 Predictor Antenna for Massive MIMO (M-MIMO) Adaptive BF

| System Model | Main Idea |
|---|---|
|  <br>In a Time Division Duplex (TDD) system, due the displacement of the car during the delay between uplink channel measurement and downlink 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 Maximum Ratio transmission (MRT) and Zero Forcing (ZF) reduce the cost of networks in terms of transmitted power and spectrum usage by exploiting CSIT. They are therefore essential to provide Network to Vehicular 5G efficient links.<br><br>Unfortunately, due to the delay $\tau$ between channel measurement and BF, CSIT is only exploitable up to a limiting speed $v$ of the vehicle. Beyond this “Wall of Speed” $v$, the network falls back to non-adaptive and less energy and spectral efficient schemes.<br><br>Previous simulation studies have shown that the Predictor Antenna make adaptive M-MIMO work for very fast moving connected vehicles.<br><br>However, up to now, this concept lacked experimental proof. |

<table>
<tr><th>Test Cases</th><th>Main Benefits</th></tr>
<tr><td>


The Nokia Bell Labs M-MIMO Test-Bed called Future Cell (F-Cell), with 64 antenna elements, has been used to measure the channel at 2.180 GHz (a frequency close to 3.5 GHz, for which we had an experimental license) to a car during drive-tests in Nokia Bell Labs Stuttgart area [PWB+18].

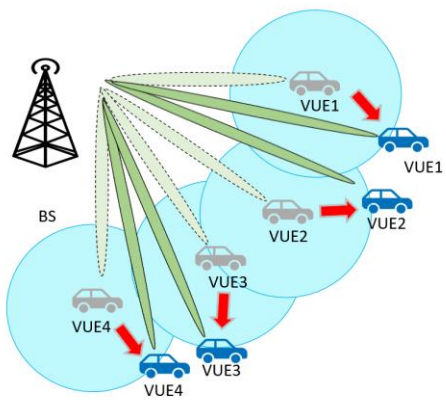

The car used during the drive-tests bears monopole antennas spaced by $d = 42\ cm$ (around 3 wavelengths at 2.180 GHz) and placed on a metallic plane
</td><td>
For the first time, experiments conducted in the 5GCAR project in November 2017 show that channel predictions based on the Predictor Antenna are accurate enough to make adaptive M-MIMO BF schemes such as MRT BF and ZF BF work even when the vehicle has moved by a displacement $\delta$ of up to 42 cm (corresponding to around 3 wavelengths at the tested frequency of 2.180 GHz) during the delay $\tau$ between channel measurement and BF.<br><br>
The corresponding supportable velocity $v$ depends on the latency between measurement and BF $\tau$ (as $v = \delta/\tau$).<br><br>
For instance, for a latency of 3 ms, the velocity of 500 km/h can be supported.
</td></tr>
</table>

## Description of Technology Component

Before 5GCAR project, the Predictor Antenna has been shown to be a promising approach for fast moving vehicles connected to the network through antennas upon their roofs [SGA+12]. Simulation studies [PHS+15] [PHS+16] [F5G-D2.3] have shown that, thanks to the Predictor Antenna, the maximum velocity (or “Wall for Speed”) up to which adaptive M-MIMO BF improves the energy and spectral efficiency of the network, could be pushed forward. 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 attains 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. However, it is important to notice that in [PHS+15] [PHS+16] [F5G-D2.3], practical solutions make sure that a fixed antenna spacing at the car side does not prevent from compensating all velocities up to $d/\tau$, where $d$ is the largest antenna spacing on the car. These solutions are based on flexible frame durations and spatial interpolation of multiple measurements from multiple Predictor Antennas. All these previous simulation studies assume that when the target antenna is at the same position as the one occupied by Predictor Antenna a bit earlier, it “sees” approximatively the same channel. In other terms, these studies assume that the measurements provided by the predictor antenna are predictions that are enough accurate, despite the fact that the predictor antenna and the target antenna are physically distinct antennas. Up to now, this assumption has been validated experimentally for a SISO only [BSG17] and never for adaptive MIMO.

Thanks to experiments conducted in the 5GCAR project in November 2017, for the first time, it is shown that the channel estimates provided by the Predictor Antenna are accurate enough to make adaptive M-MIMO (MRT BF and ZF) work for speeds of up to 500 km/h with a latency of 3 ms (equivalently up to 300 km/h with a latency of 5 ms). These experiments have been detailed in the recently accepted paper [PWB+18] and in the Annex B.8. The impact of antennas at the car side that receive different frequencies is FFS.

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

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



Blue circles indicate potential moving range for vehicle users during a certain time slot.

*Beam tracking Network with proposed GA-based scheme in a MU-MIMO System*

We consider a MU-MIMO system with moving vehicle users. The goal is to perform a system-level rate optimization by proposing and analysing 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.
</td><td>

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. Codebook-based beam refinement has been selected 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 utilised by setting the queen, i.e., the optimal beam sets, 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 realize the system-level optimization.
</td></tr>
</table>

| Test Cases | Main Benefits |
|---|---|
| 1. Beam tracking for moving vehicle users with proposed algorithm and comparison of the state-of-the-art schemes. | 1. The proposed GA-based scheme can reduce the beam refinement delay by utilising the spatial correlation. |
| 2. Compare the system-level performance in the cases of cooperative users and non-cooperative users. | 2. Cooperative users can improve the system-level performance at the expense of computation complexity and side-link communication overhead. |

### Description of Technology Component

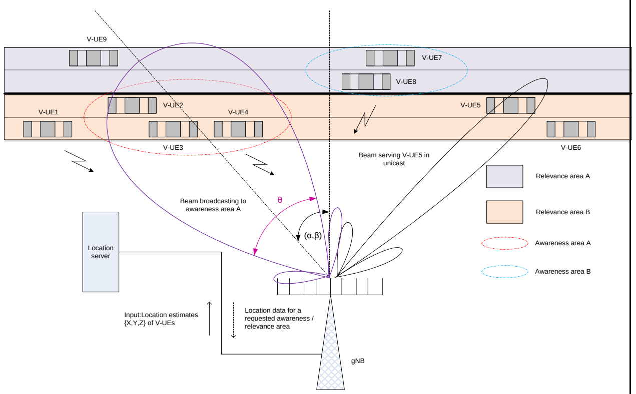
During the IA procedure, after a basic connection is established, the BSs and the users can begin exchanging messages and implement a beam refinement procedure to further improve the beam directions [MMM17D66]. The basic steps of the beam refinement approach are: selecting a precoding matrix at the BS while selecting a combining matrix at the receiver side out of predefined codebooks, sending test signal and finally updating the selection results based on the users' feedback about their performance metrics. The user mobility can also be handled by the beam refinement. With 5G, it is expected to access wireless networks not only at home or in the office, but also in high speed scenarios such as in a vehicle. In the moving scenario, the beam refinement process can keep tracking the beams by exploiting spatial correlations so that the computational delay can be remarkably reduced. Furthermore, for vehicular user equipment (V-UE), the system-level performance is improved if we allow a scheme using V2V communications to enhance the links [SS13].

Generally, IA beamforming at mmWave is different from the conventional one since it is hard to acquire the channel state information (CSI) at these frequencies. For this reason, codebook-based beamforming has been recently proposed as an efficient method to reduce the dependency on CSI estimation/feedback. Several works have been presented on both physical layer and procedural algorithms of codebook-based beamforming. However, in those works either the algorithms are designed for special metrics, precoding/combining schemes and channel models or the implementation complexity grows significantly by an increasing number of BSs/users. Moreover, the running delay of the algorithm has been rarely considered in the performance evaluation. On the other hand, generic machine learning-based schemes have been recently proposed for IA [GMS17] which can be effectively applied for different channel models with acceptable implementation complexity.

In this study, we evaluate the performance of beam refinement algorithms with our proposed GA-based method outperforming the state-of-the-art schemes: link-by-link search [QSM+15], two-level search [HKL+11] and Tabu search [GDY+16], in terms of end-to-end throughput. Moreover, the performance gain of deploying cooperative users (CUs) compared to non-cooperative users (NCUs) is also presented. GA solution is feasible to implement on-line with low complexity of reaching the sub-optimal performance. Illustrative results and conclusions are shown in Appendix B.2.

### 3.2.4 Beam-domain Broadcasting for V2N/I 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 criterion.

</td><td>

Utilization of multicast / broadcast transmission mode at mmWave band could enable high data rate V2N/I 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 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/I links utilizing geographical criteria and ii) to reduce the overhead associated with beam alignment and tracking procedures.

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

- Single cell environment with 3GPP TR 38.901 Geometry-Based Stochastic channel modelling framework.

</td><td>

- Resource efficient mechanism for the delivery of group common messages over V2N/I 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>

**Description of Technology Component**

In this study, multicast/broadcast transmission mode is employed over V2N/I links to provide means to transmit the same group common data simultaneously to a number of concerned vehicle UEs. The aim is to improve the overall system spectral efficiency while supporting identified 5G V2X applications associated to road safety, advanced / autonomous / remote driving and infotainment. Significant efficiency gains from multicast/broadcast mode compared to unicast delivery can be expected especially in high traffic density scenarios (e.g., urban city centres, major multi-lane highways, during peak hours).

More specifically, it is assumed that 5G NR cellular system can be employed at mmWave frequencies to provide Gbps V2N/I links, that is, 5G gNBs are considered to serve as infrastructure nodes for V2N/I communication. Moreover, for a multicast/broadcast beam, SC-PTM the (single-cell point-to-multipoint) scheme is utilized.

A section of a road is assumed to be covered by an NR cell. Vehicles entering the road section spanned by the cell range are assigned with a group RNTI (Radio Network Temporary Identifier) dedicated for multicasting / broadcasting of road safety and/or advanced / automated driving data across the V2N/I radio interface to V-UEs. In order to address the mobility of the V-UEs and consequent constant changes from a cell to another, V-UEs are pro-actively signalled / indicated about group RNTIs for the next cell(s) on the route. V-UEs monitor PDCCH (Physical Downlink Control CHannel) DCI (Downlink Control Information) for these RNTIs.

V-UEs send periodic standardized cooperative awareness messages (CAMs) to inform other V-UEs around them about their presence, instantaneous position estimate (e.g., navigation satellite based; with potential fusion with on-board sensor data), speed and trajectory. V-UEs geographical locations and speed can be estimated also by network infrastructure by additional means, e.g., based on uplink reference signals (RSs) transmitted by V-UEs or downlink RS based uplink measurement reports or in terms of best candidate beam indication.

A network entity, called location server, will collect, combine and host a (dynamic) database of V-UEs positions. As a centralized entity, the location server is able to compute and book-keep of different V-UE awareness range groups and keep track of V-UEs in different relevance areas by utilizing filtering based on V-UEs' geographical locations.

In the event, that a need to multicast / broadcast a group common message over V2N/I link arises, e.g., in the case of redistribution of high data rate raw sensor data or infotainment content, or delivery of data for High Definition Local Map Acquisition, the infrastructure gNB utilizes the location server database to optimize the transmit beamforming. E.g.,

- gNB may create an angular beam per awareness-range-group to broadcast/multicast the group-common message.
- In the event-triggered case, the broadcast/multicast beam can be optimized for a group of V-UEs in the relevance area.

The broadcast beam optimization discussed above refers to determining the azimuth and zenith angles (α, β) and beam width θ of the broadcast/multicast beam for a given awareness-area-group or relevance-area-group based on the location information hosted by the location server.

For each multicast/broadcast beam, the SC-PTM scheme is used. This means that SC-PTM specific Multicast Traffic Channel (SC-MTCH) is mapped on PDSCH and transmitted on PDSCH in regular subframes. This enables efficient resource utilization between unicast traffic and periodic or event-triggered multicast / broadcast traffic. A group of V-UEs receives the SC-PTM transmission by sharing a common group RNTI. This group RNTI enables concerned V-UEs to decode PDCCH and receive SC-MTCH data carried by PDSCH.

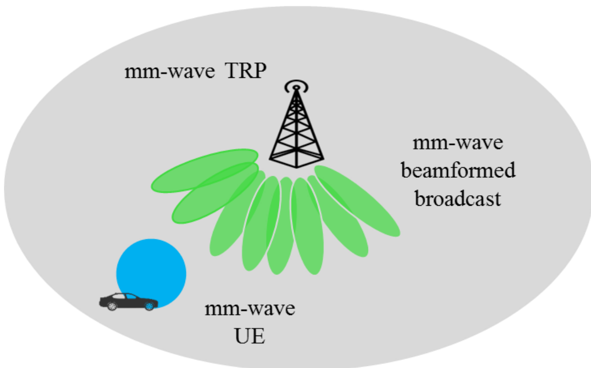
Due to use of sharp pointing beams at mmWave bands, it is necessary to align the TX and RX beams properly in order to guarantee sufficient effective Signal-to-Noise Ratio (SNR) at the receiver. While TX and RX beam sweeping process with exhaustive search could be used in case of static or modest moving V-UEs, with increasing V-UE speeds the beam alignment overhead and risk for outdated TX and RX beamforming weight vectors will increase significantly. In order to address the challenge of aligning the RX beam, this technology component investigates the feasibility of an approach wherein,

- The location information of the antenna arrays of the infrastructure nodes for V2N/I links is made available for the V-UEs.
- A V-UE estimates its relative position with respect to the gNB(s) or RSU(s) antenna array based on such a-priori information together with its own instantaneous location estimate.
- A V-UE computes RX BF weight vector based on its estimated relative position according to geometric BF principle. This may reduce the beam alignment overhead significantly.

In the research on this technology component, the goal is to leverage results of analysis and simulations to gain knowledge on the trade-offs between beamforming and resource utilization efficiency of beam-domain broadcast/multicast compared to unicast in mmWave V2N/I links.

### 3.2.5 Beam-based Broadcast Schemes for V2X Applications

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




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.*</td><td>

V2X (vehicle-to-vehicle, vehicle-to-infrastructure, etc.) communication systems revolutionizes the provisioning of diverse applications associated with driving safety, traffic management, and infotainment. For the V2X communication systems, the following technical problems are solved: Good enough coverage and reliability for V2X communication considering beamforming to assure good communication quality. Efficient beamformed broadcast to support e.g. high-definition map download, traffic information exchange, real-time positioning, etc.

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.</td></tr>
<tr><th>Test Cases</th><th>Main Benefits</th></tr>
<tr><td>

1. Comparison of latency and overhead with different beam patterns
2. Comparison of latency and overhead with different beam configurations
3. Comparison of latency and overhead with different frame structures
4. Comparison of latency and overhead with different block error rates</td><td>

1. Performance analysis of beam-based broadcast for V2X applications with different beam patterns, beam configurations, frame structures, and block error rates.
2. Leveraging the analysis and the simulation results to provide insights into the answers of key system design questions.</td></tr>
</table>

### Description of Technology Component

We assume that the TRP employs directional steerable antenna arrays and can perform both 2D and 3D beamforming. The UEs are assumed to be able to synthesize quasi-omni antenna pattern for signal reception. We consider a frame structure with length *T* consisting of a system control interval, a broadcast transmission interval, and a unicast transmission interval, as illustrated in Figure 3.2-1. In the broadcast transmission interval, the TRP broadcasts information via beam scan over different beam slots. The entire cell is covered by $N$ beam scan areas, where TRP forms $M$ simultaneous beams (limited by the number of RF chains at the TRP) to successively scan these areas. Within the duration $t$ of each slot, the formed beam(s) deliver information to UEs located in the corresponding areas. Note that these slots are separated by guard intervals (GIs) maintained for duration $t_{GI}$ reserved for beam switching in the case of hybrid or analog beamforming. The TRP periodically scans the cell via angular probing in the broadcast transmission interval within each frame, and maintain the scanning beam order in each frame, namely the beam(s) scan the same area of the cell during the same slot of each frame.

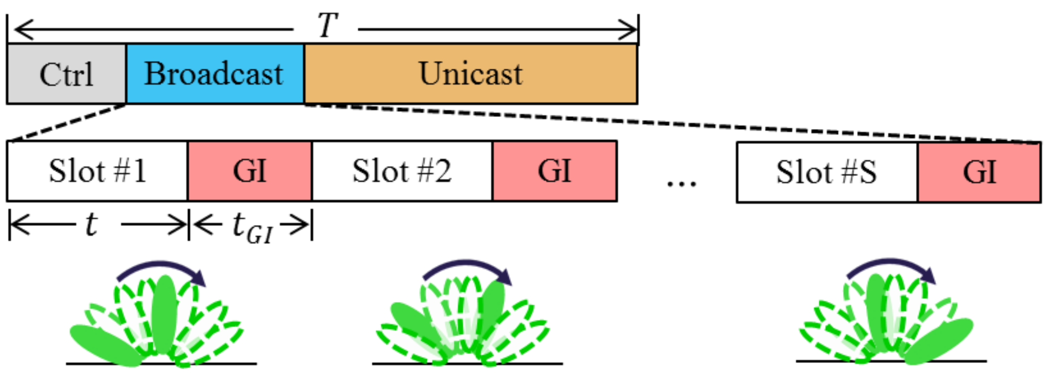



**Figure 3.2-1 Illustration of frame structure.**

The frame structure design can be further extended as follows, which is illustrated in Figure 3.2-2:

- Frame containing multiple broadcast Intervals
- Unicast-only frame
- Separating one broadcast interval into several frames

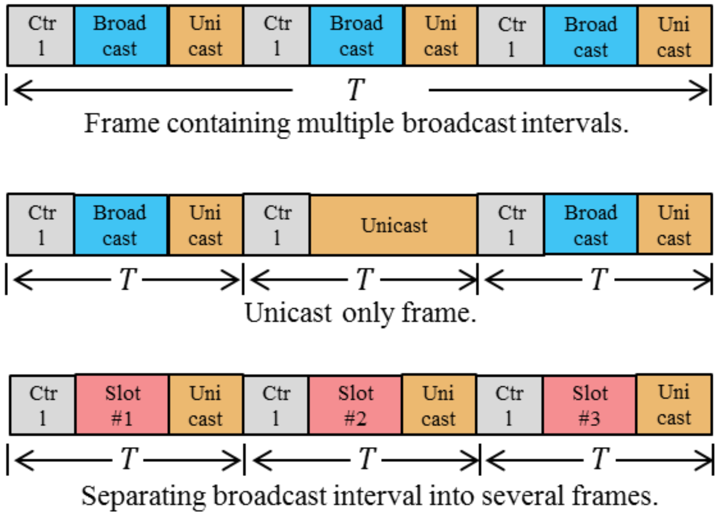


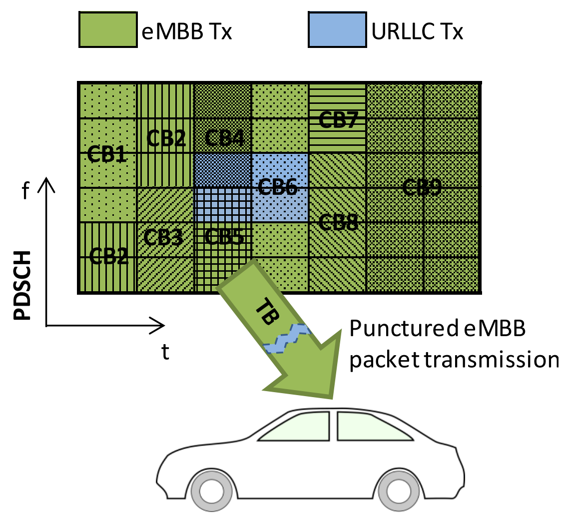

**Figure 3.2-2*: Illustration of different frame structure designs.***

To harvest the multiplexing capability, different broadcasting schemes are investigated to enable the TRP to broadcast information. The considered schemes are described as follows [LLC+17]:

- Single beam exhaustive scan: TRP scans the entire cell area with a single beam at a time in time-division (TD) multiplexing. We refer to this scheme as the baseline design, which is especially suitable for Tx with a single RF chain.
- Multi-beam exhaustive scan: If multiple RF chains are available, more than one beam can be formed simultaneously. In contrast to the baseline, this scheme exploits multiple simultaneous beams multiplexed in the frequency domain. Here, we apply three multiplexing schemes, namely frequency-division (FD), code-division (CD), and space-division.

### 3.2.6 Efficient Preemption-based Multiplexing of Services

**System Model**




Blue boxes indicate resources used for URLLC traffic, puncturing an ongoing eMBB transmission (green boxes) for a vehicle user during a certain time slot.

*Increased chance for eMBB UE failure to decode its transport block in preemption-based eMBB/URLLC multiplexing system.*

We consider a single cell environment with multiple vehicles and dynamic resource sharing between eMBB and URLLC V2X traffic in DL. The goal is to maintain high data rate eMBB service despite preemption from sporadic URLLC transmissions.

**Main Idea**

1. Puncturing of eMBB data from URLLC will lead to increased number of retransmissions. Conventional HARQ feedback does not take into account preemption knowledge at eMBB UE leading to coarse retransmission granularity which is spectrally inefficient. New HARQ feedback designs for finer knowledge of UE decoding at gNB can be useful.
2. With conventional scheduling of retransmissions after HARQ feedback, puncturing from URLLC will lead to high signalling overhead for scheduling these retransmissions and reduced eMBB UE throughput performance due to delayed correct reception of a packet. New scheduling design for subsequent (before HARQ) transmissions can be useful.

**Test Cases**

1. Evaluate the link-level performance in case of preemption to identify the impact and ways to alleviate.
2. Comparison of signalling overhead and performance between the conventional and the proposed designs.

**Main Benefits**

1. Low payload enhanced HARQ feedback designs can improve eMBB spectral efficiency at low additional signalling cost.
2. Low signalling scheduling design for subsequent transmissions can reduce overall control signalling and improve eMBB throughput performance.

**Description of Technology Component**

Puncturing (a.k.a. preemption) –based multiplexing is supported as a dynamic multiplexing mechanism in NR. Rel.15 [3GPP-38213] specifies the basic mechanism for enabling such process in DL of NR, where low-duration higher priority transmission (e.g. URLLC) can preempt an ongoing high-duration lower priority one (e.g. eMBB). Appendix B.3.1 discusses the relevance of the aforementioned scenario to the 5GCAR use cases. Furthermore, Appendix B.3.2 provides analysis, based on numerical results, used to identify areas of interest for solutions to preserve eMBB performance despite the URLLC preemption. In the following, we discuss our proposed solutions.

**Preemption indication -based HARQ-ACK feedback for single Transport Block (TB)**

In NR, multi-bit HARQ-ACK feedback per TB was introduced and code block group (CBG)-based transmission was specified; in that case, a few CBs from a TB can be grouped into a CBG to improve the system efficiency. The conventional approach for HARQ-ACK feedback is to have on ACK/NACK (Negative Acknowledgement) bit per CBG. However, when preemption indication is configured and available at UE, HARQ-ACK feedback should be designed to take it into account and obtain the throughput benefits of finer than CBG-level retransmission. To this end, our solution regards the configuration to a UE for sending *special* HARQ-ACK feedback per partially punctured CBG when receiving preemption indication. We foresee two ways of employing this (more details in Appendix B.3.3):

<u>Possibility-a</u>: More than one bit can be sent for every CBG that is partially punctured in order to give more information regarding to which CBs UE was really able to decode. For fully punctured CBG, only NACK can be given using 1-bit.

<u>Possibility-b</u>: Only 1-bit can be still sent per CBG, but ACK can be re-purposed to mean "ACK = Non-punctured area is decoded correctly".

**Binary search algorithm –based feedback for multiple TBs**

In NR, it is possible for UE to be configured to multiplex the HARQ-ACK for multiple TBs and feedback its decoding result within one uplink transmission. In that case as well, there is a tradeoff between configured CBG size (which is correlated to HARQ ACK/NACK size) and DL transmission efficiency. Obviously, if the CBG size is too small, there will be a lot of CBGs in each TB and a big ACK/NACK payload will be produced but a higher efficiency can be achieved with less unnecessary CBs retransmitted.

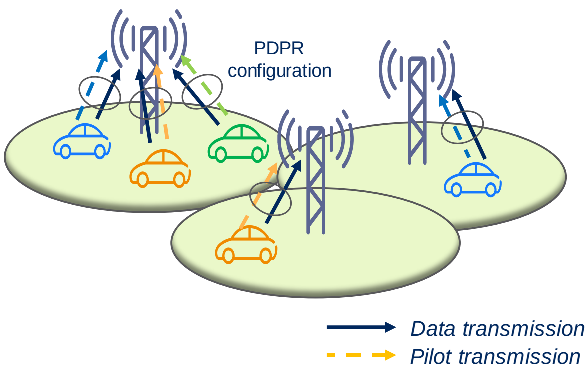
To maximize the efficiency, we propose to implement a binary step by step refined ACK/NACK indicator which can improve the granularity of CBG based ACK/NACK indication and/or the ACK/NACK payload size. The main idea behind our solution is to reuse the concept of Binary search algorithm in computer science. The procedure includes a multi-level (TB, CBG, CB) construction of the feedback bit vector where at each level *n+1*, a number of ACK/NACK bits are used to identify the successful or unsuccessful decoding of a CBG/CB only if the respective comprising TB/CBG at level *n* is denoted as NACK. In Appendix B.3.4 we visualise the proposed solution for an example case.

**Preconfigured, one-to-one mapped eMBB/URLLC data resource regions**

When preempted data needs to be retransmitted, gNB will have to decide which resources to schedule and how to indicate this to the victim UE. gNB can wait for a NACK response from UE and then use UE-specific DCI of next available scheduling unit to arrange the retransmission. This approach ensures that retransmission of resources occurs only when necessary and may burden less the DL throughput performance. However, delay may be introduced to the successful decoding of a punctured TB (or CBG) which cannot be reconstructed correctly just by using the preemption indication.

The performance degradation of preempted transmissions can be improved by using a preemption indication (PI) in conjunction with subsequent transmission of the preempted resources, i.e. a (re)transmission of preempted data before corresponding HARQ feedback. According to the scheduler capability and possibly load, UE could be advised to expect such subsequent transmission and monitor the respective scheduling DCI. Since gNB has deeper knowledge of expected data corruptions due to preemption (e.g. ratio of preempted resources, channel quality, MCS used) there will be cases where an unsuccessful UE decoding can be predicted with high probability. In that case, subsequent transmission can be beneficial in terms of reduced delay and UL signalling. Some more discussion on the proposed approach is provided in Appendix B.3.5.

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

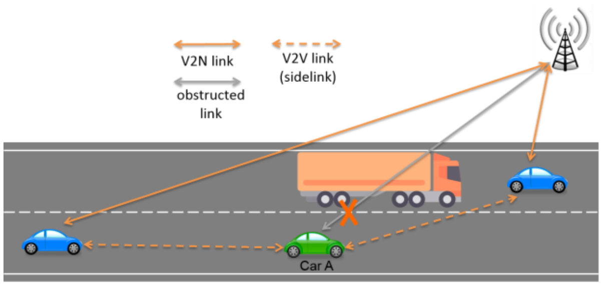
| **System Model** | **Main Idea** |
|---|---|
| <br><br>Same colour indicates the same pilot sequence (pilot contamination)<br>*Multicell V2N Network as a MU-MIMO System*<br><br>The multicell V2N system is modelled as a multicell multiuser MIMO (MU-MIMO) system, in which both the uplink data and pilot transmissions cause interference to each other. The pilot interference (contamination) is caused by intercell pilot transmissions, whereas both intra- and intercell interference is present for data transmissions. 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. | Previous studies have shown that the pilot-to-data power ratio (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 mean squared error (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 player, and tries to minimize 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 that is close to a global optimum sum-MSE. In the multicell case, the performance of the proposed algorithm is left for future work. |
| **Test Cases** | **Main Benefits** |
| 1. Single cell environment with uncorrelated Rayleigh fading channels<br>2. Single cell environment with correlated channel models. | 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.<br>2. The channel estimation quality at the BS improves, which in a TDD system can also be used for precoding in the downlink. |

### Description of Technology Component

We model the vehicular network as a MU-MIMO system, in which the V-UEs transmit orthogonal pilot sequences to facilitate channel state acquisition at their serving BS. The pilot sequences are constructed such that they remain orthogonal as long as the number of spatially multiplexed MSs 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 channel (a physical resource block [1]) 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.

We assume that the BS uses either the least squares (LS) or the minimum mean squared error (MMSE) estimator to obtain an estimate of the channel at the receiver in the uplink. 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, which we call 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 also close to a globally optimal power allocation. In highly mobile multi-cell systems, we expect that the system will continuously update its state due to changes in the channel conditions, vehicle mobility and changes in the intercell interference levels. The analysis of the impact of these types of system dynamics is left for future work.

### 3.2.8 Enhancing Reliability in V2X Communication by Exploiting Diversity from Cooperative Links

| System Model | Main Idea |
|---|---|
| <br>Vehicles moving on a highway are connected to a single BS; inter-cell interference is created by adjacent BSs with constant load. All vehicles maintain a V2N connection to the BS as well as V2V links to the vehicles in the vicinity. The V2N link to any vehicle may be blocked by a bypassing trailer, which is modelled by an appropriately configured shadow fading model. | We consider URLLC traffic with high demands on reliability and strict latency constraints in V2N communication. If the direct link between car A and the BS is blocked by a bypassing trailer, hampering reliable V2N transmission of data between BS and car A, communication to car A can still be maintained by cooperative behaviour of other cars in the vicinity of car A: Given that those cars maintain a good V2N connection to the BS themselves, they may forward a DL signal received from the BS to car A through the V2V link, or they can forward an UL signal received from car A through that V2V link to the BS. |
| **Test Cases** | **Main Benefits** |
| 1. Selection of cars in the vicinity (by car A / by BS) for packet retransmission after packet reception failure of car A.<br>2. Collaborative retransmission of packets by a group of cars in the vicinity after packet reception failure of car A. | 1. Maintain reliability for URLLC traffic in highway scenarios with deep shadowing occasions by exploiting link diversity through UE collaboration.<br>2. Enable Quality of Service (QoS) guarantee for URLLC services in V2N communication. |

**Description of the technology component**

We consider URLLC traffic with high demands on reliability and strict latency constraints in V2N communication. Deep shadowing of the link between BS and car A may render reliable transmission problematic, since successful reception of a packet cannot be guaranteed by retransmissions within the limited latency budget. In a highway scenario, a large trailer driving next to a car A can easily create such a deep shadowing effect, taking car A off communication with the BS. In this case, cars driving in the vicinity of car A, who themselves maintain a good connection to the BS (V2N link) and a good sidelink communication to car A (V2V link), can support V2N transmissions between BS and car A by collaboratively forwarding corresponding UL and DL packets. The key challenge in this scenario is the facilitation of cooperative communications by the cars in the vicinity with minimum additional signaling, while strictly fulfilling the latency constraints of the URLLC service. In our study, different collaboration schemes will be taken into account; their performance with respect to reliability and latency will be evaluated, and the required signaling for enabling the cooperation schemes will be assessed.

### 3.2.9 Fundamental Trade-offs between Reliability and Latency

| System Model | Main Idea |
|---|---|
| We model communication over fading channels with a block fading model, where a certain block of symbols experiences the same (or similar) fading coefficient. The number of resource elements within a block is a parameter depending on how fast the channel is changing. In the extreme case, each resource element experiences a different channel fading realisation. | The aim is to obtain design guidelines for coded modulation schemes according to the channel characteristics, ensuring high reliability with a limited latency. It is known that there is a trade-off between latency and reliability. The idea is to understand this trade-off from the theoretical perspective and optimize the coded modulation parameters accordingly. The obtained design guidelines will later be used to design actual coded modulation schemes. |
| **Test Cases** | **Main Benefits** |
| Single cell environment with fading channels having different characteristics, e.g. with different number of independent fading coefficients. | Understanding the fundamental limits and obtaining design guidelines for coded modulation schemes. |

**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. This bound, however, can only be achieved asymptotically, i.e. with 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 is an increased interest in this topic, e.g. [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 section, we first focus on the optimal design parameters for higher order modulation in the asymptotic regime, and later we evaluate the performance in finite lengths by using the tools from [PPV10].

If 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 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.

### 3.2.10 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. |
| **Test Cases** | **Main Benefits** |
| Single communication link. | The proposed scheme increases the system performance in terms of spectral efficiency.<br><br>It also increases the flexibility of the scheduling mechanism. |

**Description of Technology Component**

We consider a short TTI (shorter than the 1 ms in LTE), 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.

Unlike classical approaches where a retransmission is done immediately after the reception of a NACK, here we suppose that the transmitter can wait a duration of time equal to $x$ (in ms) before retransmitting the packet. Accounting for the latency budget, we can then calculate the maximum number of transmissions that can be allowed for a packet, which is denoted by $K(x)$.

Based on the above, the transmission policy we adopt can be described as follows:

- 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*; see Figure 3.2-3.
- A packet can be transmitted a maximum number of times equal to *K(x)*; i.e. the maximum number of allowable retransmissions is *K(x)*-1.

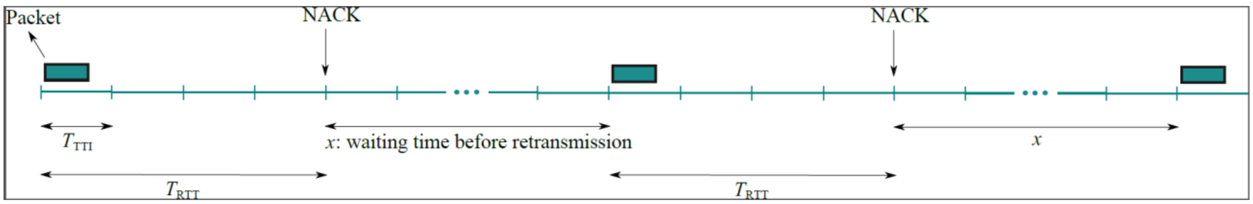



**Figure 3.2-3*: Example illustrating the proposed transmission policy.***

Our proposed transmission policy increases the flexibility of the scheduling mechanism, due to the waiting period (*x*) after the reception of a NACK and before retransmitting the packet. This flexibility is for instance important for scheduling URLLC services with very tight latency budgets. As a simple example, suppose there is a URLLC service with a latency budget of 5 ms. For such a service, and under some specific settings, we can afford to wait before retransmitting a packet in case of a NACK. If meanwhile there is a URLLC service with a more tighter latency budget (e.g. 1 ms), then this service can be scheduled during the waiting period.

Although we assume that the channel changes (independently) between two transmissions, our proposed transmission policy is also important for the more general case where the channel between two transmissions may not change; in such a case, the coherence time is greater than the RTT. Since the reception of a NACK generally implies a bad channel quality, waiting for the channel variation before retransmitting the packet can be beneficial because we may have a better channel quality (i.e. diversity).

Let $S_e(x,m)$ denote the spectral efficiency metric, which is a function of the waiting time *x* and the MCS level (i.e. mode) *m*. Our objective is to maximize $S_e(x,m)$ for a given URLLC service, i.e. under constraints of latency and reliability. This will be done by defining the corresponding optimization problem and finding the optimal *x* and *m*.

In Annex B.9, results on the optimal maximum number of transmissions, the optimal MCS level and the optimal spectral efficiency as a function of the average SNR are presented.

## 3.3 Sidelink-Based V2X Technical Components

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

**System Model**

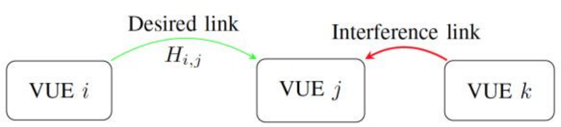
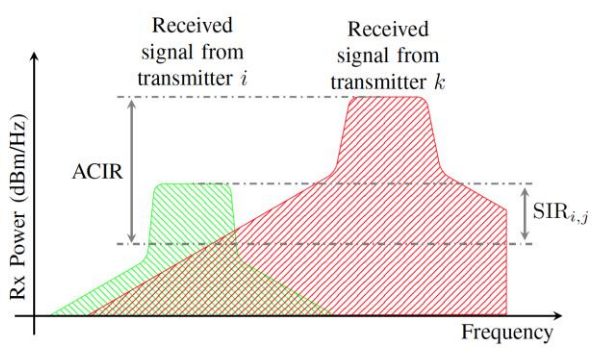



Fig. 1: System model




V-UE *i* and *j* are the desired transmitter and receiver, respectively. The received signal-to-interference ratio (SIR) at V-UE *j* is mainly affected by the interferer V-UE *k*, which is transmitting on a nearby frequency slot. The problem is severe when V-UE *k* is located near to V-UE *j* and/or when the transmit power of V-UE *k* is high compared to V-UE *i*.

We assume V-UE *i* is connected to V-UE *j*, if the received signal-to-interference and noise ratio (SINR) of V-UE *j* is above a certain threshold.

**Main Idea**

1. The performance of V2V and V2I communication links depend on both co-channel interference (CCI) and ACI. However, CCI can be avoided by scheduling V-UE all transmitters in non-overlapping frequency slots. In this work, we first quantify the impact of ACI in V2V communication. In order to reduce the impact of ACI, we propose efficient scheduling and power control schemes. Our scheduling and power control schemes can be extended to include V2I links as well, when channel parameters are slowly time varying.
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 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 is also a highly sensitive problem, we propose methods to reduce the sensitivity of the problem formulation.

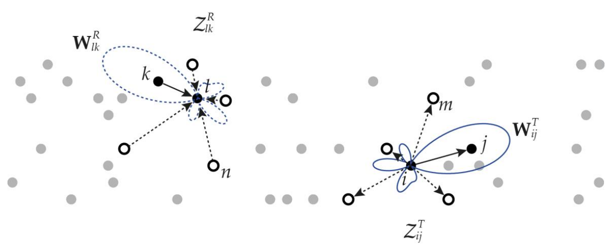
| Test Cases | Main Benefits |
|---|---|
| Quantify the effect of ACI for various transmission schemes.<br><br>We consider a convoy of *N* V-UEs, where each V-UE wants to broadcast periodic or non-periodic messages. The periodic messages include a V-UE's current status (position, velocity, etc.), which enable the V-UEs to enhance the awareness of its environment. We compare the number of connected V-UEs with our proposed scheduling and power control algorithms to some state-of-the-art schemes. | • 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 have better performance compared to a non-ACI aware scheduler.<br>• The problem of optimal scheduling and power control is formulated mathematically. The optimal scheduling and power control significantly improve the communication link performance.<br>• Heuristic schemes proposed for scheduling and power control are less complex than the optimal approach, but 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 B.10). Next, we study how to reduce the impact of ACI by using various scheduling and power control strategies. 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 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].

### 3.3.2 Sidelink Resource Allocation with Network Assistance using Multiple Antennas

<table>
<tr><th>System Model</th><th>Main Idea</th></tr>
<tr><td>We consider a cellular network with sidelink UEs, which are in cellular coverage and are connected to the BS. The UEs perform measurements and report information their BS, whereas 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.</td><td>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.</td></tr>
<tr><th>Test Cases</th><th>Main Benefits</th></tr>
<tr><td>To be studied further.<br><br></td><td>1. Increase in system capacity, as the sidelink scheduler (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 channel, as interference is suppressed at the physical layer.<br>2. Low overhead (reporting of nulling sets to BS), compared to the overhead that would be incurred if the full channel state information (CSI) were reported.</td></tr>
</table>

#### Description of Technology Component

In *scheduled resource allocation* mode (mode 3), 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 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., up to 16 transmit and receive antennas.
- 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 3.3-1, 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 neighbouring UEs. Moreover, based on the pilot assignment scheme as also shown in Figure 3.3-2, UEs can estimate the channel to a set of these nearby UEs. We refer to such a set as transmit nulling set $Z_{ij}^{T}$. 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 $Z_{lk}^{R}$.

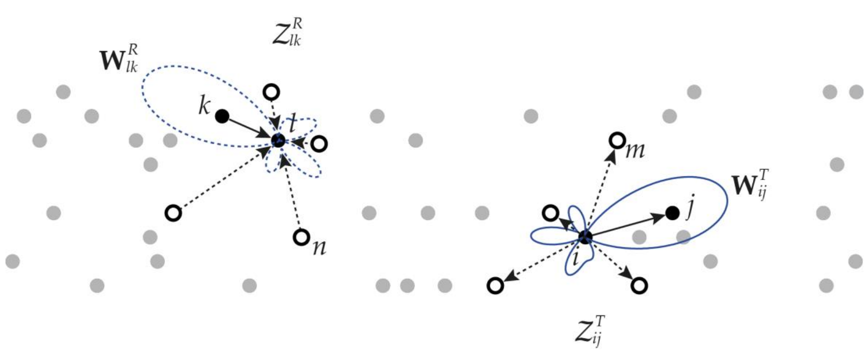
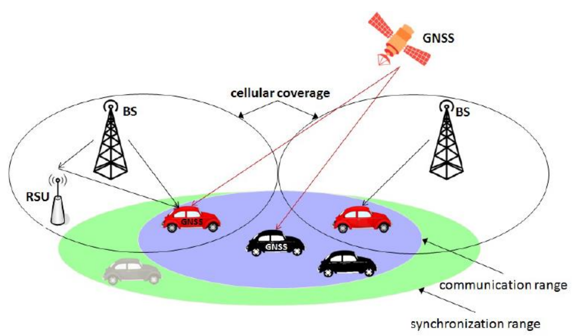



**Figure 3.3-1**: **Illustration of transmit- and receive side nulling sets, here denoted by ($Z_{ij}^{T}$) and ($Z_{lk}^{R}$).**

In general, the sets $Z_{ij}^{T}$ and $Z_{ij}^{R}$ does 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. In the sequel, however, the same notation $Z_{ij}$ is used for simplicity, covering both cases. Thus, $Z_{ij}$

denotes the set of UEs toward which UE $i$ can form nulls when transmitting/receiving to/from UE $j$.

### 3.3.3 Synchronization for the V2V Sidelink: Sequences and Algorithms

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

A scenario of a mobile (vehicular) network in a cellular environment is considered, including in- and out of coverage UEs, some of which are equipped with a GNSS receiver. Co-existence of possibly in-band sidelink and cellular uplink/downlink transmissions within a frequency band requires time alignment of all over-the-air signals to avoid interference between multiple links. Thus, time synchronization between the network nodes, including gNBs, relays/ RSUs, sidelink-capable UEs and other cellular UEs is required.</td><td>A novel scheme for generating hierarchically structured sequences, which can be used to distinguish between different synchronization cases, e.g. synchronization status or the type of synchronization source of a transmitting UE. Sequences defined by $n$ segments, where each segment is chosen from a set of two possible sub-sequences, can identify $2^n$ different cases. Defining further the sequences to be complex conjugate with each other is a computationally efficient choice. Considering LTE framework as a starting point, Zadoff-Chu sequences can be used for designing such sidelink synchronization signals. By selecting the root indices for the sequences according to this proposal, orthogonality between sub-sequences can be further maintained.</td></tr>
<tr><th>Test Cases</th><th>Main Benefits</th></tr>
<tr><td>Evaluation of the detection rate of the proposed sequences over time-continuous fading radio channels.</td><td>• More efficient usage of the time/frequency resources occupied by synchronization signals.<br>• Additional information carried by the synchronization signals, e.g. type of synchronization source or coverage status.</td></tr>
</table>

## Description of Technology Component

For the sidelink, several sidelink synchronization sources are available, including base stations, GNSS, or other sidelink-capable UEs. This information is typically not transmitted through the sidelink synchronization sequences and therefore hierarchical synchronization/prioritization of synchronization signals is not possible during the detection procedure. Following hierarchical search, in-coverage users synchronize to their serving BS, which requires detecting downlink synchronization signals. In the absence of cellular coverage, the time reference of GNSS shall be used. If GNSS reference is not available, out-of-coverage UEs synchronize through sidelink synchronization signals sent by other in- or out-of-coverage UEs. In order to apply a hierarchical selection/combination, information about the type of the synchronization source and optionally the number of hops between the initial source and the UE transmitting the sequences will need to be carried by the synchronization signals.

Using two different sequences (PSS1 and PSS2) for the primary synchronization signal e.g. with *n* segments, $2^3$ = 8 different cases can be "binary encoded" and thus distinguished. By further using complex-value property PSS1 = PSS and PSS2 = PSS*, with {}* denoting the complex-conjugate operator, any cross-correlation-based detection will be computationally more efficient. For both PSS and PSS* cross-correlation of incoming signal S, two of the real terms will the same when applying a cross-correlation with local copies of PSS and PSS*, resulting thus in 50% lower complexity compared to using totally different sequences.

$$S \times PSS = Re\{S\} \times Re\{PSS\} + Im\{S\} \times Re\{PSS\} + Re\{S\} \times Im\{PSS\} + Im\{S\} \times Im\{PSS\}$$

We further recall a Zadoff-Chu sequence property: for a sequence with length L (L=63 in LTE) and root index u1 (u1 a relative prime number to L), sequence using u2 = L – u1 is its complex conjugate. It is noted that PSS1 and PSS2 remain orthogonal with each other.

Considering all above, Figure 3.3-2 shows an example for n=2, which distinguishes 4 different cases. Compared to the resources occupied by legacy LTE signals this scheme comes with no additional overhead.

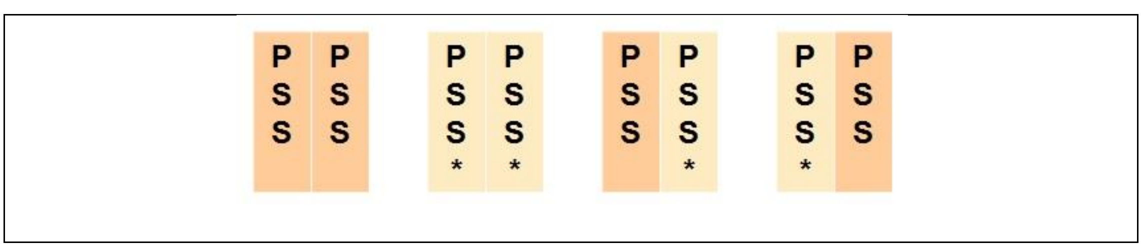



**Figure 3.3-2 – Example for two-segment sequence. With n=2, up to 4 different cases can be distinguished.**

The above methodology further results in the following proposal, as shown in Figure 3.3-3. Here, the benefit of the scheme is that it allows for one-by-one parameter detection and –as shown in the following- backwards compatibility with legacy LTE signals and UEs.

| Seq. part | Part 1 | Part 2 | Part 3 |
|---|---|---|---|
| Info. | User-ID (first part of it) | Cellular network or GNSS reference | Direct reference or over another UE |
| Comment | Same as in LTE | Essential information | Additional information |

**Figure 3.3-3 – A concrete proposal for the LTE sidelink with n=3 segment sequence.**

For reference, Figure 3.3-4 shows an implementation of the two-step detection at a receiver. In addition to the basic cross-correlation based operations, which have been already described above, it is recommended to perform the procedures highlighted in blue. There, the phase shifts estimated due to time/frequency offsets are compensated, before the operation is performed again (blocks with dashed lines). This validates and refines the initial estimates and provides a less-distorted signal to the next steps of the signal processing chain.

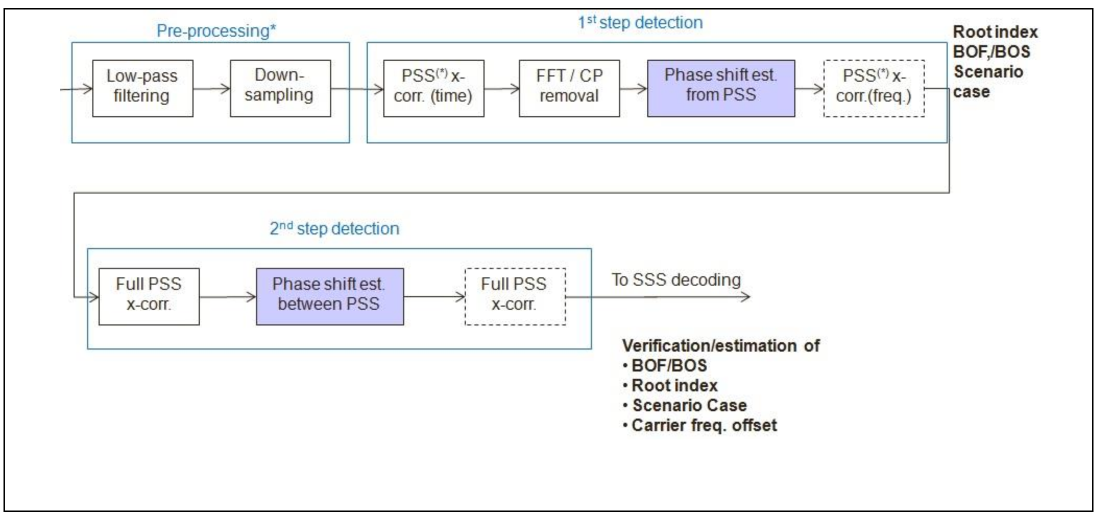



**Figure 3.3-4– Implementation of the two-step detection procedure at the receiver. User identification, time synchronization, "case" (e.g. type of synchronization source) and frequency synchronization can be performed during the acquisition phase.**

Figure 3.3-5 depicts the sequence detection probability over the signal-to-noise ratio (SNR) for the first step of the procedure shown in Figure 3.3-4. More concretely, cross-correlation with both possible signals' segments is applied to the incoming signal in the time-domain, and a correlation peak is considered as valid if exceeding a threshold depending on the noise level. If two significant peaks are detected and the actually transmitted signal is correctly identified, the PSSS detection is considered as valid. The reference curves are shown for the AWGN channel, while 1000 independent, identical distributed (i.i.d.) realizations of a multipath channel with continuous Rayleigh fading over the length of received signal block for a speed of 240 km/h has been considered as a more realistic and challenging scenario. For system bandwidths above 1.25 MHz, time-domain low-pass filtering and down-sampling is applied, resulting thus in similar performance for all system bandwidths. The results show that for SNR values around 0 dB, the PSSS detection probability approaches 100%, even under fast-fading channel conditions, which is an encouraging result. The confirmation of correct PSSS sequence detection of the first step by the second step has been found to approach 100%. Therefore, the role of the second step is mainly seen in the refinement of the residual time and carrier frequency estimates and the improvement of overall synchronization accuracy. For more details on this work refer to [MXC17].

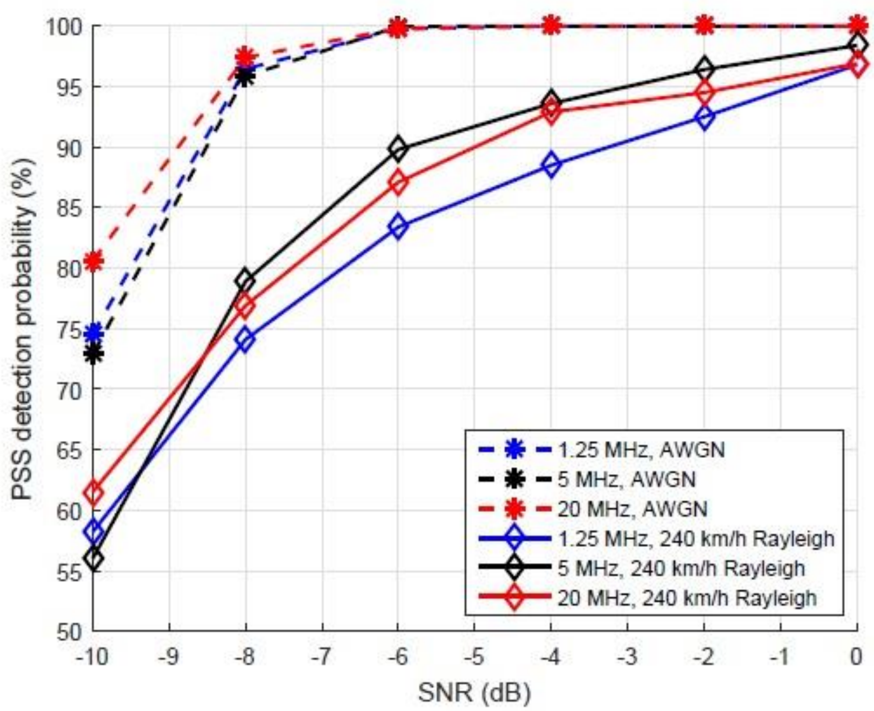
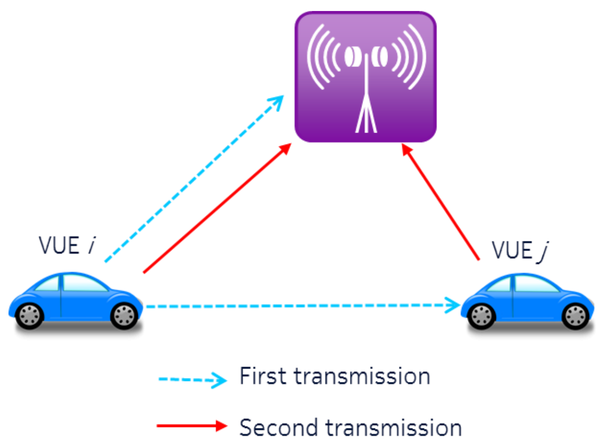



**Figure 3.3-5– Probability of correct sequence detection over the SNR.**

### 3.3.4 Sidelink Assisted Reliable Communication

**System Model**




Suppose V-UE *i* and *j* have discovered each other and configured as V-UE pairs by 5G gNB. Due to the short distance between these two vehicles and related better propagation channel conditions, V-UE *j* can provide helps in case V-UE *i* is with bad channel condition towards gNB. The received signals at gNB can be combined together to achieve diversity gain in time and also spatial domain at least to increase the overall reliability. Similar concept can be applied to DL as well although in the figure it shows the case for UL.

**Main Idea**

A simple solution to increase communication reliability is repetition as specified in 5G NR. Repetition can take place in time/frequency/spatial domain in order to get the diversity benefits.

In our study, we provide a method to achieve reliable communication with the help of sidelink. To be more specific, with the assumption that the discovery phase is completed, V-UE *i* and V-UE *j* formed as one group (with unique group ID) which is known to network (NW). Once V-UE *i* has UL data to be sent, the allocated 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. In addition, gNB will also allocate resource to UE *j* for forwarding the received packet from UE *i*. Then gNB can combine the received packets from both V-UEs.

**Test Cases**

Evaluate the performance in terms of needed retransmissions and also benefits from latency point of view without degrading reliability performance.

**Main Benefits**

- Sidelink acting as one diversity branch to increase the overall reliability.

**Description of Technology Component**

Device discovery is one necessary step to enable the proposed technology component, here it is assumed that the device discovery phase is completed. In other words, V-UE *i* and V-UE *j* are a sidelink or D2D pair. Furthermore, they are allocated with one group ID for example SL_RNTI (sidelink RNTI).

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. One example procedure is given as following:

- V-UE *i* will send resource request (e.g. scheduling request) in a normal way to gNB, at the same time it can indicate V-UE *j* can help for UL retransmission for enhancing reliability. Of course, after discovery network can select and configure V-UE *j* to assist V-UE *i* in advance as well and in this case SR of UE1 does not need to indicate the required helps from V-UE *j*.
- gNB allocates resource to V-UE *i* over downlink control channel with SL_RNTI as the target identification, in this way V-UE *j* can decode the same message as well and get the knowledge about on which resource blocks UE1 will send UL data.
- V-UE *i* sends data packets with the allocated resource. Since the resource information is known to V-UE *j* as well, then V-UE *j* can receive the same packet as well. Due to the short distance, it is very likely that the packet can be decoded correctly at V-UE *j.*
- In case gNB is not able to decode the first transmission correctly, gNB will send back feedback signal with allocated resource known to both V-UE *i* and V-UE *j*.
- Both V-UE *i* and V-UE *j* can retransmit the packet. gNB receives the same packet retransmitted from both UE1 and UE2 which can reduce the latency for multiple retransmissions. As one special format, the retransmission from UE1 and UE2 can take SFN type of UL transmission (i.e. UE1 and UE2 sharing the same resource and also transmission format) as well which does not increase resource usage as discussed in [AMW+17].

One example procedure is shown below in Figure 3.3-6.

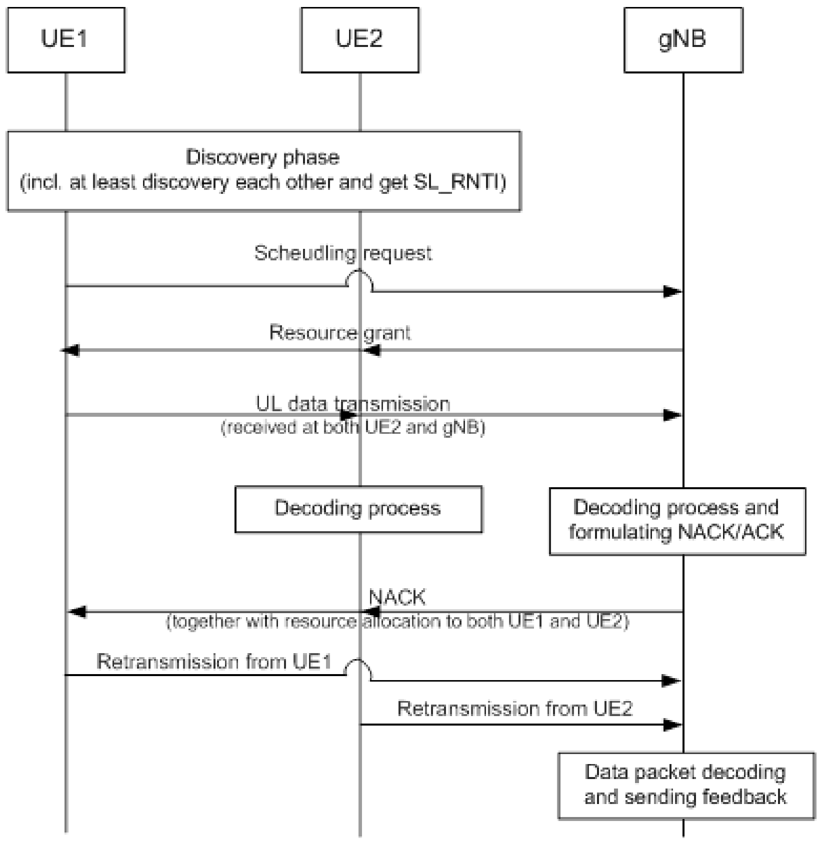
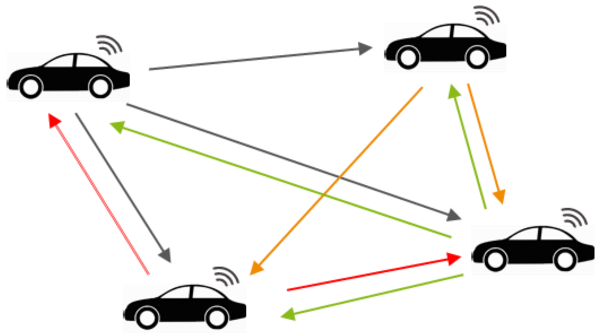



**Figure 3.3-6 Example procedure for sidelink assisted reliable communication**

With this approach, the number of retransmissions from the original V-UE can be decreased also the overall communication latency is reduced as well. As initial studied in [AMW+17], in order to achieve $10^{-5}$ BLER, without the assistance from sidelink, 5 transmissions are needed. However, in case sidelink is available for enhancing reliability, 3 transmissions are sufficient to achieve the same reliability level. In the next phase, we will evaluate the performance with system level simulations.

### 3.3.5 Reference Signals Design for Direct V2X Communication

<table>
<tr><th>System Model</th><th>Main Idea</th></tr>
<tr><td><br>Multilink communications directly between vehicles<br>The direct device-to-device (sidelink-based) V2X system is modelled as a broadcast and possibly also multiple unicast system. As such, a node can either send a message to all other nodes or to a subset of the other nodes. In such a system, 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 due to overlapping transmissions.</td><td>To obtain a robust reference signal design against detrimental effects of the propagation environment, a single link in the system is in 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 in designing reference signals. At the same time, the design will be complimented by methods for mitigating the pilot contamination effect, i.e., the multiuser or multilink aspects. The design aims balancing its robustness and the induced overhead.<br>The final design may contain more than one type of reference signals.<br>The design is applicable to both in-coverage and out-of-coverage scenarios. The design concerns both V-UEs and P-UEs but focuses more on V2V communication.</td></tr>
<tr><th>Test Cases</th><th>Main Benefits</th></tr>
<tr><td>Evaluate performance (e.g. in terms of BLER vs. SNR or mean squared channel estimation error) of the proposed reference signal designs for transmissions in a single link (possibly with co-channel interference), at frequency bands identified in 5GCAR and under channel models developed in 5GCAR.</td><td>The proposed reference signal designs ensure robustness against the adverse impacts of the V2X propagation conditions and pilot contamination, allowing for reliable communication via the sidelink interface.</td></tr>
</table>

#### Description of Technology Component

Reference signals are widely used in wireless communications for multiple purposes. Examples of reference signals 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 called the CSI-RS or

SRS). An effective design of reference signals for 5G sidelink V2X should address at least the following targets:

- Efficiently mitigating adverse propagation conditions as outlined in Section 2.1, namely the severe Doppler and delay spreads as well as frequency and phase error, especially at high vehicle speeds and high carrier frequencies.
- Minimizing the overhead of reference signals. Note that, unlike the uplink and downlink physical channels, in general the slot for sidelink V2X needs resources to account for the automatic control gain (AGC) settling and the guard period, see, for example [3GPP14-36885]. This reduces the amount of available resources for data and reference signals.
- Allowing effective separation of reference signals at the receiver. Unlike the uplink and downlink design, in the sidelink the transmissions of different nodes can happen in the same slot but without proper coordination, which makes them interfere with each other. At a receiver it is important to be able to separate and estimate the channels to the individual transmitters.
- Facilitating channel state acquisition at the transmitter (CSIT) if necessary, for enabling advanced transmission schemes.

Additionally, the reference signals design might be different for control channel and data channel, due to different characteristics of these channels. In the following we will first focus on the DMRS design for the data channel, which nevertheless will also shed light on the DMRS design for the control channel.

To start with, since the targeted vehicle speeds can be up to 250 km/h as indicated in the evaluation assumptions (Annex A), a high density of reference signals is expected. Based on the DMRS design for LTE sidelink V2X, which specifies four DMRS symbols in one subframe [3GPP-36885], it can be deduced that a similar amount of DMRS symbols should be a sensible option for a 14-symbol slot in 5G V2X.  However, there are several unique issues that need to be addressed in 5G V2X. First, the very stringent requirements in latency and reliability set by [5GCAR-D2.1] will partly translate into a need of a more robust DMRS structure than in LTE V2X to allow for correct decoding of a transmission and avoiding the need of retransmissions. Second, at higher carrier frequencies the carrier frequency offset and the phase noise become more detrimental and need to be effectively corrected by the reference signals. Also, a potential shift from DFTS-OFDM waveform for LTE V2X to OFDM for NR V2X may have some impacts on the designing of the DMRS, e.g., OFDM is more flexible than DFTS-OFDM in terms of multiplexing DMRS resource elements with data resource elements in the frequency dimension.

As a starting point, we can consider the reference signals used for demodulation purpose in 3GPP NR for eMBB services in the uplink and downlink, which are currently being finalized for Rel-15. According to the NR design, the DMRS used for eMBB transmissions can have several structures, as shown in Figure 3.3-7. In each slot of 14 OFDM symbols there is one or two consecutive (double) front-loaded DMRS symbols and possibly some additional DMRS symbols. In the case of a single front-loaded DMRS, there can be up to three additional DMRS, and in the case of double front-loaded DMRS there can be one additional double DMRS. The agreed positions of DMRS symbols are shown in Figure 3.3-7 (left). Additionally, to effectively mitigate the effect of common phase error (CPE), the phase tracking reference signal (PTRS) was agreed to be used also for demodulation of signals. This reference signal can be rather dense in the time domain, as illustrated in Figure 3.3-7 (right). Initial evaluation results of the NR eMBB's DMRS performance in V2X environment is presented in Annex B.12, which gives insight into DMRS design for V2X.

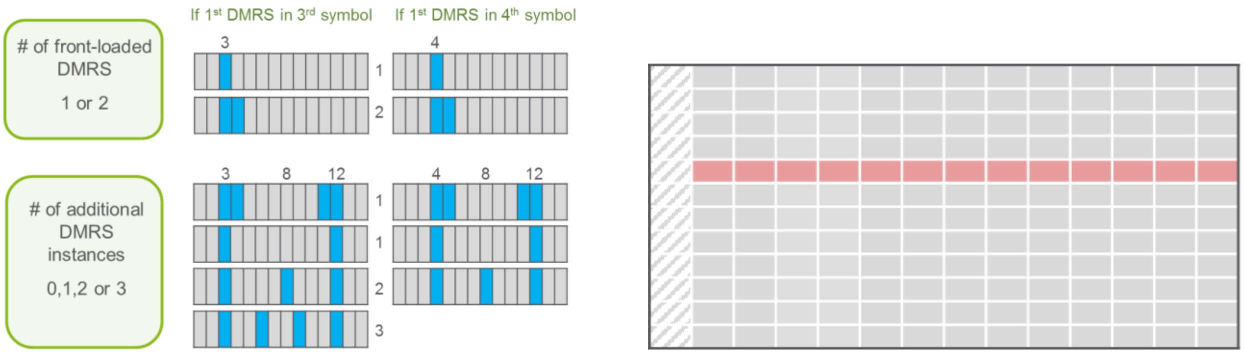
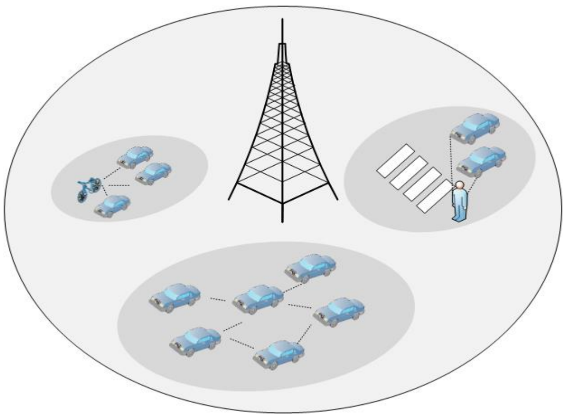



**Figure 3.3-7: DMRS (left) and PTRS (right) for NR eMBB. Different options for the density of DMRS and PTRS are not shown in the figure.**

### 3.3.6 Code-expanded Random Access for Reliable V2X Discovery

<table>
<tr><th>System Model</th><th>Main Idea</th></tr>
<tr><td><br>Network snapshot where vehicles/users are grouped in discovery groups and a discovery entity (at the network side) acts as a central coordinator aiming to discover all potential links in a centralized manner.<br>Each vehicle/user is interested in discovering a part of vehicles/users in its close proximity for sidelink communication establishment. The discovery process follows the principles of the LTE and NR random-access procedure and consists of three sequential phases of message exchange among each transmitting vehicle/user, each vehicle/user within its discovery distance, and the discovery entity.</td><td>Conventional discovery schemes may fail to address the stringent requirements of 5GCAR use cases in terms of reliability, latency and scalability. The high-mobility vehicular environments along with the high density of vehicles render existing discovery schemes inefficient due to the increased signalling overhead which in turn leads to underutilization of the scarce radio resources. This technology component inherits the advantages of a code-expanded radio access mechanism to address vehicle discovery problems in event-based vehicular scenarios. Following the principles of the LTE and NR random access procedure, 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. To this end, it performs better in establishing and managing multi-hop vehicle communication compared to conventional beacon-based discovery schemes.</td></tr>
<tr><th>Test Cases</th><th>Main Benefits</th></tr>
<tr><td>Single cell environment with independent Rayleigh-fading channels. Evaluate the performance with respect to state-of-the-art discovery schemes in terms of latency, spectral efficiency and link discovery ratio and identify trade-offs (latency-reliability) for different configurations of the code-expanded discovery scheme.</td><td>Due to the lower signalling overhead in the discovery process, i) resource utilization is expected to improve as well as ii) the minimum required latency for discovering all potential links.<br>These benefits will be capitalized in network environments with high mobility and/or density of vehicles.</td></tr>
</table>

### Description of Technology Component

As identified in D2.1, several use cases involve a V2X discovery process prior to the actual data transmission. In lane merge (UC1) and vulnerable pedestrian protection (UC3) scenarios, vehicles/users need to first be discovered with each other in a reliable and timely manner. After the discovery step, which may also involve message exchange with road side units, the local vehicle information can be processed to ensure collision avoidance and guarantee minimum impact on the ongoing traffic flow. This event-triggered discovery process poses important design challenges and conventional discovery schemes may not be sufficient to address the stringent requirements in terms of latency, reliability and spectral efficiency that 5GCAR use cases introduce. In addition, in high-mobility and dense vehicular environments the goal is to minimize the signalling overhead of the discovery process and avoid an underutilization of the scarce radio resources.

To this end, we propose a V2X discovery scheme tailored to LTE/LTE-A and 5G NR systems that relies on the principles of the LTE random-access mechanism and is well suited for network scenarios with dense vehicle connectivity and/or high-mobility vehicular environments, such as future 5G V2X networks. Our proposed technology component is advantageous since it i) discovers pairs in a centralized manner allowing the access network to centrally control the formation of sidelink communication pairs, ii) utilizes the system resources more efficiently, and iii) achieves lower latency for discovering all links present in the system. The proposed V2X discovery scheme is based on a discovery entity, i.e., eNodeB or RSU, which gathers information relevant to the proximity of the vehicles or road side users, in order to discover pairs capable for sidelink message exchange. Upon the completion of the discovery process, the discovery entity acquires full knowledge about the proximity relations in a given area. This is particularly important in high-mobility vehicular environments, where a distributed (beacon-based) discovery scheme may lead to underutilization of the resources available for discovery. Recent analysis has shown that the successful transmissions and timely delivery of beacons in large-scale vehicular deployments cannot be guaranteed due to interference and erroneous transmissions [SSK+17] [ZDL+17]. This is largely because of channel saturation in the bandwidth-constrained wireless networks.

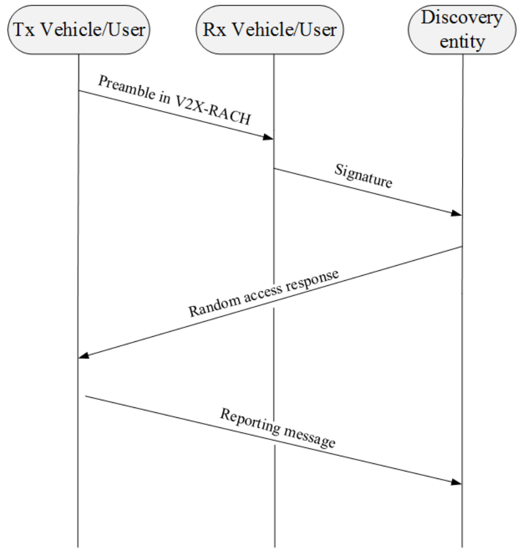



**Figure 3.3-8 – Message exchange for the proposed V2X discovery scheme.**

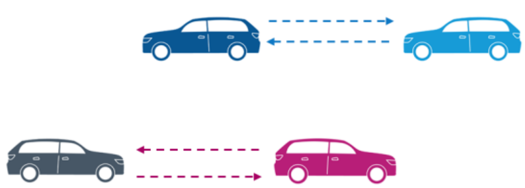
We consider a single cell centred by an eNodeB. A high number of vehicles/users is assumed to be involved in the discovery process in the cell. For coarse filtering of the network entities during the discovery procedure, we assume that each vehicle/user is interested in discovering only a part of all vehicles/users (peer vehicles/users) that reside within a discovery distance. In each cycle of the discovery process, each vehicle/user randomly selects either a transmit state or a receive state. The discovery scheme consists of three consecutive phases that involve message exchange among each transmitting vehicle/user, each receiving vehicle/user (residing within a predefined discovery distance), and the discovery entity. In particular, the discovery process is initiated (i.e., first phase) by a transmitting vehicle/user which sends a preamble to its nearby vehicles/users (i.e., its discovery group) via a newly introduced physical channel, coined V2X-RACH (Random Access CHannel). The V2X-RACH is in the uplink band and takes up one or several resource blocks.

At a second phase, each receiving vehicle/user listening to the V2X-RACH, upon the reception of a preamble, sends a signature to the discovery entity. Note that if there are more than one nearby transmitting vehicles/users that send the same preamble, the receiving vehicle/user is still able to detect that preamble, i.e., the collisions in the preamble space are assumed to be non-destructive, and the resulting collision is still interpreted as an activated preamble. This represents a logical OR operation, since a preamble is detected as activated if there is at least one vehicle/user that transmits the preamble. This observation motivates the use of Bloom filter for the signature generation, a data structure based on OR operation for testing set membership. In particular, the signature is constructed in a way that contains information on the identity of the receiving vehicle/user as well as the indices of the preambles received by the activated vehicle/user during the first phase. The rationale of the signature construction is compatible with the NR random access preamble format which consists of one or multiple/repeated random access preamble(s). Using an analytical framework, we can properly tune the signature properties based on the target spectral efficiency.

In the third phase, the discovery entity allocates an uplink resource block for each reported preamble so that vehicles/users which initially sent a preamble via the V2X-RACH, can send a reporting message back to the discovery entity. Similar to the LTE random access procedure, the discovery entity, using a broadcast message, notifies the transmitting vehicles/users for the uplink resource grants. In turn, the vehicles/users decode the broadcast message to identify whether there are allocated resource blocks corresponding to their transmitted preamble. In case that resources are identified, then a reporting message is transmitted to the discovery entity. A collision happens if two or more vehicles/users selected the same preamble during the first phase. The successful delivery of this reporting message ends the discovery process and a pair of vehicles/users, which are located in each other's proximity, can be identified by the discovering entity by comparing the reported preambles. Once the discovery entity discovers pairs of nearby vehicles/users, sidelink connectivity can be established.

For performance analysis, stochastic geometry tools will be used to derive fundamental metrics, such as collision probability (at all discovery stages) and link discovery probability, and assess the proposed discovery scheme in terms of resource utilization and minimum required time slots for completion of the discovery process.

### 3.3.7 Distributed RRM for Direct V2X Communication

| System Model | Main Idea |
|---|---|
| <br>We consider a highway environment and simultaneous unicast V2V links with different sender-receiver distances. 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. 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 |

| Test Cases | Main Benefits |
|---|---|
| Evaluate the performance in terms of packet reception ratio and throughput and quantify the gain compared to existing sidelink mode 4. | • Increase the reliability of the unicast transmissions by reducing the collision probability as compared to current LTE sidelink mode 4 while exploiting the advantage of semi-persisting scheduling<br>• 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 |

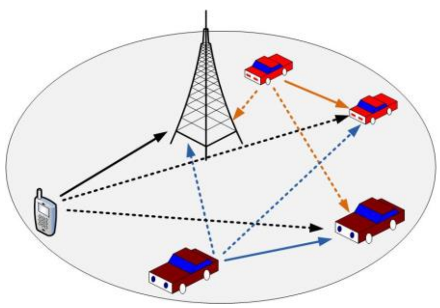
**Description of Technology Component**

Existing sidelink-based solutions are designed for broadcast communications where the goal is to reach the vehicles located in the vicinity. For the case of autonomous resource selection as defined in LTE-V2X mode 4, the resource selection is performed by the sender based on local information and does not include any knowledge about the radio resource usage at the targeted receiver. This may lead to collisions if same resources are selected by different users. To reduce the collision probability, LTE-V2X release 14 defines a sensing mechanism to allow the user identifying candidate free resources that could be used for its transmissions depending on the latency requirements: a selection window is defined in the time domain based on the maximum allowed latency. Short latencies result in reduced size of resource set and increase the collision probabilities. The sensing benefits from the prediction of regular interference patterns created through the semi-persistent scheduling (SPS). The resources are reserved for a certain period of time, usually in the order of a second, within which they are reoccurring with a given periodicity selected based on an indication from the application. The information about the reserved resources are shared with other vehicles in the vicinity using the sidelink control information (SCI) to help them avoiding the same resources and hence reducing the risk of potential collisions. However, the lack of feedbacks from the receivers and the knowledge about the resource situations at the intended receivers prevent the sender from optimal selection of resources for both transmission and retransmissions. Although the availability of such feedbacks might be difficult in the case of broadcast, in the case of unicast communications these can be exploited in a relatively simple way and be beneficial for optimizing the radio resource management.

This technology component proposes a distributed procedure for radio resource management for unicast transmissions which could be used for example to improve the performances for the cooperative perception use case. This could be used an enhancement of the current LTE- V2X mode 4 to support unicast communications and increase the reliability or as basis for the NR sidelink to achieve even lower delays. We assume that both unicast and broadcast communications share the same resource pool and that sidelink control information are 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-persisting scheduling accordingly. This includes adapting the amount of resources which could be reserved, the reservation duration (by means of the reselection counter), the modulation and coding schemes. For example, if the receiver fails to decode a packet and detect a collision occurring within the resource blocks indicated in the SCI due to other interfering transmission, it signals it back to the sender to trigger a new resource reselection. Also using its channel measurements, the receiver might recommend to the sender increasing or decreasing the modulation and coding or to adjust the amount of resource 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.

The exchange of the local information can start directly after the discovery phase where both the sender and receiver jointly select the initial parameters of the semi-persistent scheduling. The reservation might cover resources to be used in both direction of the link and the set of resources are then marked as resource reserved for the link (the pair of users). Both users 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 and help achieving better throughput. For the performance analysis the packet reception ratio, the throughput will be used to evaluate the gain compared to the current solution in addition to the estimation of the control overhead.

### 3.3.8 Radio Resource Management in 5G enabled Vehicular Networks

<table>
<tr><th>System Model</th><th>Main Idea</th></tr>
<tr><td><br>UL radio resources are shared by C-UE and V-UEs<br>• Single cell with simultaneous UL and direct V2X transmissions<br>• Orthogonal RB allocation of C-UEs<br>• 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>Test Cases</th><th>Main Benefits</th></tr>
<tr><td>Single-cell scenario with UL radio resources shared by one C-UE and potentially multiple V-UEs.</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.

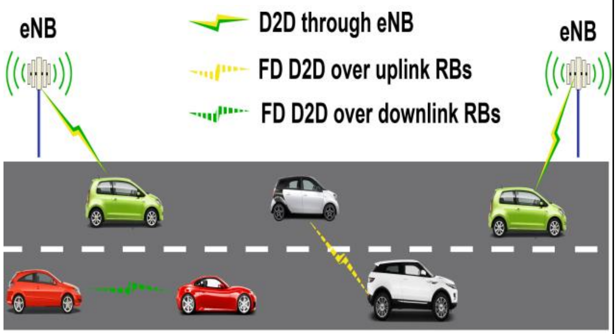
We consider a single cell environment where C-UEs and V-UEs share the available UL radio resources, and the current D2D underlay is only used by V-UEs. We assume that both C-UEs and V-UEs are using SC-FDMA waveform. Following the basic principle of UL scheduling, RBs are allocated to C-UEs in an orthogonal 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 with in 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 fact, this stage is quite similar with the RRM design for conventional UL LTE/NR systems. 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.
- Moreover, some evaluation results of the proposed algorithm are presented in Annex B.13.

### 3.3.9 Cognitive Full Duplex Communications in V2X networks

| System Model | Main Idea |
|---|---|
| <br>Red cars are in the coverage area of a BS or gNB and white cars are out of coverage area of any gNBs.<br>*Bilateral full duplex communications between two cars over downlink or uplink channels of a 5G network in an autonomous D2D manner.*<br>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. | 1. 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.<br>2. 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 an 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.<br>3. Return of a cellular user to the spectrum in use by SUs will cause a collision which will be detected and will force SUs to switch to another available channel.<br>4. Asynchronous FD transmission will result in shorter collision durations and less interference. |

| Test Cases | Main Benefits |
|---|---|
| 3. Duration of collision with cellular users and collision probability are formulated.<br>4. Throughput of D2D communication of SUs with partial self-interference suppression has been derived and evaluated. | 1. A novel scheme for FD D2D communication of two cars in a 5G network has been proposed.<br>2. This method causes less interference than conventional underlay D2D methods. |

**Description of Technology Component**

Recent advances in self-interference suppression (SIS) techniques pave the way for deployment of full-duplex wireless communications in vehicular networks to enhance throughput and decrease delay in D2D communications, and to improve the reliability and timeliness of V2V safety messages by counteracting direct collisions [CMB+17]. In D2D mode, vehicles in close proximity communicate directly, which eventually decreases the latency and offloads the traffic from gNBs.

In this work, we propose a novel cognitive full duplex scheme for D2D communications between two cars over the unoccupied downlink or uplink cellular resources. 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). If both secondary users, or at least one of them is in the coverage area of a gNB, then secondary pairs will establish their FD D2D connection over available downlink channels. Otherwise, they will use uplink channels for communication, in order to minimize any possible interference with cellular users when approaching the coverage area of a gNB. Awareness of a primary user's signal appearance is acquired through collision event and resulting error in D2D communication. Asynchronous FD transmissions in this scheme will result in shorter collision durations and less interference.

Collision duration and probability, as well as D2D communication throughput in this scheme has been calculated for a Rayleigh flat fading channel model and vehicles equipped with On Board Units (OBUs) with imperfect self-interference suppression capability [TS16]. Initial results can be found in Annex B.14.

## 3.4 Positioning as Enabler for V2X Communications

Ubiquitous, accurate, and real-time knowledge of users' position and trajectory is a crucial requirement and enabler for many V2X use cases, and its support is consequently an important component in the V2X radio interface design. Due to that the significance of the topic will come in the following up deliverable D3.2 (Report on Channel Modelling and Positioning for 5G V2X), in this deliverable, we will briefly summarize the envisaged technical solutions related to positioning as enabler for V2X communications.

### 3.4.1 Trajectory Prediction with Channel Bias Compensation and Tracking

This solution consists of three successive components that can be applied independently from each other.

**Uplink Time Difference of Arrival (UTDOA)-based positioning scheme with NLOS compensation**

UTDOA-based positioning suffers from unresolvable multi-path propagation and NLOS relations between transmitter (UE) and receivers (a set of BSs). Consequently, the measured time of arrival values include a so-called *channel bias*. The basic idea of our solution is to estimate the probability density function of the channel bias and to consider it in the multilateration algorithm that determines the most likely position from the time or arrival measurements. The estimation of the channel bias distribution parameters is described in [PLH16].

**Trajectory estimation with Unscented Kalman Filter (UKF) and Particle Filter (PF)**

The basic idea is to track and predict the movement of a user based on a dynamic motion model and to update the prediction with new measurements [Ber99]. For vehicles we have implemented the Constant Velocity (CV) model and the Constant Turn Rate and Velocity model (CTRV) [SRW08]. The set of measurements is not limited to the abovementioned UTDOA-based positioning, but it can also include GPS or supporting sensor data from the user, e.g. its speed, acceleration, or direction.

The tracking algorithms considered are UKF and PF. The UKF is a parametric estimation of the probability density function of the state variables aiming to track mean values and covariance through a non-linear transformation [JU04]. The PF is a non-parametric estimation method where the probability density function of the state variables is represented by a swarm of so-called particles with associated weights [AMG+02]. In general, the PF provides a higher performance potential, especially with highly non-linear systems and multi-modal distributions, but requires also more computational effort. The choice of the filter also depends on the used motion model. For the simple CV model, the UKF or even a classical Kalman filter is sufficient, whereas the PF can exploit its benefit over the UKF when applying the more complex CTRV model. The reason is that the PF estimates the probability distribution of the state variable in its entirety, and not just parameters such as mean value and variance. Consequently, the result of the estimation is much more accurate.

As next step, we will integrate map information as additional a-priori information source in the PF implementation. This will impact the weights of the particles, weakening those locations that lie outside of the street.

Once the user trajectories are estimated, we can start design algorithms that exploit this information to detect potential future collisions.

**Collision Detection with Machine Learning**

Our plan for the second year of the project is to evaluate the estimated trajectories of several users, e.g. a vehicle and a pedestrian aiming to predict a potentially critical situation. Examples are: car driver losing control and skidding on the sidewalk, a cyclist falling, or a pedestrian crossing the street behind a curve. The main challenge will be to generate reliable warning messages, since there is a trade-off between missed detection and false alarms. On the one hand, all critical situations must be detected and reported, but on the other hand false alarms, i.e. an uncritical situation which is classified as critical, shall be minimized in order to increase the acceptance of the offered service.

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

Thanks to the large bandwidth of 5G signals and large number of antennas at the BSs, it is possible to precisely position the UE with a single BS. We propose a solution in the downlink for tracking the UE's position and orientation by estimating the Time-of-Arrival (TOA), Direction-of-Arrival (DOA) and Direction-of-Departure (DOD) associated with the strongest paths. A remarkable property of the proposed approach is that 3D positioning is possible without accurate time-synchronization between the UE and the BS, and without measuring the round-trip time, provided that enough paths exist. This is because each path provides geometric constraints, where the number of such constraints grows faster than the number of unknown parameters,

**Algorithm description**

The main idea of the algorithm is to periodically feed estimates of the TOA/DOA/DOD of the strongest LOS/NLOS paths to a tracking algorithm. A message passing algorithm is used for fusing the latest measurements with the prior knowledge. The unknown parameters tracked by the filter consist of: (a) the UE's location and rotation on the horizontal plane, (b) the Virtual Anchors (VAs) of the NLOS paths, and (c) the time offset between the BS and UE clocks. VAs are a succinct way to represent specular reflections on wall [LMR+15].

The steps of the proposed algorithm are detailed in what follows:

1. UE estimates the DOA, DOD and TOA of the dominant paths using downlink pilots. We use a simple estimator based on classical estimation theory and tensor decomposition.
2. Detection of a LOS or NLOS scenario, and in the former case identification of the LOS path. The estimated parameters for all paths form a set of 3-tuples (DOA, DOD, TOA). Because the NLOS paths depend on the VAs, while the LOS path does not, it is necessary to identify the LOS for the later stages of the algorithm.
3. Once the 3-tuples have been estimated and categorized as LOS or NLOS, it is necessary to perform data association between the NLOS paths and the VAs estimated from previous iterations. A sub-optimal solution can be obtained by the Hungarian algorithm [Kuh55] or other assignment algorithms.

4. Update the UE and VA positions. We derive a factor graph between the estimated parameters (DOA, DOD and TOA), and the parameters of interest (UE's position and rotation, VA's positions and the clock bias). By performing message passing, we obtain posteriori distributions on the parameters of interest.

### 3.4.3 Beam-based V2X Positioning

This technique focuses on UE-based approaches for the V2X positioning and investigate the potential of NR-specific technology, namely angular information provided by beamforming, with respect to positioning accuracy. A UE-based approach allows the vehicle to estimate its own position based on the locally available measurements, including relative measurements between vehicles using the sidelink or other sensors. Compared to the network based approach where the location server, which can be e.g. placed in the core network, calculates 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.

Two scenarios are considered for this investigation, namely *network-assisted V2N absolute positioning* and *V2V relative positioning*. As a first step, network assisted V2N positioning, thanks to the 2D beamforming capability on the BS side, angular information can be obtained in the horizontal plane as well in the vertical plane for each BS. This allows each V-UE to estimate its 2D coordinates using single BS. As a second step, beam-based V2V relative positioning is investigated, since one advantage of UE-based approaches is that sidelink-based measurements can be efficiently exploited. Assuming multiple antenna panels deployed at the bumper level for V2V communication, angular information can be obtained. This, planned as contribution for the next step, may lead to location service enhancement for the V2X scenario.

### 3.4.4 Harnessing Data Communication for Low-latency Positioning

This technique focuses on the problem of minimizing the latency to acquire location related measurements. The main idea is to exploit, in addition to pilot symbols, data symbols so that position information can be (quasi) continuously tracked and progressively improved in terms of accuracy. In this approach the assumption of reliable data transmission is key since it will be used to re-estimate the channel parameters with a turbo-channel estimation approach. The block-diagram of the technique is illustrated in [5GCAR-IR3.1] and consists of the following steps:

1. Standard channel estimation and data detection chain: channel is estimated using pilot symbols, whereas data symbols are detected and decoded using the channel estimate result
2. Enhanced channel parameter estimation for positioning: AOA, AOD (if needed) and TOA are estimated using dedicated positioning reference signals as well as re-encoded data symbols. The estimator will also benefit of location-awareness to define prior information on the AOA, AOD and TOA.

3. Position estimation and channel parameter prediction: position information is calculated based on AOA, AOD and TOA and a new location prediction is inferred to provide prior information to the enhanced channel parameter estimation block.

If location processing is not limited by computational constraints, this approach can provide location update at the symbol level.

### 3.4.5 Enhanced Assistance Messaging Scheme for GPS and OTDOA Positioning

In LTE, GPS and OTDOA positioning sessions include the exchange of messages between the location server and the UE in order for the latter to acquire assistance information. This solution will introduce new mechanisms to transmit assistance messages more efficiently in order to improve GPS and OTDOA 3GPP positioning schemes.

Conventional GPS positioning requires the UE to transmit the assistance request message. This causes extra positioning delay and energy consumption at UE device. The situation is more severe when the UE is not in Connected State, as several messages have to be exchanged between the BS and the device to establish the LTE connection, time during which the position of the UE may also change. Besides, the assistance scheme is always unicast (sent to a unique device) and sent for each positioning session even if the assistance has not changed. The main idea of the proposed enhancement is to broadcast messages per cell. For GPS positioning those broadcast messages will include some GPS assistance (e.g. semi-statically broadcasted ephemeris).

On the other hand, conventional OTDOA positioning works only in a UE-assisted way; the device only reports RSTD (Reference Signal Time Difference) measurements but it cannot compute its own position as this would require knowledge of position of the BSs. The drawbacks of such a scheme include a) mandatory assistance for OTDOA positioning; b) device is totally unable to compute its position; c) device must transmit the report; d) the assistance scheme is also always unicasted and sent for each positioning session. The broadcast messages of this solution for OTDOA positioning will include some OTDOA assistance as well as the positions of the BSs surrounding the cell.

The envisaged changes in positioning protocol will allow some new usages and use cases by allowing UE-based OTDOA positioning and by reducing the GPS positioning delay.

## 3.5 Summary of V2X Radio Technologies

Considering radio technologies, the 5GCAR objective is to develop efficient and scalable enhanced 5G air and sidelink interfaces for low-latency, high-reliability V2X communications. Taking the latest advancements in 3GPP as the starting point, we have been looking at radio research related challenges from the identified 5GCAR use case classes and use cases. Various technology components as described in previous sections are proposed to address the major challenges. The proposed technology components cover both Uu interface and sidelink interface, in addition to efficient ways of using positioning information for V2X communications. The proposed technology components cover all different aspects for V2X communications as shown in Figure 3.5-1.

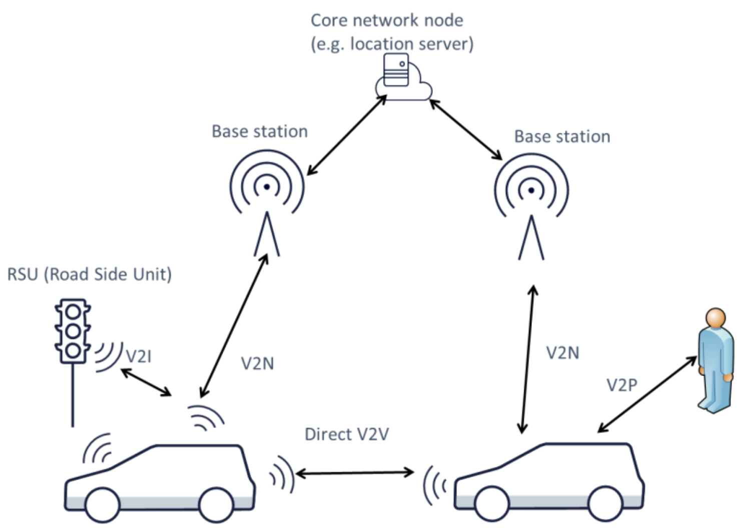



**Figure 3.5-1 Various V2X communication scenarios**

The major topics covered with the present technology components can be summarized as follows:

- Infrastructure-based solutions
  - Fundamental Trade-offs between Reliability and Latency
  - Multiple antenna related enhancements
  - Efficient multiplexing between eMBB and URLLC services
  - Beam based broadcasting for V2X applications
  - Optimization on link adaption/HARQ,
  - Tx power setting between pilot and data (in case they are sent in the same slot)
  - Enhancing reliability by exploiting diversity from cooperative links including sidelink
- Sidelink-based solutions
  - Reference signals and synchronization signal design
  - V2X discovery with code-expanded random access
  - Sidelink radio resource management
  - Adjacent Channel Interference

- Positioning as enablers for V2X communications
  - Trajectory prediction with channel bias compensation and tracking
  - Beam-based V2X positioning
  - Tracking of a vehicle's position and orientation with a single base station in the downlink
  - Harnessing data communication for low latency positioning
  - Enhanced assistance messaging scheme for GPS and OTDOA positioning

In 3GPP, the current focus of 5G work is to complete the basic design of Rel-15 New Radio. At this moment, the active V2X work is about V2X enhancement from LTE track. And the main technical topics include carrier aggregation, supporting for 64-QAM, resource pool sharing between mode-3 and mode-4 users, feasibility study about transmit diversity over sidelink etc. From 5G side, the active topic under discussion regards the evaluation methodology of new V2X use cases for LTE and NR and includes aspects such as the evaluation scenarios, V2X channel models, traffic model, BS and RSU deployment, antenna model, etc. As shown in Annex A, the evaluation scenarios under discussion in 3GPP are quite similar to the ones identified within 5GCAR project. Channel model related work from 5GCAR project will be included in the coming D3.2.

Regarding the V2X solution based on NR, it is widely expected that NR V2X communication will be part of Rel-16 work. For example, during RAN Plenary meeting#79, RP-180426 [3GPP-RP-180426] was discussed as the outcome from RAN WG. The following topics are currently identified as essential topics to be studied during Rel-16 time frame in order to support the identified advanced V2X use cases:

- NR sidelink design
- Uu enhancement
- Uu-based sidelink scheduling
- Radio Access Technology (RAT) selection
- QoS management (both Uu and sidelink)

while it is still debated what bands for sidelink frequency should be part of the study (i.e. only <10 GHz or both <10 GHz and mmWave) as well as whether the following topics should be covered by Rel-16 work:

- V2X positioning (could be studied in parallel within Rel-16 due to big scope)
- Relay/Range extension solutions
- Feasibility of coexistence mechanisms

The outcome covered in this deliverable aligns very well with the expected V2X relevant topics in Rel-16. As next step, all 5GCAR partners can contribute the research outcome to the standardization organizations including 3GPP, 5GAA or other V2X standardization organizations in addition to various publications. Furthermore, better integration of the proposed technology components as one over the air solutions is expected.

# 4 Summary

Moving forward from the latest available technology, including the V2X solutions developed by the 3GPP, and keeping in mind the research challenges especially in terms of latency, reliability, availability and accurate positioning resulting from the identified 5GCAR V2X use case classes and use cases, this deliverable summarizes the intermediate outcome of 5GCAR project on the technology components designed for the 5GCAR V2X radio interface.

After evaluating the use cases identified in 5GCAR, the main research challenges from a radio interface design perspective are discussed in Chapter 2. The challenges cover many aspects of V2X communications, both direct communication and infrastructure-based communication. The most challenging requirements include ensuring low latency, high reliability, effective beam management and providing real-time highly accurate positioning services.

The objective of V2X air interface work is to develop an efficient and scalable enhanced 5G radio interface including both Uu and sidelink interface for V2X communications. Even using the latest available technology as the starting point, there is room for further improvement. Therefore, Chapter 3, presents a short state of the art overview and discusses the V2X radio interface design challenges in detail and presents the proposed technology components that aim to solve these challenges. The technology components are classified as infrastructure-based, sidelink-based and positioning based ones.

With respect to infrastructure-based technologies, as described in subsection 3.2, these shall be further developed and brought to a mature level within the remaining period of the project. The design of the physical layer interface shall consider both cm- and mmWave frequency bands. As realized from the work performed up to now and preliminary results, challenges are indeed seen in the radio channel with high mobility especially in mmWave bands and the corresponding hardware constraints, in designing advanced beamforming schemes and manage the interference, and in the very low latency and reliability requirements and the coexistence of very different types of link requirements.

To this direction, realistic multi-antenna channel estimation and prediction schemes, as well as their validation in outdoor field trials will be performed and further evaluated. For mmWave transmission, broadcast and beamforming schemes will need detailed investigation, in order to meet different sets of requirements and considering different transceiver architectures. As a clue for establishing robust links, sources of diversity shall be exploited in multi-beam/multi-node multi-vehicle communication techniques; scenarios in which aspects such as interference control and load balancing to guarantee critical QoS metrics at mobile speeds will need consideration as well. Ongoing work on reference symbol design will focus on the scenarios with high mobility, whereas their corresponding power allocation schemes shall be extended to also cover multi-cellular scenarios, in order to enhance the cell-edge performance.

System-level evaluation of resource management across parallel service type links to support different requirements at the same time will be performed, in order to gain insight into the most influential factors and optimize the proposed solutions. At the same time, for dynamic multiplexing of mission critical messages and other traffic types, trade-offs between signalling overhead and achievable spectral efficiency will be further investigated and evaluated. In particular for initial access, resource allocation will need careful design in order to enable low latency and robust multi-vehicle communication at high mobile speeds. Radio frame design aspects and investigation of optimal retransmission schemes to achieve very low BLER will be investigated for realistic highly mobile scenarios.

The sidelink-based V2X technology components proposed in subsection 3.3 enable the delivery of V2X services in the absence of infrastructure nodes and take advantage of network assistance under infrastructure coverage. The 5GCAR sidelink technology components include a network assisted reliable discovery mechanism, synchronization and reference signals, adjacent channel interference mitigation and several radio resource management, power control and scheduling mechanisms. The 5GCAR sidelink can also be used to enhance the reliability of cellular communication and can take advantage of full duplex capability at vehicles. In the second part of the project, we plan to evaluate the performance of these technology components by link and system level simulations, using the simulation parameters listed in Annex A.

Concerning positioning, the methods in subsection 3.4.1 (trajectory prediction with channel bias compensation and tracking) can be applied independently from a certain scenario and frequency band. As pure radio-based positioning can achieve mean position errors of below 10m, a combination with sophisticated tracking algorithms like the Particle Filter is required to improve the accuracy. However, to achieve the envisaged sub-meter performance, further extensions like fusion with car sensors, refinement of motion models and soft map-matching are necessary and will be investigated as the next step. The remaining proposals assume the availability of antenna arrays to exploit spatial information, i.e. the angles of departure and angles of arrival of directive beams. These methods address the dense urban scenario and are tailored for frequencies above 6 GHz. The algorithm presented in subsection 3.4.2 (Beam-based V2X positioning) still assumes the transmission of more than one beam. It is a UE-centric, network-assisted method tailored for V2X communication. As next step relative positioning with sidelink-based measurements will be investigated. The solutions in subsections 3.4.3 (downlink transmission) and 3.4.4 (uplink transmission) operate with a single base station and antenna arrays both at the base station and terminal. Consequently, the position accuracy becomes better if the number of propagation paths increases. The presence of a LOS path is also advantageous. Next step is a further evaluation of the algorithm with respect to localization and orientation estimation of the UE (vehicle) as well as integration with tracking. A particularity of the uplink approach in section 3.4.4 is joint communication and positioning without compromising the data rate. Finally, in section 3.4.5 (Enhanced assistance messaging scheme for GPS and OTDOA positioning), we propose possible extensions of the LTE positioning protocol that will require standardization.

To facilitate the performance evaluation of different technology components, together with WP4, we have proposed the most relevant deployment scenarios and system assumptions as shown in Annex A. In addition, more practical vehicle UE parameter settings are obtained with the help of Original Equipment Manufacturers (OEM) involved in the project.

For the next step, in summary, 5GCAR project will further develop and evaluate the proposed technology components, investigate newly developed concepts, and continue to investigate the applicability of these technology components in 5GCAR scenarios. We also plan to integrate selected technology components into a unified system and thereby to contribute to fulfilling the objectives of the 5GAR project.

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# Annex

# A Simulation Assumptions

This annex contains simulation assumptions to be used in performance evaluation of technical components proposed in 5GCAR, divided into two parts:

- The first part contains simulation assumptions for system-level simulations, including the deployment scenarios, user deployment and mobility, antenna models, traffic models, channel models, and performance metrics.
- The second part contains a suggested list of parameters to be included in link-level evaluation results. Other parameters can be deduced from the system-level simulation assumptions, where appropriate.

The simulation assumptions in this annex may not be complete to cover all evaluations and are not restrictive. It rather provides a list of configuration options and environments, from which each partner can select an appropriate configuration for their evaluation. Partners are encouraged to provide detailed simulation assumptions used in the respective evaluation. Note some scenarios and parameters in this annex refer to the evaluation assumptions established in [3GPP-36885] and to an ongoing study item in 3GPP [3GPP-171093], where some partners of 5GCAR are active contributors.

## A.1 System-level Simulation Assumptions

### A.1.1 Deployment Scenarios for Base Stations

**Table A.1.1: Deployment scenarios for base stations**

| Deployment scenario | Highway | Urban |
|---|---|---|
| **BS antenna height** | 35 m for Inter-Site Distance (ISD) 1732 m,<br>25 m for ISD 500 m | 25 m, above rooftop |
| **Number of BS antennas elements (TX/RX)** | Up to 256 | Up to 256 |
| **Number of BS antenna ports** | Up to 16 | Up to 16 |
| **BS antenna gain** | 8 dBi | 17 dBi |
| **Maximum BS transmit power** | 49 dBm per band (in 20 MHz) | 49 dBm per band (in 20 MHz) |
| **BS noise figure** | 5 dB (below 6 GHz) | 5 dB |

| | | |
|---|---|---|
| | 7 dB (above 6 GHz) | |
| **BS Carrier center frequency for evaluation** | 800 MHz, 2 GHz, 3.5 GHz, 4 GHz<br><br>5.9 GHz<br><br>28 GHz, 63-64 GHz (mmWave) | 2 GHz, 3.5 GHz, 4 GHz<br><br>5.9 GHz<br><br>28 GHz, 63-64 GHz (mmWave) |
| **BS Carrier bandwidth for evaluation** | 20 MHz+20 MHz per carrier (below 6 GHz)<br>In case with CA, maximum number of carrier: up to 8.<br>Up to 100 MHz at 3.5 GHz<br>10 MHz at 5.9 GHz<br><br>200 MHz per carrier (above 6GHz)<br>In case with CA, maximum number of carrier: up to 5 | 20 MHz+20 MHz per carrier (below 6 GHz)<br>In case with CA, maximum number of carrier: up to 8<br>Up to 100 MHz at 3.5 GHz<br>10 MHz at 5.9 GHz<br><br>200 MHz per carrier (above 6 GHz)<br>In case with CA, maximum number of carrier: up to 5 |
| **BS Inter-site distance** | 500 m and 1732 m | 200 m and 500 m |
| **Backhaul/fronthaul (BS-BS, BS-RSU, RSU-RSU)** | For wireless self-backhaul/fronthaul, same technology as for radio access is used.<br>For non-ideal backhaul, values of [0.5, 1, 5 and 30] ms and [0.05, 0.5 and 10] Gbps can be used for one-way latency and throughput, respectively. | |

## A.1.2 Deployment Scenarios for Road Side Units

**Table A.1.2: Deployment scenarios for RSU**

| **Deployment scenario** | **Highway** | **Urban** |
|---|---|---|
| **RSU antenna height** | 5m - 10m (Applies for both BS-type and UE- type) | |
| **Inter-site distance** | 100 m – 500 m | |
| **Number of RSU antennas elements (TX/RX)** | For BS-type-RSU: Up to 8 TX/RX | |
| **Number of RSU antenna ports** | Up to 8 | |
| **Backhaul/fronthaul (BS-BS, BS-RSU, RSU-RSU)** | For wireless self-backhaul/fronthaul, same technology as for radio access is used.<br>For non-ideal backhaul, values of [0.5, 1, 5 and 30 ms] and [0.05, 0.5 and 10 Gbps] can be used for one-way latency and throughput, respectively. | |
| **RSU type** | **BS- type** | **Vehicle / UE – type** |
| **RSU antenna gain** | 8 dBi | 3 dBi |
| **Maximum RSU transmit power** | 24 dBm/33 dBm (in 20 MHz) | 23 dBm (in 20 MHz) |

| | | |
|---|---|---|
| **RSU noise figure** | 5 dB (below 6 GHz)<br>7 dB (above 6 GHz) | 9 dB (below 6 GHz)<br>13 dB (above 6 GHz) |
| **RSU Carrier center frequency for evaluation** | 800 MHz (only highway), 2 GHz, 3.5 GHz, 28 GHz, 63-64 GHz (mmWave) | 2 GHz, 3.5 GHz, 28 GHz, 63-64 GHz (mmWave)<br>5.9 GHz (RSU UE-type) |
| **RSU carrier bandwidth for evaluation** | 10 – 20 MHz (below 6 GHz)<br>Up to 100 MHz at 3.5 GHz | |

### A.1.3 Deployment Scenarios for Road UEs

**Table A.1.3: Deployment scenarios for UE**

| Parameters | Pedestrian UE | Vehicle UE |
|---|---|---|
| **Vehicle antenna height** | 1 – 1.8 m | 0.5 – 1.6 m |
| **Number of Vehicle antennas elements (TX/RX)** | 1/1, 2/2 (C-V2X), 4/4 (LTE Cat 16), 8/8 | |
| **Number of Vehicle antenna ports** | 4/4 | |
| **Vehicle antenna gain** | 0 dBi | - V2I/V2N: 3 dBi for non-mmWave; 14 dBi (for 64 GHz)<br>- V2V: 3 dBi for non-mmWave; up to 21 dBi (for 64 GHz)<br>- Roof antenna 0 dBi |
| **Maximum UE transmit power** | 23 dBm | 23 dBm (33 dBm can also be considered) |
| **Vehicle noise figure** | - Below 6 GHz: 9 dB<br>- Above 6 GHz: 13 dB (baseline performance), 10 dB (optional) | |
| **Carrier center frequency for evaluation (Direct/Sidelink Communication)** | 5.9 GHz, 3.5 GHz,<br>28 GHz, 62 GHz (mmWave),<br>76-81 GHz (Currently for radar application) | |
| **Distribution of antennas** | Co-located | |
| **Polarization** | Co-polarized (vertical) as starting point | |
| **Antenna array type** | Uniform Linear Array (ULA) and rectangular | |

## A.1.4 User Deployment and Mobility

### A.1.4.1 Urban Scenario

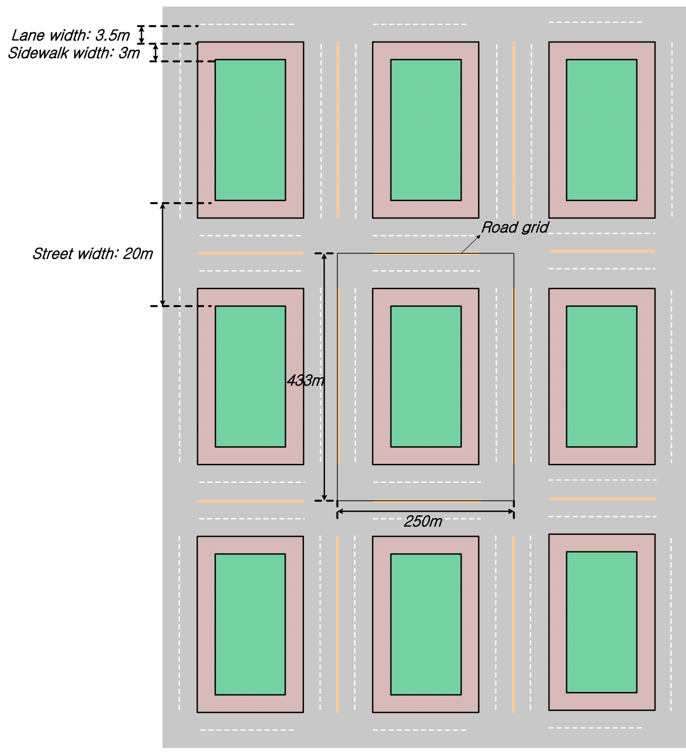



**Figure A.1.4.1: Road configuration for urban traffic efficiency and safety evaluation [3GPP-36885]**

Users in the urban scenario are deployed by the following procedure:

- Every road between the buildings contains two lanes per each direction (3.5 m width).
- Vehicles are dropped on roads according to a spatial Poisson process with an average inter-vehicle distance of 2.5 s times vehicle speed, in the middle of each lane.
- The total road length within the 433x250 area formed by 1 building, its surrounding sidewalk and rings of lanes, is equal to 2684 m.
- In the urban synthetic deployment scenario, vehicles move along the streets with up to 60 km/h.
- At the intersections, vehicles have 50% probability to go straight and 25% probability of turning left or right. Vehicle position is updated every 100 ms on the simulation.
- In the urban realistic scenario, cars, buses, and pedestrians are dropped and move within the Madrid Grid according to car mobility models and trace.

### A.1.4.2 Highway Scenario

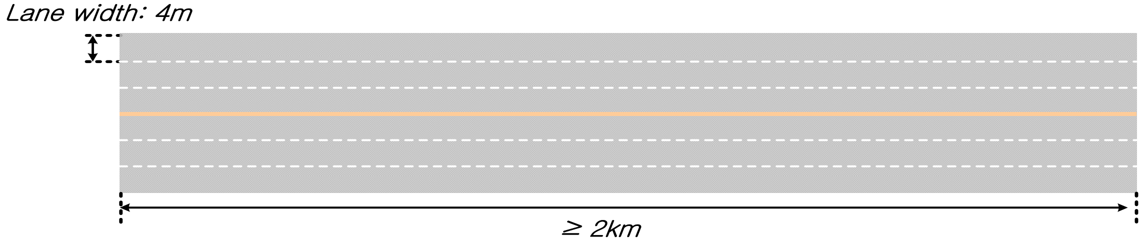



**Figure A.1.4.2: Road configuration for highway traffic efficiency and safety evaluation [3GPP-36885].**

- The depicted highway presents 3 lanes in each direction, with a lane width of 4 m.
- It is required to have a highway length of at least 2 km.
- Vehicles are dropped in the roads according to a spatial Poisson process with an average inter-vehicle distance of 2.5 s times vehicle speed.
- In the highway (synthetic) scenario, vehicles move along the lanes of the highway at up to 250 km/h. Vehicle position is updated every 100 ms of the simulation.

Note:

- For platooning use case, the inter-vehicle distance can be shorter e.g. 0.3 s.
- SUMO traces could be generated & used. But this is an optional tool.

## A.1.5 Data Traffic Models

**Table A.1.5: Traffic models**

| Type of traffic | Description |
|---|---|
| **Periodic traffic model** | Deterministic model, i.e., no randomness in the message generation interval and message size.<br>On top of that, consider adding jitter (small variations) in packet arrival time and unexpected missed packet arrivals. The jitter can be modelled by assuming either uniform or truncated Gaussian distributions. Missed packets can be modelled with probability ‘p’. |
| **Event-triggered traffic model** | The modelling can be done using randomized packet arrival, e.g., according to Poisson process. |
| **eMBB-like traffic model** | Necessary for eV2X use-cases like 3D video composition, local dynamic map sharing, tethering via vehicle, collective perception of environment with burst eMBB-like traffic with a certain data rate.<br>MBB-like traffic can be modelled using FTP traffic model 2 with updated values on file sizes, reading time and burst length etc. |
| **Full-buffer traffic model** | Always-on traffic. |

Note: by varying different parameters in the traffic models, e.g., periodicity, packet size, data rate, various use cases can be covered.

### A.1.6 In-band Emission Model

- Below 6 GHz: Reuse the model in 3GPP TR 36.843 Table A.2.1.5-1 with [W,X,Y,Z]=[3,6,3,3].
- Above 6GHz: TBD.

### A.1.7 Channel Models

Refer to channel models in the coming deliverable [5GCAR-D3.2].

### A.1.8 Performance Metrics

**Table A.1.6: Performance metrics for evaluations**

| Metric | Description |
|---|---|
| **Reliability** | Packet reception Ratio (PRR) [3GPP-36885]:<br>- For one Tx packet, the PRR is calculated by X/Y, where Y is the number of UE/vehicles that located in the range (a, b) from the TX, and X is the number of UE/vehicles with successful reception among Y. CDF of PRR and PRR are used in evaluation.<br>- PRR is relevant to safety applications and should be the primary metric for reliability evaluations.<br>- PRR should be calculated taking into account the latency budget. This can then be represented as CDF of ‘average PRR over latency’ as well as” PRR over distance for a certain latency budget”. |
| **Latency** | Received inter-packet spacing:<br>- A metric which can capture the aspect of persistent collisions<br>- Details can be found in Section 4.1.2 in 5GCAR D2.1 |
| **Throughput/spectrum efficiency** | - SINR distribution<br>- Symbol error distribution, MSE<br>- Throughput distribution<br>- Spectral efficiency (bits/s/Hz) |
| **Positioning accuracy** | Absolute and/or relative accuracy. |

# A.2 Link-level Simulation Assumptions

**Table A.2: Suggested list of parameters to be included in link-level evaluation results.**

| Parameters |
|---|
| Receiver algorithm |
| Time and frequency accuracy |
| Reference signal structure |
| PHY packet size |
| Channel codes (for control and data channels) |
| Modulation and code rates (for control and data channels) |
| Signal waveform (for control and data channels) |
| Subcarrier Spacing |
| CP length |
| Frequency synchronization error |
| Time synchronization error |
| Channel estimation (e.g., DMRS pattern and symbol location) |
| Number of retransmission and combining (if applied) |
| Number of antennas (at UE and BS) |
| Transmission diversity scheme (if applied) |
| UE receiver algorithm |
| Automatic Gain Control (AGC) settling time and guard period |
| Error Vector Magnitude (EVM) (at TX and RX) |

# B Additional Details on Technical Components

## B.1 Sensitivity Analysis of the Predictor Antenna System

### Illustrative Numerical Results

The temporal covariance matrix of the received signals, $C_{r_\tau}$, at different ports of a multiport moving antenna system at a certain time delay $\tau$ has been derived and is used to investigate the temporal correlation between the two port signals at $\tau = \tau_d$ time delay in a rich uniform multipath environment. This multipath environment is a good reference environment due to the fact that it can be emulated in a reverberation chamber [RK05]. The corresponding results are shown in Figure B.1.1.

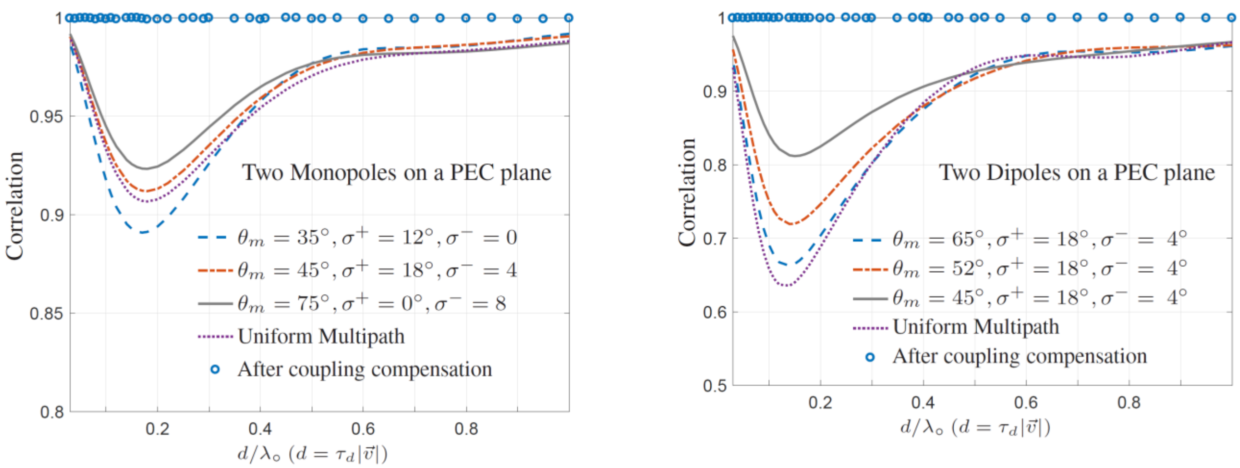



**Figure B.1.1: Normalized temporal correlation vs. the element separation in double-exponential non-uniform multipath environments**

Figure B.1.1 presents the results on the normalized temporal correlation versus the element separation in double-exponential non-uniform multipath environments. Here, the angel of arrival (AOA) distribution in azimuth plane is uniform, and the one in the elevation plane is double exponential. Parameters $\theta_m$, and $\sigma^\pm$ stand for the mean elevation angle and the associated spread angles around it. The minimum antenna separation is 0.03 $\lambda_0$. It can be seen from the figure that the probability of having erroneous channel prediction does not exceed 12% in the monopole case, and 37% in the dipole case. Moreover, using the open-circuit decoupling method, it is possible to almost perfectly compensate for the coupling effect.

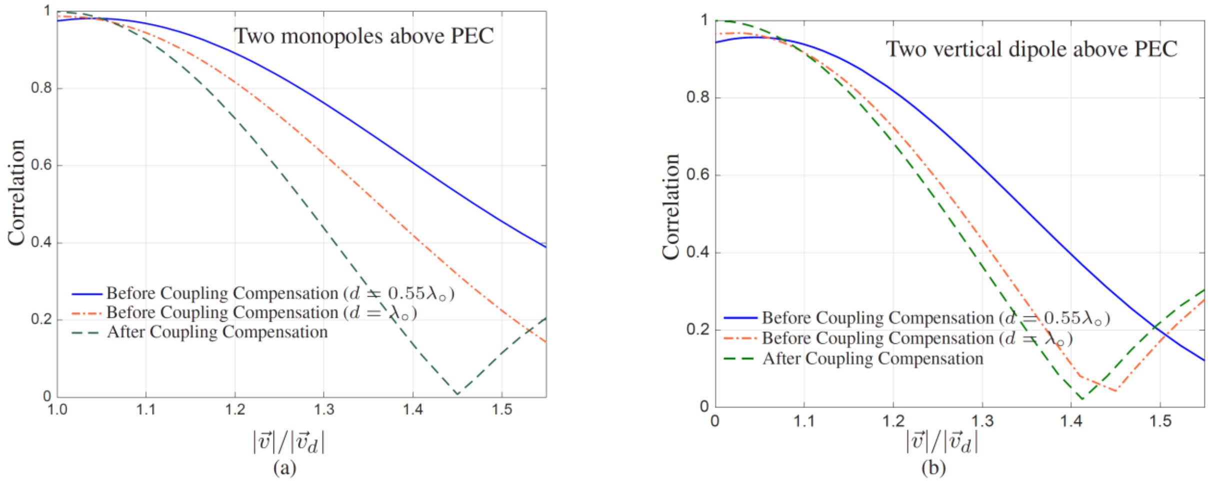
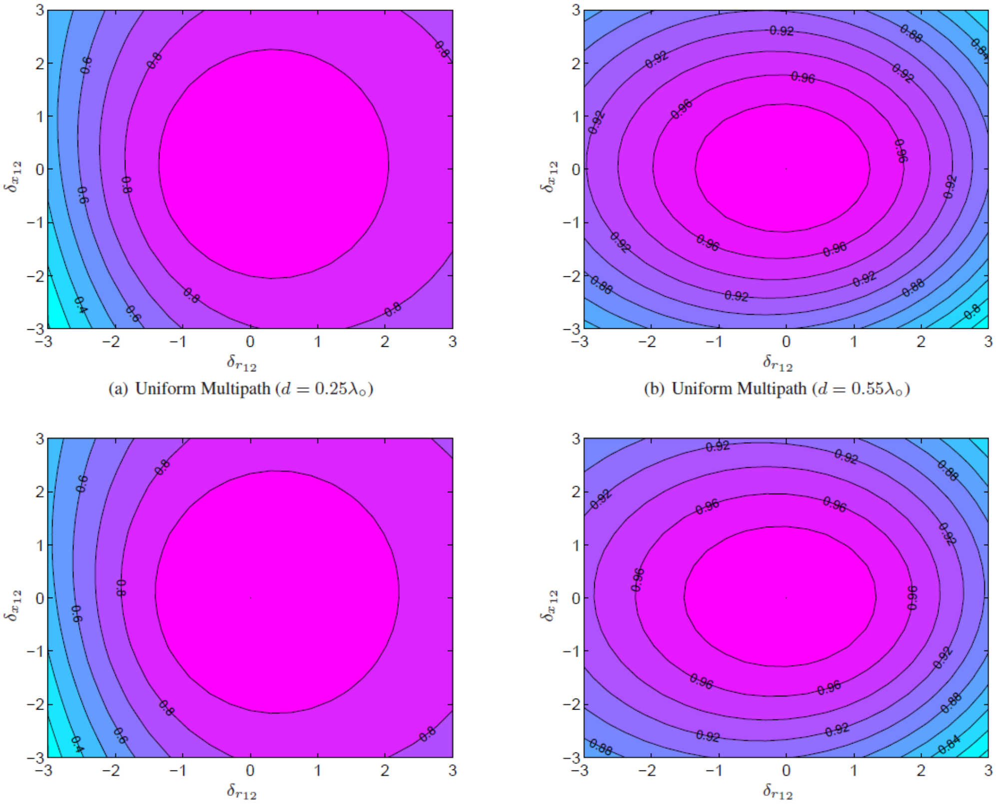



**Figure B.1.2: Effect of over-speeding on prediction performance.**

Figure B.1.2 shows the temporal correlation for over-speeding scenario. $\vec{\upsilon}_{\mathrm{d}}$ denotes the intended speed. It is clear from this simulation that for over-speeding exceeding 10% − 20% of the target speed, coupling compensation does not seem to be advantageous for the two selected antennas with the specified separations. Also, we stress that these results are quite dependent on the element separation and the type of antennas used. This study show that decoupling is not generally useful for the prediction reliability.

Figure B.1.3 presents the contours of maximum temporal cross-correlation versus relative errors in resistive and reactive components of mutual impedances for two monopoles above an infinite PEC plane. For the non-uniform multipath case, we selected uniform distribution for the AOA in the azimuth plane and double exponential distribution in the elevation plane with $\theta_m = 45°$, $\sigma^+ = 18°$, and $\sigma^- = 6°$. We can see that the impact of error in mutual impedance $(Z_{12}, Z_{21})$ is relatively higher in uniform multipath environments.



(a) Uniform Multipath ($d = 0.25\lambda_\circ$) (b) Uniform Multipath ($d = 0.55\lambda_\circ$)

(c) Non-uniform Multipath ($d = 0.25\lambda_\circ$) (d) Non-uniform Multipath ($d = 0.55\lambda_\circ$)

**Figure B.1.3: Dependency of open-circuit decoupling method on Z-matrix.**

## B.2 Genetic-Algorithm Based Beam Refinement for Initial Access in Millimeter-Wave Mobile Networks

### Illustrative Numerical Results

For illustration purposes, in this deliverable, we consider a single cell MU-MIMO system, in which four vehicles are served on the same time-frequency resource. We present the results of the beam tracking performance for moving vehicles and the performance gain of cooperative users.

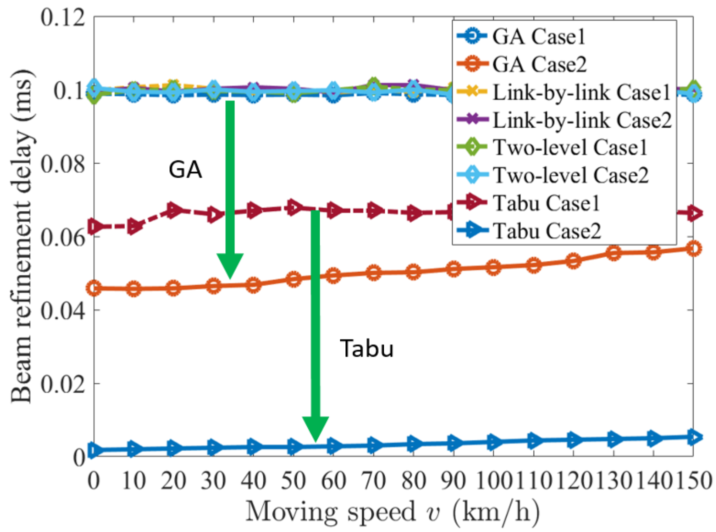



**Figure B.2.1: The beam refinement delay for a broad range of user speeds with the considered methods. The green arrows refer to the reduction from Case 1 to Case 2 for the GA and the Tabu search**.

Figure B.2.1 shows the effect of the users' mobility on the beam refinement delay for the considered algorithms. We evaluate the beam refinement delay (we assume that each iteration takes 10-4 overhead of the considered moving time slot) of each algorithm in two cases to check how well these algorithms are suitable for the mobile users. Here, the number of transmit and receive antenna are 32 and 8 respectively (2 antennas for each user), and the transmitted power to receiver noise SNR is 32 dB while the moving time slot is 1 ms. Case 1 refers to the situation that the algorithm uses random guesses at the starting point while Case 2 means the algorithm starts with the optimal sets from the previous time slot by exploiting the spatial correlation. The algorithm running delays in Case 1 and Case 2 of each method are all presented in the plot.

As seen in the figure, both the GA-based algorithm and the Tabu-based algorithm can remarkably reduce the beam refinement delay for a broad range of user speeds, since they can use the beam refinement solution before moving as the initial guess when the moving distance is not large. Note that Tabu search has the lowest delay in both cases since it simply changes the queen to its neighbours which takes full advantage of the spatial correlations. However, as the users speed increases the beam refinement delay increases slightly, intuitively because the spatial correlation between the positions in successive time slots decreases. Moreover, both the link-by-link search and the two-level-based search do not show noticeable performance gain.

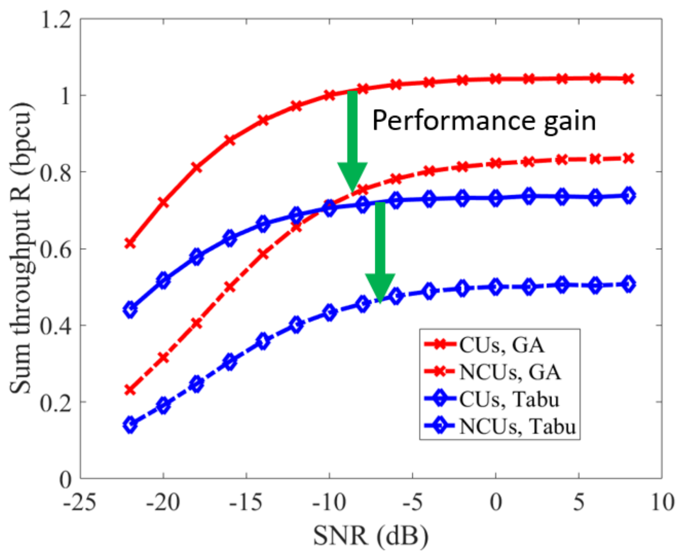



**Figure B.2.2: The optimized end-to-end sum throughput of all users with cooperative and non-cooperative cases for the GA and Tabu method.**

**Table B.2.1: Average number of required iterations in different cases. M is the number of transmit antenna while N is the total number of receive antenna, with N/4 being the number of antennas per user.**

| $M/N$ | GA, CUs | GA, NCUs | Tabu, CUs | Tabu, NCUs |
|---|---|---|---|---|
| 32/12 | 502 | 1 | 498 | 1 |
| 32/8 | 500 | 1 | 501 | 1 |
| 32/4 | 488 | 1 | 502 | 1 |

Figure B.2.2 shows the effect of the users' collaboration on the end-to-end throughput for the GA and Tabu methods. Here, the results are presented with 32 transmit antennas and 8 receive antennas (2 antennas for each user). Also, Table B.2.1 present the average number of required iterations for both the GA and the Tabu search in the cases with the CUs and the NCUs. As seen in the figure, the performance of both the GA-based algorithm and the Tabu-based algorithm are reduced in the case of NCU. Also, these reductions decrease as the SNR increases. On the other hand, in Table B.2.1 it can be seen that the NCU case requires much smaller iteration time compared with the CUs case for the considered system configurations.

## B.3 Efficient Preemption-based Multiplexing of Services

### B.3.1 Relevance to 5GCAR Use Cases

Considering the specific 5GCAR use cases [5GCAR-D2.1], some vehicular users may require concurrent transmission (in UL or DL) of URLLC and eMBB service to support simultaneously in a carrier both automated driving and infotainment. For example, when network assists a vehicle by communicating high data rate (eMBB-like) information, e.g.:

- in the “lane merge” use case (UC1), when a vehicle intends to merge from one road to another, or
- in the “high definition local map acquisition” use case (UC4), when cloud is reporting the local dynamic map to the vehicle

it should be possible that the same communication link can be used at the same time in order to pass on crucial (URLLC-like) information to the vehicle regarding, e.g.:

- a triggered event of the “network assisted vulnerable pedestrian protection” use case (UC3), where alerts are sent to the vehicle regarding a Pedestrian User Equipment (P-UE) unit crossing the street.

In another example, the communication sidelink used for a triggered event of the “see through” use case (UC2), which requires high data rates for video sharing between two vehicles, should be able to support at the same time high priority messages regarding cooperative manoeuvres (UC1) between the two vehicles.

### B.3.2 Illustrative Numerical Results

We have evaluated the BLER performance in an example where 1 or 2 out of 14 symbols in an eMBB transmission are punctured by URLLC. We consider a “robust small packet” case where a small (~100bits) packet with robust Tailbiting Convolutional Coding (TBCC) is transmitted. Figure B.3.1 shows that if eMBB receiver does not know which region is punctured, eMBB BLER performance can be significantly degraded (even under good channel conditions and robustly coded transmission).

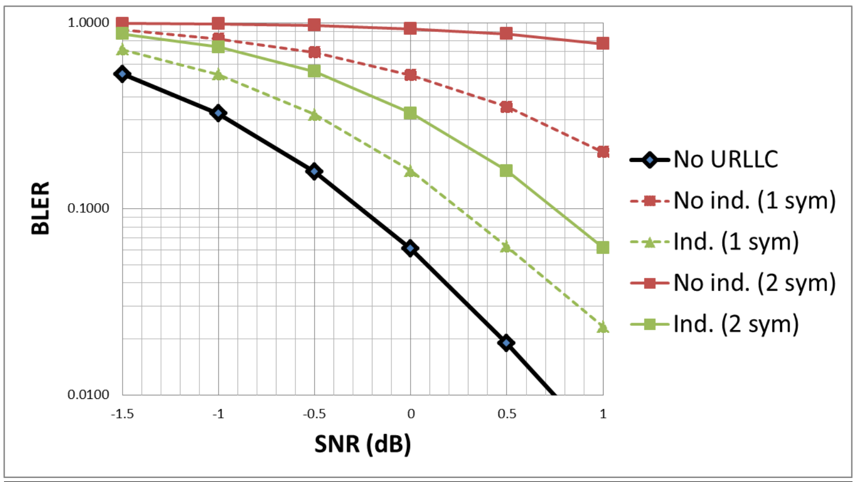



**Figure B.3.1: Preemption effect on robustly coded transmission with/without indication on preemption at Rx. Simulation assumptions: QPSK for both eMBB, URLLC; 11 bytes TB size; 1/3 TBCC coding; Interleaving within CB; 1-2 symbols for URLLC; 14 symbols for eMBB; 12 SCs of 15kHz SCS; 1 Tx-1 Rx; ideal channel estimation; soft HARQ combining at UE.**

We also evaluated, again for the robust small packet case, the eMBB BLER performance in case the punctured data are provided at the eMBB receiver with HARQ retransmission and combining. Both cases with and without preemption indication known at the receiver were considered. The main observation from Figure B3.2 is that when a further transmission follows a punctured one, and eMBB UE is aware of punctured previous received signals at the current reception, BLER performance of eMBB with HARQ can be significantly improved.

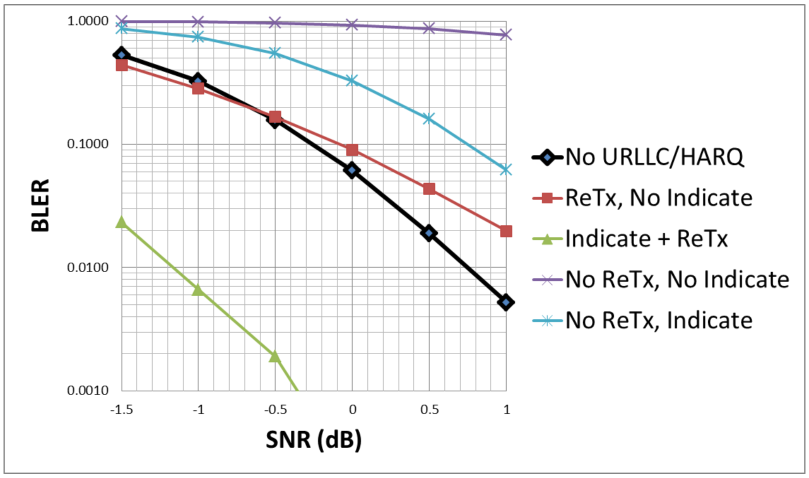



**Figure B.3.2: Preemption effect on robustly coded transmission with/without HARQ and indication on preemption at Rx.**

Based on the analysis above, the following aspects have been identified as areas of interest for solutions on the challenge of preserving eMBB performance despite the preemption in downlink:

- Preemption indication (PI). Indicating the time/frequency region of impacted eMBB resources can assist on eMBB data decoding, e.g. by nulling out LLRs (log-likelihood ratio). If such indication is received early enough at UE to decode impacted CBs on-the-fly, retransmissions can be reduced. If received late, at least UE can improve its soft combining with retransmission. Rel.15 already defines a basic preemption indication signaling mechanism for notifying eMBB UEs about preemption in DL [3GPP-38213].
- HARQ feedback. Conventional HARQ feedback does not take into account preemption knowledge at eMBB UE. This will lead to coarse retransmission granularity which is spectrally inefficient.
- Retransmission. With conventional scheduling of retransmissions after HARQ feedback, frequently preempted data will lead to a high number of retransmissions even when the non-preempted part of a block is large and has been successfully decoded by victim UE. Together with high signaling overhead for scheduling these retransmissions, user perceived throughput performance will be significantly reduced.

Within this technical component we focus on technical components regarding the two latter aspects.

### B.3.3 Preemption Indication-based HARQ-ACK Feedback for Single TB

In LTE, each codeblock (CB) is protected by a CRC and it could be theoretically possible for the UE to provide CB-level HARQ-ACK for DL transmissions. However, it was decided for only transport block (TB)-level HARQ-ACK to be fed back from the receiver to transmitter (i.e. 1 bit to notify ACK or NACK of a TB). The advantages from having TB-level feedback include a) reduced signalling overhead and b) guaranteed HARQ-ACK transmission reliability in coverage limited case due to smaller HARQ ACK codebook size. A disadvantage is the low transmission efficiency for data with large payload size since even one erroneous CB in a TB will lead to the retransmission of the whole TB. However, this was deemed acceptable considering the HARQ-ACK feedback savings and that the extreme case in LTE is to have only up to 32 CBs per TB in DL (for 20 MHz, 110 PRB, 2 spatial layers transmission).

In NR, however, the larger TBS than LTE to achieve envisioned higher throughputs means increased number of CBs per TB. Also, the introduction of preemption-based multiplexing (and also the possibility of CB-specific interference to eMBB slot transmission due to other mini-slot transmissions) amplifies the possibility of having single or few erroneous CBs within a TB. For this, multi-bit HARQ-ACK feedback per TB was introduced and code block group (CBG)-based transmission was specified; in that case, a few CBs from a TB can be grouped into a CBG to improve the system efficiency.

In case CBG-level retransmission is configured, the most straightforward way for HARQ-ACK feedback is to have one bit per CBG to denote ACK or NACK of the CBG as a whole. There is however a drawback with such design, in case of preempted transmission: HARQ-ACK feedback for a preempted CBG is a NACK even if the preemption is partial from the CBG point of view. Then, the spectral efficiency can be very low, especially when CBG size is configured to be relatively high, resulting to the similar problematic case experienced in LTE with 1-bit TB-level HARQ-ACK feedback. Considering also that CBG size configuration might be a slow process (Radio Resource Control (RRC) based), it will not take into account the sporadic URLLC traffic. Hence, we shouldn't expect that a gNB will align URLLC transmissions with CBG configuration.

An extreme solution to overcome such low SE issue could be to report ACK/NACK per CB. Although with such approach UE will notify most accurately every erroneous CB to gNB, it will be highly inefficient. The following table shows also the trend for HARQ-ACK payload increase when a number of failed CB indexes can be reported.

| CBG size in # of CB's | 5 | 10 | 20 | 30 | 40 | 50 | 60 |
|---|---|---|---|---|---|---|---|
| Bits needed to report one CB index | 3 | 4 | 5 | 5 | 6 | 6 | 6 |
| Bits needed to report two CB indexes | 4 | 6 | 8 | 9 | 10 | 11 | 11 |

More details on our proposed solutions are provided below.

- Possibility-a: Considering 2 feedback bits sent for every CBG that is partially punctured as an example, UE could at least clearly inform the gNB if there was correct decoding of: a) the whole CBG; b) the bundle of non-punctured CBs. The following Figure illustrates the aforementioned 2 feedback bits example.

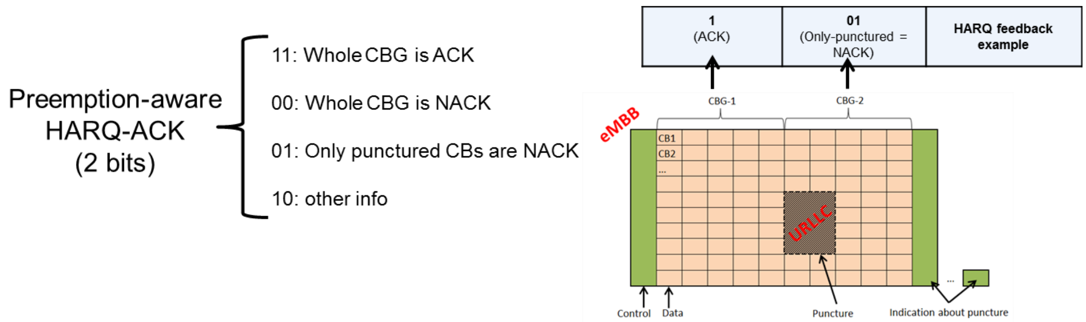



**Figure B.3.3: Proposed PI-aware HARQ-ACK feedback. 2 feedback bits example**.

- Possibility-b: One disadvantage of the 1-bit alternative (i.e. repurposed ACK approach) compared with the 2-bit alternative is that the whole punctured area has to be assumed erroneously decoded. If there are partially preempted CBs that have been successfully decoded at UE, there will be DL data throughput loss. On the other hand, an issue arising from having multiple bits per punctured CBG regards the case where a puncturing indication is sent by gNB but missed by UE. In that situation, understanding between gNB and UE on transmitted HARQ-ACK codebook will be corrupted since gNB will translate a larger number of (Uplink Control Information) UCI bits received as of HARQ-ACK feedback. We plan to look further for solution on this issue.

### B.3.4 Binary Search Algorithm–based Feedback for Multiple TBs

An example is given below, with 5 outstanding TBs per HARQ message, 4 CBGs per TB and 10 CBs per CBG. In total, according to the conventional approach of 1 ACK/NACK bit per CBG, 20 ACK/NACK bits are required to indicate all CBGs with the current method and any incorrect CB will result in all CBs within the CBG retransmitted.

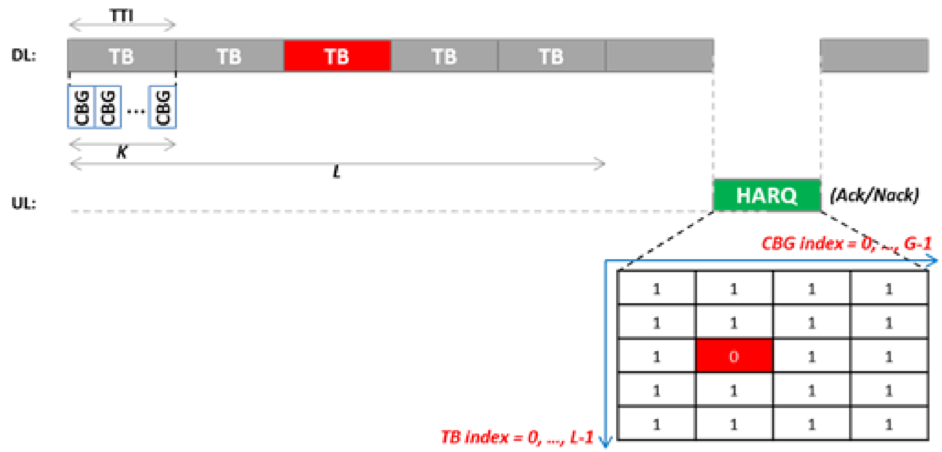



**Figure B.3.4: Example for conventional HARQ-ACK feedback on multiple TBs**

We see the following drawbacks of the aforementioned design,

1) Inefficient transmission for both control and data
    a. Several ACK/NACK bits are used to indicate a correct TB (in grey) which results in very inefficient UL control transmission
    b. A single ACK/NACK bit is used to indicate one CBG (in red) which results in inefficient DL data retransmission in case of partial CBG unsuccessful decoding.
2) Highly variable ACK/NACK payload size with many different combinations of the number of scheduled PRBs and the MCS used will result in a very complicated specification.

The following figure explains our solution for the previous example case of 5 TBs..

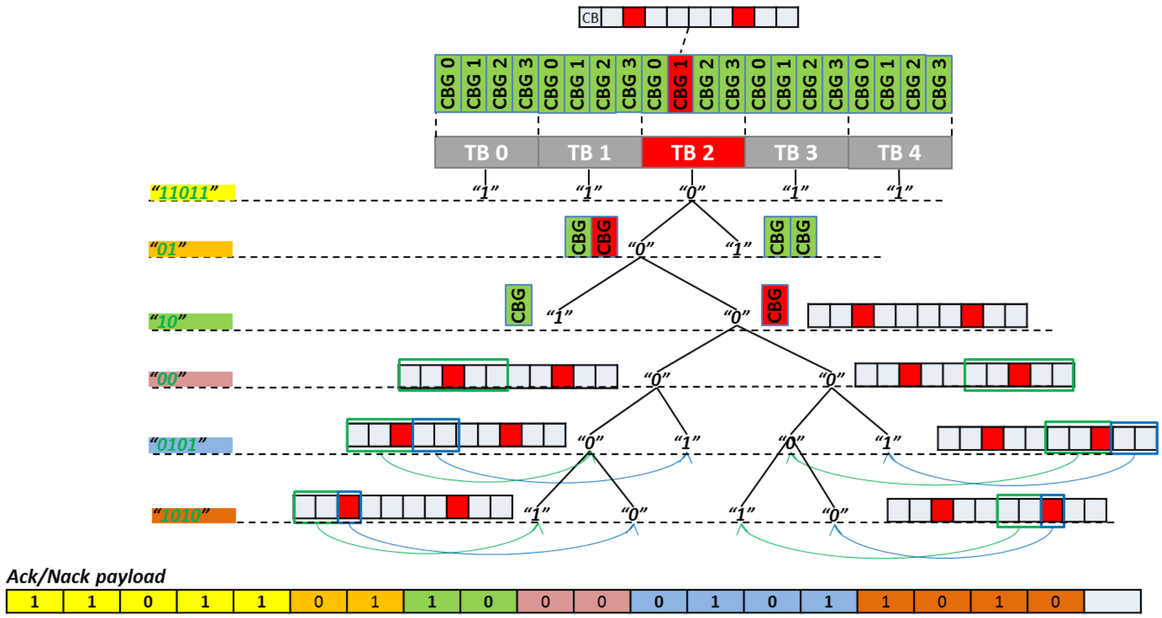



**Figure B.3.5: Example of proposed binary search based HARQ-ACK feedback for multiple TBs.**

### B.3.5 Preconfigured, One-to-one Mapped eMBB/URLLC Data Resource Regions

Figure B.3.6 is a visual example of the proposed approach for subsequent transmission of preempted data before corresponding HARQ feedback.

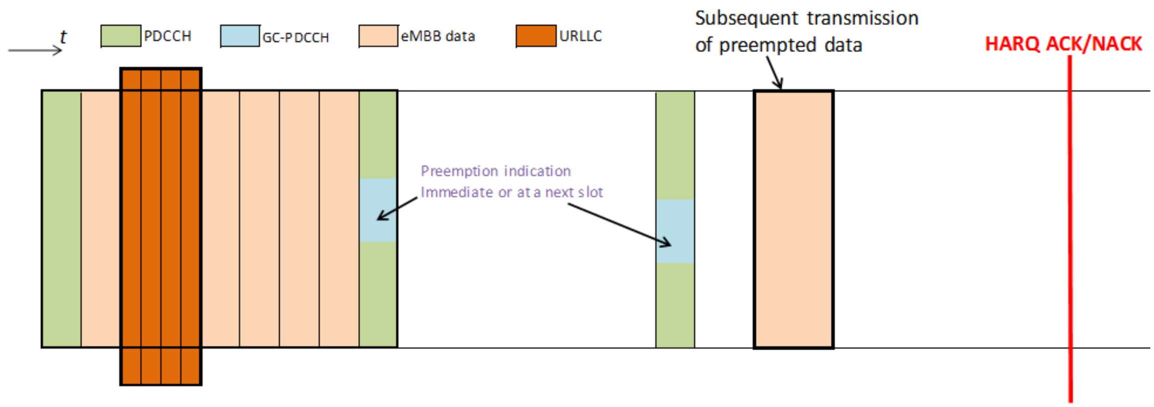



**Figure B.3.6: Subsequent transmission of preempted data.**

It is important that the scheduling procedure for subsequent transmission is kept as efficient as possible in terms of overhead and scheduling complexity introduced. Keeping full flexibility on resource allocation of subsequent transmissions will incur significant signalling overhead as well as control channel decoding complexity at victim UE, especially when amount of such transmissions is large. Therefore, instead of adopting CBG-based retransmission, it would be beneficial to have pre-configured regions within e.g. eMBB resource to potentially allocate subsequent transmissions. The victim UE will just need to know if a pre-configured region is enabled (and contains partial information for a previously received TB) or not (and contains new data). In addition, a method for one-to-one mapping of URLLC regions to subsequent transmission regions could provide an efficient way of scheduling implicitly the resources to be used.

## B.4 Decentralized Pilot-to-Data Power Ratio Configuration in Multi-Cell Multi-User MIMO Systems

### Illustrative Numerical Results

For illustration purposes, in this deliverable, we consider a single cell MU MIMO system, in which two vehicles are served on the same time-frequency resource. The two connected vehicles tune their respective pilot and data power levels by playing a 2-user non-cooperative game.

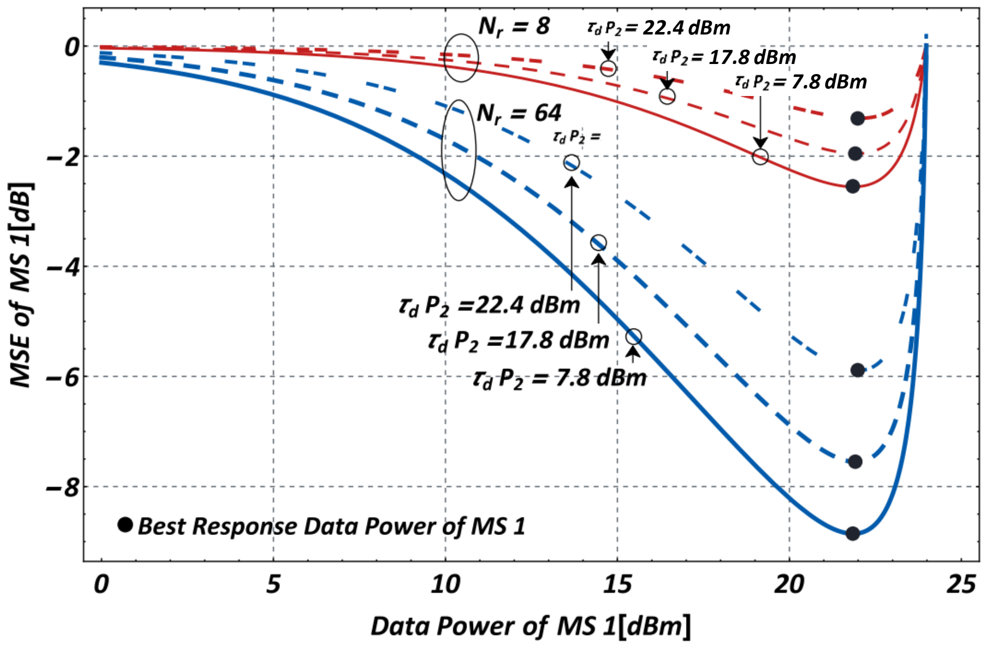



**Figure B.4.1: The MSE of User-1 in a two-player pilot-to-data power ratio tuning game. Increasing the number of receive antennas from Nr=8 to Nr=64 and tuning the pilot-to-data power ratio under a total power constraint (24 dBm) helps to reduce the MSE. ($\tau_d$ denotes the number of pilot symbols, and $\tau_d P_2$ denotes the total pilot power used by MS2.)**

Figure B.4.1 shows the MSE performance of MS1 as a function of the data power of MS1 P1, while setting the total data power level of MS2 to the fixed value of 7.8 dBm, 17.8 dBm and 22.4 dBm and employing Nr = 8 and Nr = 64 receive antennas at the BS. First, notice that the MSE of MS-1 is quasi-convex with respect to P1. In all three cases of P2, there exists a unique best response data power, which is marked by a dot in the figure. An important observation is that as the data power of MS 2 increases, the best response data power of MS 1 also increases. As an example, for the three cases of P2 with Nr = 8, the best response data powers of MS 1 are 21.85 dBm, 21.93 dBm and 22.00 dBm, respectively. This initial result clearly suggests, that there is a great potential of increasing the number of antennas and tuning the PDPR in terms of the achieved mean squared error for each vehicle. The performance analysis of the proposed game theoretic decentralized power control algorithm in multicell systems is left for future work.

## B.5 Enhancing Reliability in V2X Communication by Exploiting Diversity from Cooperative Links

### Illustrative numerical results

The baseline scenario represents URLLC packet transmission between the BS and the single cars on the highway through the V2N link. The traffic is modeled by URLLC packets of size 200 bytes, which are transmitted in a regular pattern every 10 ms. The deep shadow fading caused by bypassing trailers or cars is characterized by a random model, where shadowing events occur with a probability of 25%. The shadowing attenuation is determined according to the model described in [SJS+15], where we assume the distance between the trailer blocking the V2N link and car A to lie between 2 to 10 m. The particular distance value is randomly selected, yielding shadowing attenuations to lie between 23 to 30 dB. For the baseline scenario, no retransmission is considered.

Figure B.5.1 (top) shows the received average power of the DL reference signal vs. the time it takes for 3 cars driving along a section of a highway, where each car is represented by a coloured curve. The cars are driving in close vicinity, and are thus considered as a cluster. The bottom figure shows the corresponding packet loss observed in the time duration. The reference car A is represented by the green curve. From the top figure, we observe that 4 deep shadowing events occur, where the received power drops by more than 20 dB. However, packet losses occur only if the power level drops below -120 dB, as observed in the bottom figure. The reason lies in the proper adjustment of the MCS for the packet transmission if the power level is larger than -120 dB; only if it drops below, a proper MCS either cannot be found or insufficient resources are available. From both figures, we can observe that once car A (green) experiences a deep shadow fading, at least one of the other cars (blue and black curve) still experiences a good reception quality and thus can maintain a packet transmission without any losses. These cars can well support car A in receiving a missed URLLC packet, while ensuring latency and reliability constraints.

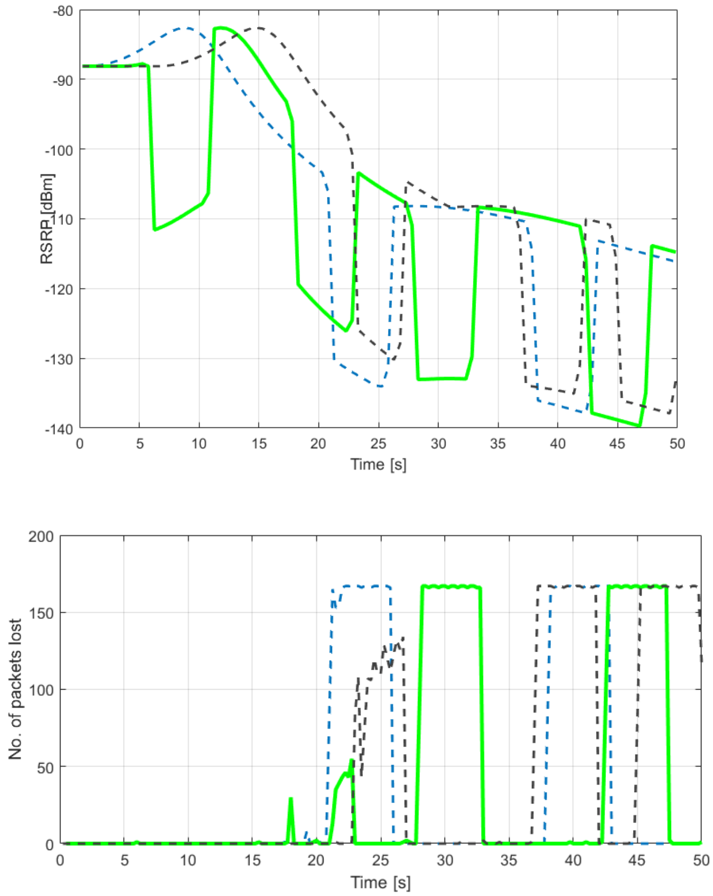



**Figure B.5.1 Received average power (RSRP) vs. time for 3 cars forming a cluster (top) and corresponding packet losses measured (bottom). Conditions of each car are represented by individually coloured curves.**

## B.6 Beam-based Broadcast Schemes for V2X Applications

### Illustrative Numerical Results

By evaluating the performance metrics including broadcast latency and overhead, we make the following performance insights:

- *How wide should the beam be*: Latency is optimized when the thinnest beam is formed, as shown in Figure B. 6.1 (a). Here, latency is defined as the duration between the time when the eNB starts to broadcast the cell discovery related information and when the UE successfully decodes this information. Interestingly, the beamforming architecture has no impact on the latency, which makes the performance of analog/hybrid beamforming the same as the digital beamforming in terms of the latency. By contrast, thinner beam results in higher overhead, as shown in Figure B.6.1-b.

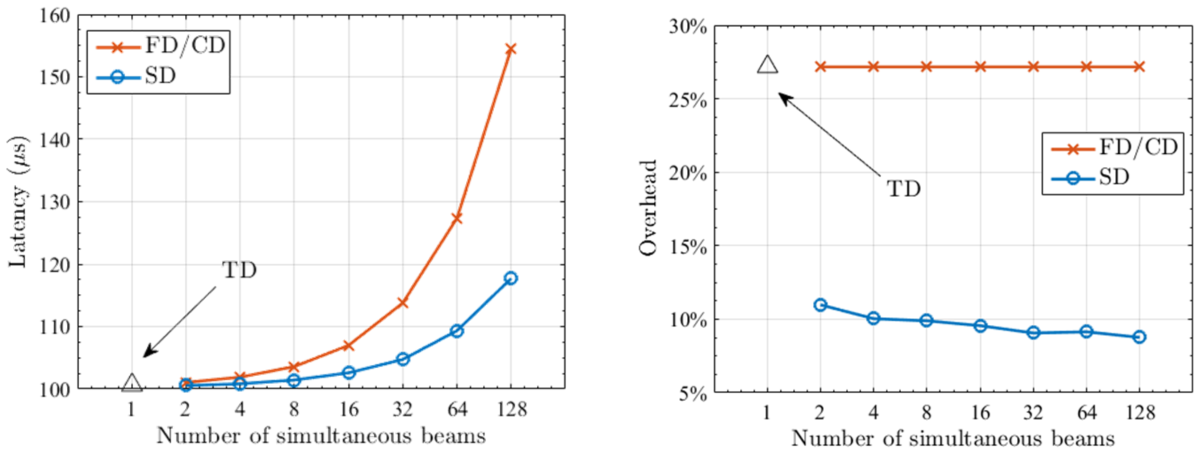



**Figure B.6.1: Performance of different broadcast schemes for V2X applications are compared in terms of (a) latency and (b) overhead.**

- *Is it beneficial to exploit multi-beam simultaneous scan*: As depicted in Figure B.6.1 (a), multi-beam simultaneous scan leads to a latency penalty. Single beam exhaustive scan is found to be optimal in terms of the latency. This is reversed when considering the overhead, where the single beam exhaustive scan, as well as frequency-division/code-division multi-beam scan, suffer from high overhead, as shown in Figure B.6.1 (b). The spatial-division multi-beam scan, however, achieves the lowest overhead. In a word, by configuring the number of simultaneous beams, latency can be traded with overhead, or vice versa.

- *How does frame structure affect the broadcast performance*: It is clear from Figure B.6.2 that frame containing multiple broadcast Intervals results in lower latency at the price of higher overhead. On the contrary, unicast only frame and/or separating one broadcast interval into several frames, are recommended to achieve lower overhead with relative high latency.

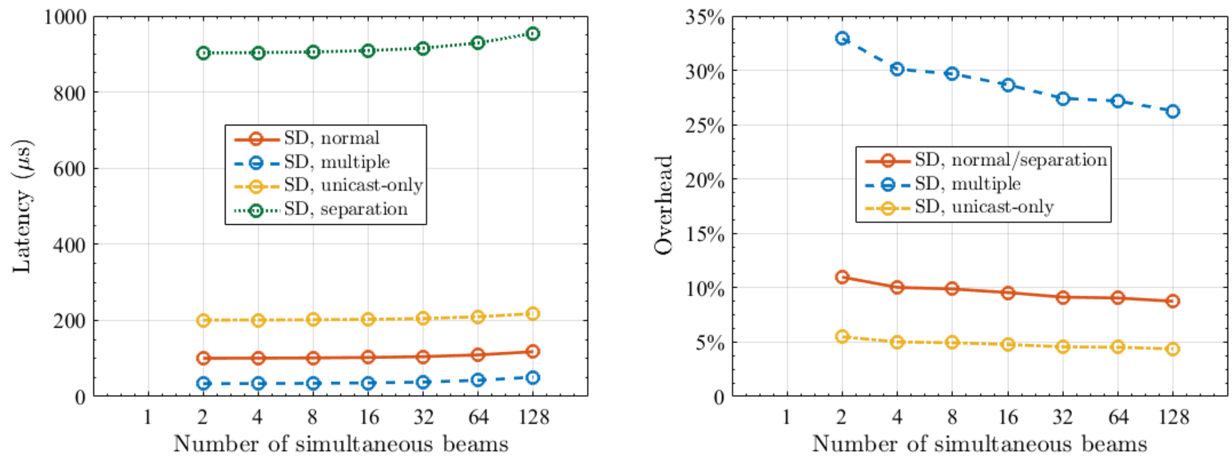



**Figure B.6.1*:* Performance of different broadcast schemes for V2X applications are compared in terms of (a) latency and (b) overhead.**

- *What is the impact of block error rate*: It has been demonstrated in Figure B.6.3 that the latency and the overhead are relatively insensitive to extreme low block error rates ($10^{-5}$). Therefore, the relative low block error rate ($10^{-3}$) would be sufficient for V2X beam-based broadcast, unless extreme coding scheme is desired to achieve better performance.

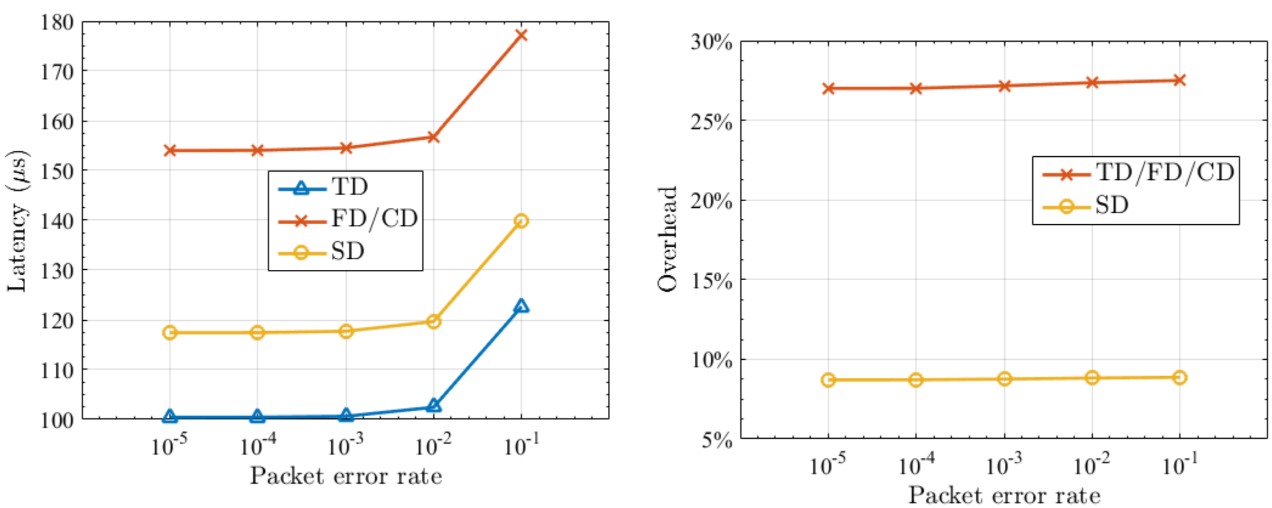



**Figure B. 6.3 Performance of different block error rate for V2X applications are compared in terms of (a) latency and (b) overhead.**

## B.7 Fundamental Trade-offs between Reliability and Latency

**Illustrative Numerical Results**

One key metric for obtaining high reliability on fading channels is the diversity order, which can be described as the slope of the BLER-vs-SNR relationship. A scheme with a high diversity order has a steeper BLER curve, allowing to approach low BLERs more quickly. Figure B.7.1 shows the theoretically obtainable maximum diversity order for different choices of $R_c$, if the message is transmitted over a channel with $N_b$ different fading blocks, i.e. $N_b$=2 means that two halves of the message experience two different fading coefficients. We observe that the obtained diversity order depends both on $N_b$ and $R_c$, and using a low $R_c$ helps to obtain high diversity order. Recall that $R=mR_c$, and hence for a fixed $R$, if a lower channel coding rate $R_c$ is chosen, one needs to increase the modulation order $m$. This suggests using higher order modulation with low channel coding rates to obtain high reliability for fading channels. Instead of using QPSK, one should rather use higher order modulation with lower coding rates to obtain high reliability, especially for high values of $N_b$, e.g. for fast fading channels.

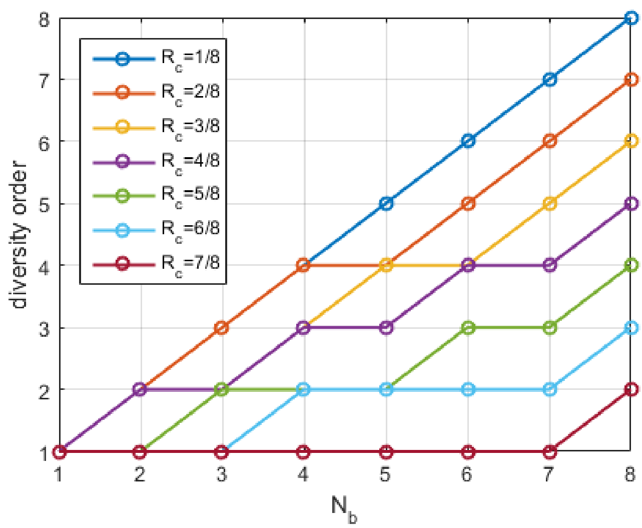



**Figure B.7.1 Maximum diversity order for code rate $R_c$ and $N_b$ fading blocks**

To evaluate the mentioned results in the finite length regime, we estimate the BLER performance for a practical case by using the ideas from [PPV10]. We use 128 resource elements to transmit a message of length 192 bits (resulting in $R$=1.5 bits/use) for $N_b$ = {1, 2, 4, 8} fading blocks with QPSK (dashed lines) and Gaussian signalling (solid lines), which can be considered as the upper limit for the highest order modulation. We observe in Figure B.7.2 that as long as $N_b$ is larger than 1, BLER curves with Gaussian signalling show better slopes and have higher diversity orders. For example, if $N_b$=4 is considered, QPSK modulation has a gap about 10dB at a BLER of $10^{-4}$ as compared to Gaussian signalling, which can be compensated by switching to a higher order modulation and lowering the channel coding rate $R_c$, without altering the rate $R$. Also note that this gap become especially visible at low BLERs, which become especially important for the URLLC use cases.

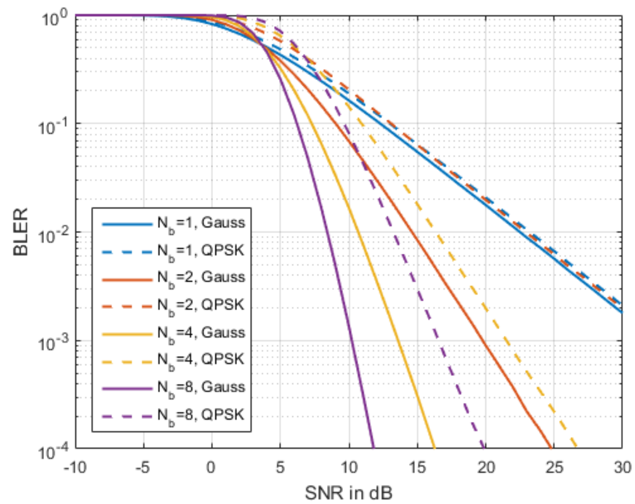



**Figure B.7.2 BLER performance in finite lengths (128 resource elements) for R=1.b bits/use**

To sum up, depending on the characteristics of the channel, which also influence the selection of $N_b$, higher order modulation can allow for a higher diversity order and hence improve the BLER significantly. Therefore, the coding rate and the modulation order should be selected carefully if low BLERs are targeted. As a next step, the performance with practical codes (e.g. polar or LDPC codes) will be considered.

## B.8 Predictor Antenna for M-MIMO Adaptive BF

### Illustrative Numerical Results

During several drive-tests, we measure the true channel $h_m$ and the predicted channel $h_p$ for three different scenarios: the ideal channel prediction, prediction based on the outdated channel measurements and prediction based on the predictor antenna measurements. As illustrated in Figure B.8.1, to make a fair comparison between the three schemes, we constrain the prediction horizon $\delta = v\tau$ (where, $\tau$ is the delay between measurement and BF and $v$ is the velocity) and the antenna spacing $d = \delta$ to be identical. Then, we compute offline the power that would be received at the target antenna with MRT BF based on these three different predicted channels. The channel measurement campaign is detailed in the coming D3.2 and the full methodology and results are detailed in [PWB+18].

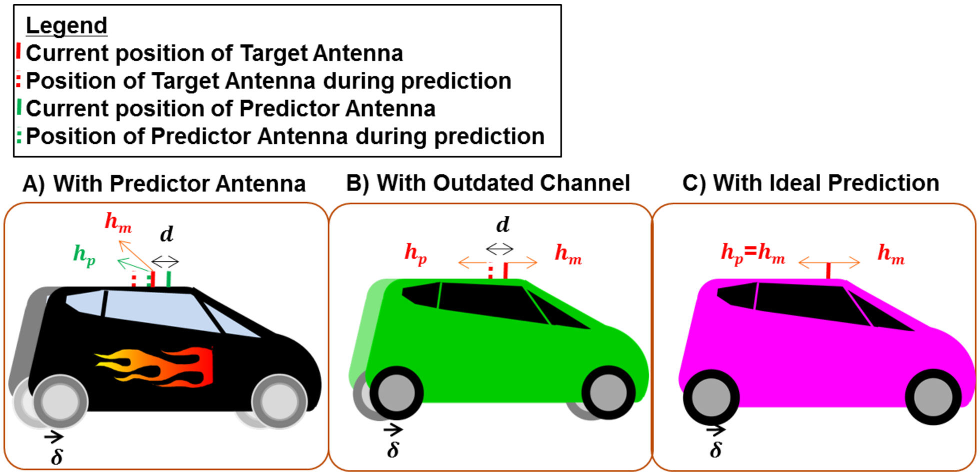
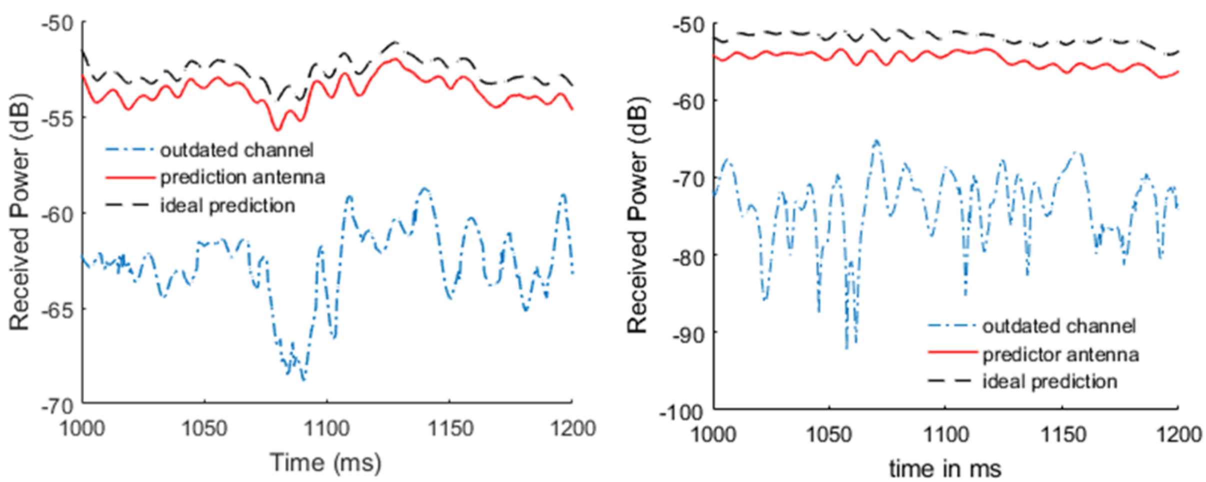



**Figure B.8.1: Compared scenarios**

Fig. B.8.2 shows the received power for the three prediction mechanisms and two different horizons. As illustrated by this figure, channel predictions based on the predictor antenna concept are accurate enough for adaptive M-MIMO BF schemes such as MRT even for a horizon as large as 42 cm (i.e. around 3 wavelengths). On purpose, we have used inaccurate speed estimates (corresponding to an error on the positioning accuracy of +/- 0.075 wavelength) to produce the results illustrated in Figure. B.8.2, and show that the Predictor Antenna with a basic speed accuracy is enough for adaptive M-MIMO MRT BF. In [PWB+18], we have compared this scheme to a one with a better speed accuracy and shown better performance results also for SF BF [PWB+18].




a) $d$=11 cm (~0.8 wavelength)

b) $d$ = 42 cm (~3 wavelengths)

**Figure B.8.2: Results for two different horizons**

Using the relation $d = \delta = v\tau$, one can derive the velocities $v = \frac{d}{\tau}$, for which M-MIMO MRT is supportable, based on these successful experiments at 2.180 GHz with $\delta$=42 cm, in Table

B.8.1. Future studies with larger horizons will enable us to locate the “Wall of Speed”, which is ***beyond these values***.

**Table B.8.1: Speeds supported with horizon = 42 cm**

| Latency $\tau$ (ms) | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Speed Latency $v$ (km/h) | 1521 | 756 | 504 | 378 | 302 |

### B.9 Joint Optimization of Link Adaptation and HARQ Retransmissions for URLLC Services in a High-Mobility Scenario

In this section 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 MCS level are determined for each URLLC service and average SNR. In what follows, representative results are presented.

**Illustrative Numerical Results**

We consider $T_{\mathrm{RTT}}$ = 0.5 ms and $T_{\mathrm{TTI}}$ = 0.125 ms, which is one among many possible timing attributes related to downlink HARQ for a flexible timing approach in 5G [PKB+17].

In Figure B.9.1, we consider a URLLC service with latency budget and reliability of 5 ms and 1-$10^{-4}$, respectively. The optimal maximum number of transmissions (resulting from the optimal waiting time), denoted $K_{\mathrm{opt}}$, and the optimal MCS level, denoted $m_{\mathrm{opt}}$, are calculated for different values of the average SNR. The different MCS levels considered are given in Table B.9.1.

**Table B.9.1: Modulation and Coding Schemes**

| | MCS 1 | MCS 2 | MCS 3 | MCS 4 | MCS 5 | MCS 6 |
|---|---|---|---|---|---|---|
| Modulation | BPSK | QPSK | QPSK | 16-QAM | 16-QAM | 64-QAM |
| Coding rate | 1/2 | 1/2 | 3/4 | 9/16 | 3/4 | 3/4 |

In Figure B.9.2, we compare the optimal spectral efficiency $S_{\mathrm{e}}(x_{\mathrm{opt}},m_{\mathrm{opt}})$ which is an output of the optimization problem, with the spectral efficiency $S_{\mathrm{e}}(0,m_{\mathrm{opt}})$ which corresponds to the case $m = m_{\mathrm{opt}}$ (i.e. link adaptation) and $x = 0$ as MCS and waiting time, respectively. We point out that $x = 0$ means that the maximum number of transmissions is equal to $K(0)$, which is the largest possible value of $K(x)$ given a certain latency budget. The reliability is set to 1-$10^{-4}$, and two latency budgets of 5 and 10 ms are considered. The spectral efficiencies $S_{\mathrm{e}}(x_{\mathrm{opt}},m_{\mathrm{opt}})$ and $S_{\mathrm{e}}(0,m_{\mathrm{opt}})$ are illustrated for different values of average SNR. It can be noticed that, unlike $S_{\mathrm{e}}(x_{\mathrm{opt}},m_{\mathrm{opt}})$, $S_{\mathrm{e}}(0,m_{\mathrm{opt}})$ does not always increase with the average SNR. This results from the fact that $S_{\mathrm{e}}(0,m_{\mathrm{opt}})$ is not the maximum spectral efficiency for each value of the SNR. Furthermore, the gain in terms of spectral efficiency is higher for greater latency budget.

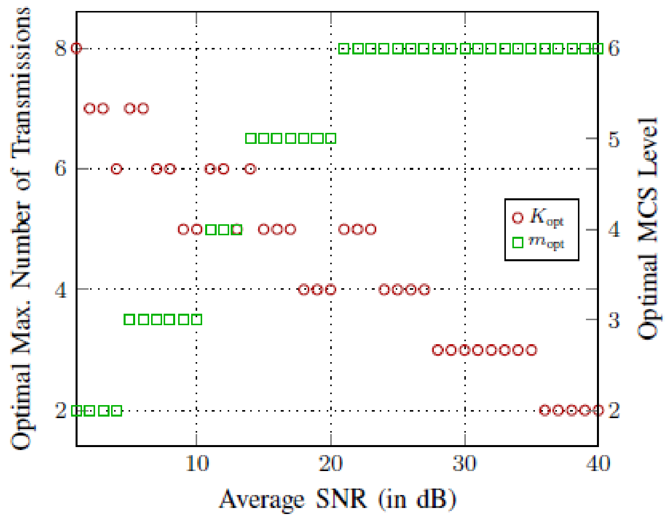



**Figure B.9.1: Optimal Max Number of Transmissions and Optimal MCS Level vs Average SNR, with latency budget 5 ms and reliability 1-10$^{-4}$.**

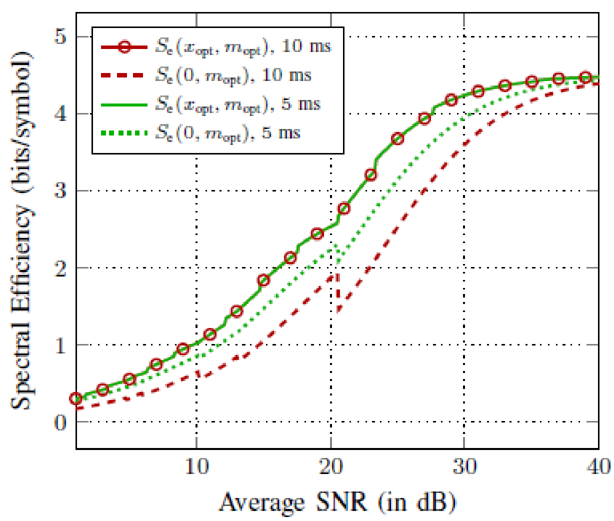



**Figure B.9.2: Optimal Spectral Efficiency $S_e(x_{opt},m_{opt})$ and spectral efficiency $S_e(0,m_{opt})$ vs Average SNR for different latency budgets, with reliability 1-10$^{-4}$.**

## B.10 Power Control and Scheduling to Mitigate Adjacent Channel Interference in Vehicle-to-Vehicle Communication

### Illustrative Numerical Results

Fig. B.10.1 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.

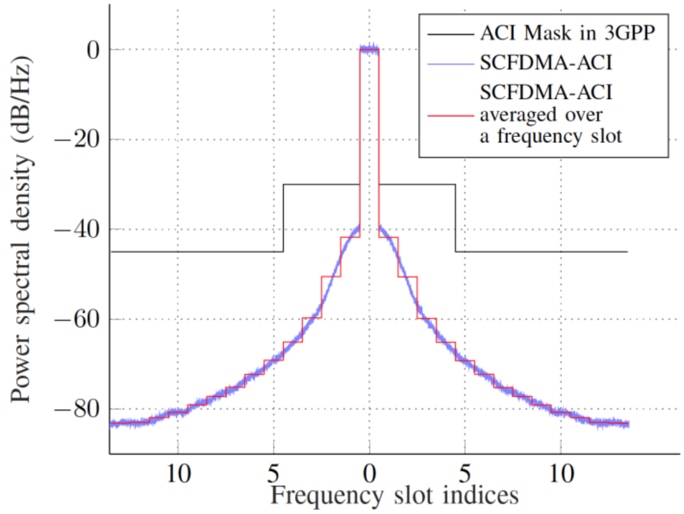



**Figure B.10.1 Different ACI models.**

In Fig. B.10.2, 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 black and blue curves correspond to a typical block interleaver scheduler (BIS) with a design parameter *w*. The green curve is our proposed heuristic scheduling scheme, and the red curve is the near-optimal performance that can be achieved by solving the scheduling problem formulation. For all the details, please refer to [HSB+17].

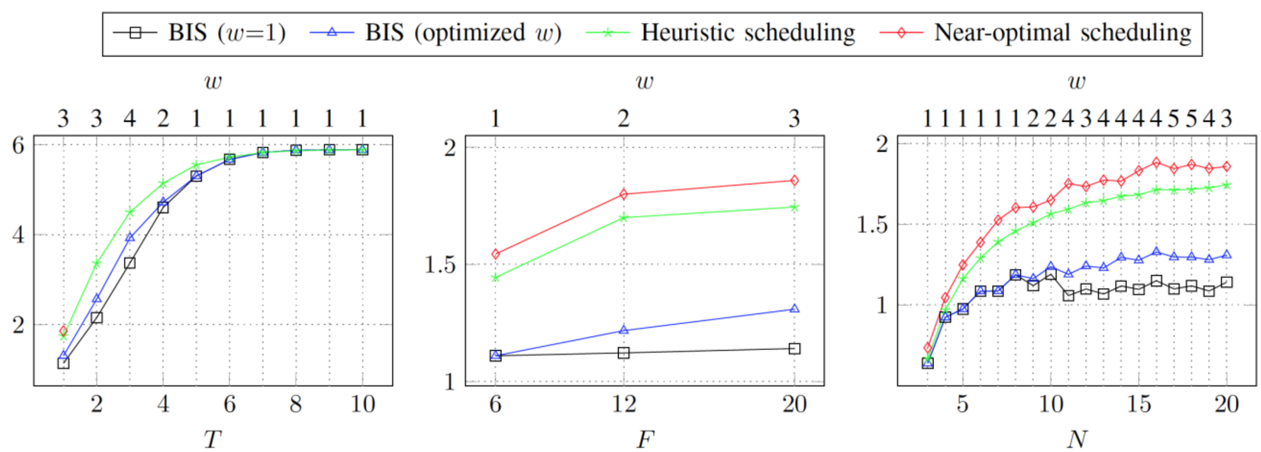



**Figure B.10.2 Average number of successful links per V-UE for various scheduling algorithms.**

## B.11 Sidelink Resource Allocation with Network Assistance using Multiple Antennas

According to the state-of-art solutions, a sidelink scheduler would try to minimize interference by ensuring sufficient physical separation between UEs transmitting/receiving on any given radio resource $s$. In such baseline approach, upon receiving a request for resources from UE $i$ to transmit to UE $j$ on link $(i,j)$, the sidelink scheduler (BS) considering a set of candidate resources, where each candidate resource $s$ fulfills the following constraints:

- UE $i$ is sufficiently far away from all UEs $l$ scheduled to receive in $s$.
- UE $j$ is sufficiently far away from all UEs $k$ scheduled to transmit in $s$.

This approach, however, does not take advantage of the UEs' ability to mitigate interference by means of multi-antenna transmission/reception – and thus may result in a small set of candidate resources, especially when the network is under high load.

According to the proposed extension, if the sidelink scheduler (BS) is aware of the nulling sets $\mathcal{Z}_{ij}$ for each link $(i,j)$ (or a subset thereof), this relaxes the above constraints as follows:

- UE $i$ is sufficiently far away from all UEs $l$ scheduled to receive in $s$, excluding those toward which it can form nulls (i.e., $l \in \mathcal{Z}_{ij}$) as well as those which can form nulls toward UE $i$ (i.e., $i \in \mathcal{Z}_{lk}$).
- UE $j$ is sufficiently far away from all UEs $k$ scheduled to transmit in $s$, excluding those toward which it can form nulls (i.e., $k \in \mathcal{Z}_{ji}$) as well as those which can form nulls toward UE $j$ (i.e., $j \in \mathcal{Z}_{kl}$) .

One of the benefits of the particular scheme is that it requires relatively low signalling overhead between the UEs and the cellular network. In every reporting cycle, only a list of IDs of the nearby UEs forming the nulling sets (transmit and receive) needs to be reported or updated to the BS. Based on the reported nulling set, the BS needs to select the users for which interference shall be mitigated and instruct each UE accordingly. Goal of the selection process could be also to e.g. avoid selecting possible high-mobility users which are only reported a single time and prioritize long-term neighbours. For the MIMO/beamforming process itself, mobility, location changes and channel aging effects might degrade the performance of such schemes. Therefore, the multi-antenna schemes are calculated based on recent up-to-date measurements, which are frequently performed between sidelink UEs, possibly more frequently that the topology update reporting to the BS.

**Example**

In Fig. B.11.1, UE $i$ can form a null toward UE $m$ when transmitting to UE $j$ (i.e., $m \in \mathcal{Z}_{ij}$). Thus, in spite of UE $i$ being physically close to UE $m$, UE $i$ may be allowed to transmit on a resource UE $m$ is receiving on, without causing interference to UE $m$.

Similarly, UE $l$ can form a null toward UE $n$ when receiving from UE $k$ (i.e., $n \in \mathcal{Z}_{lk}$). Thus, in spite of UE $l$ being physically close to UE $n$, UE $l$ may be allowed to receive on a resource UE $n$ is transmitting on, without suffering interference from UE $n$.

**Overview of the procedure**

The proposed method comprises the following steps (described from the perspective of UE $i$, as shown in Fig. B.11.1):

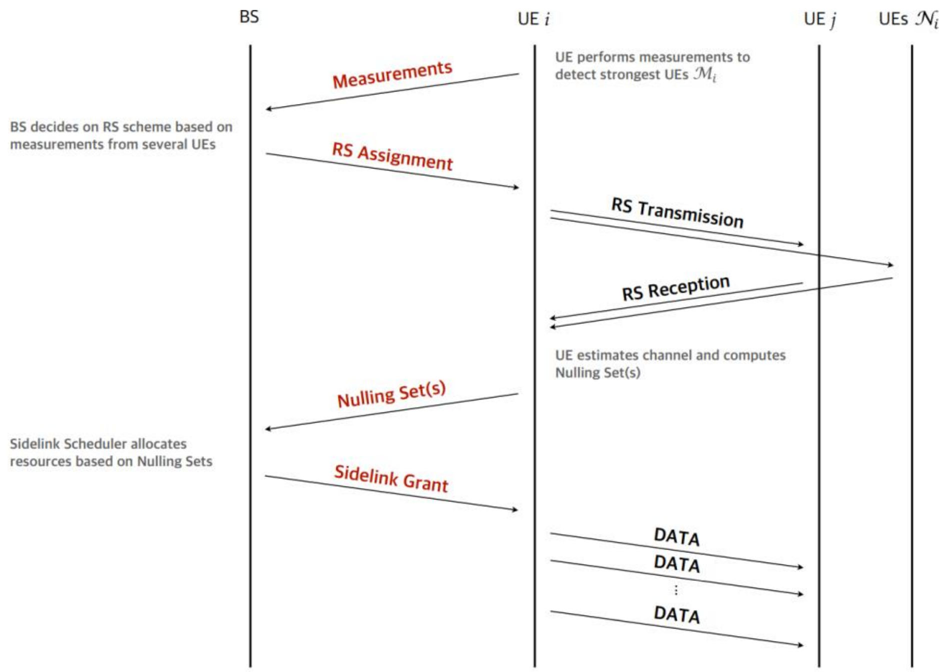



**Figure B.11-1: Message sequence chart of proposed procedure**

1. **Measurement reporting**: Based on own measurements, UE $i$ reports a list of strongest detected UEs $k \in \mathcal{M}_i$ to its serving BS. Together with the UEs' IDs, location information and signal strengths observed from these UEs can also be reported if available at the UE.

2. **Reference Signal (RS) assignment**: UE $i$ receives instructions from the BS about the RS scheme to use, which includes RS symbols and their allocation in time/frequency/beam/antenna.

3. **RS transmission/reception**: UE $i$ transmits/receives RSs based on the assigned RS scheme.

4. **Channel estimation**: UE $i$ estimates the channel matrix $\mathbf{H}_{ij}$ to a set of neighbor UEs $j \in \mathcal{N}_i \subseteq \mathcal{M}_i$ based on the RS sequences received from UE $j$. If UEs support beamforming, this phase also includes the selection of the best set of beams.

5. **Nulling set determination**: Based on these measurements and –if provided– knowledge of UEs' positions, UE $i$ determines a nulling set $\mathcal{Z}_{ij}$ for each neighbor UE $j \in \mathcal{N}_i$. This can be implemented via beamforming and/or MIMO precoding in both transmit and/or receive direction by the UE.

6. **Nulling set reporting**: UE $i$ reports its nulling sets $\mathcal{Z}_{ij}$, for all $j \in \mathcal{N}_i$, to its serving BS. This information includes the user IDs, time/frequency and spatial resources to which interference mitigation applies and may also include information about the expected interference level (including beamforming/precoding), channel measurements (complex-valued or power levels), etc. In case UEs are served by different BSs, this information

needs to be exchanged between BSs (e.g., over the backhaul network).

7. **Sidelink resource allocation**: The sidelink scheduler (BS) uses the reported nulling sets when determining candidate resources for link scheduling. The scheduling decision is transmitted to the UE via a Sidelink Grant.

8. **Multi-antenna transmission/reception of sidelink data**:

   In the general case of transmit- and receive-side beamforming and MIMO processing, the MIMO signal received by an arbitrary UE $j$, which has been scheduled to receive a data symbol/vector $\mathbf{s}_{ij}$ from UE $i$ on a particular time/frequency resource, is given by

$$\mathbf{y}_j = \mathbf{W}_{ji}^R \left( \mathbf{H}_{ij} \mathbf{W}_{ij}^T \mathbf{s}_{ij} + \sum_{k \neq i} \sum_{l \neq j} \mathbf{H}_{kj} \mathbf{W}_{kl}^T \mathbf{s}_{kl} + \sum_{m \neq j} \mathbf{H}_{ij} \mathbf{W}_{im}^T \mathbf{s}_{im} + \mathbf{z}_j + \mathbf{n}_j \right)$$

   where

   $\mathbf{W}_{ji}^R$ receive filter (postcoding matrix) used by UE $j$ to receive data from UE $i$

   $\mathbf{H}_{ij}$ channel between UE $i$ and UE $j$ (including small- and large-scale fading as well as the antenna gains on transmit and receive side)

   $\mathbf{W}_{ij}^T$ beamforming/precoding gain (digital, analog, or hybrid) used by UE $i$ to transmit data to UE $j$

   $\mathbf{z}_j$ out-of-cluster interference at UE $j$

   $\mathbf{n}_j$ thermal noise at UE $j$

   The first term inside the bracket is the desired signal, the second term represents other transmitter interference, while the third term represents interference caused by transmitter $i$'s transmission to other UEs. By signaling the nulling sets and performing MIMO processing, the interference (second and third terms) can be mitigated.

The sequence diagram in Fig. B.11.1 is shown from the perspective of UE $i$, meaning that this is the UE measuring and reporting information to the BS and receiving instructions from the BS for transmission to another UE $j$. The same procedure of measurement reporting is followed by UE $j$ and other UEs as well, so that RS assignments and sidelink grants are assigned by the BS based on the information provided by all involved UEs.

**RS assignment (details of step 2 above)**

In order for the UE to be informed about the RS schemes used by its nearby UEs, i.e., the channels it needs to estimate, the BS instructions are provided in form of:

a. "RS group index", determining the group (family) of RS sets to which the UE (and its own RS scheme) belongs.

b. "RS user index", defining the particular RS scheme of the UE within the group.

Based on these two indices, the UE has full information about its own RS scheme, as well as the RS schemes of neighboring UEs, whose channel it needs to estimate. These are implicitly given by the remaining "user indices" of the RS schemes defined by the "group index".

in general, the set of active neighbor UEs (corresponding to the channels detected by the UE) is denoted by $\mathcal{N}_i \subseteq \mathcal{M}_i$, meaning that not all RS user indices need to be permanently used. This may be the case if fewer neighboring UEs exist, or the existing ones do not have the beamforming/MIMO capabilities.

Naturally, the number (and exact IDs) of the UEs which will form the beamformed/MIMO transmission/reception group is not known before/during channel estimation. Therefore, the “RS group index” must include a sufficiently large number of different RS schemes, allowing for the estimation of a sufficiently large number of channels to different UEs. Out of these UEs, the particular UEs which will be included into the final beamformed/MIMO transmission/reception will be selected.

In order to avoid interference on RS symbols, the same “RS group index” may be reused, e.g. in sufficiently separated geographical areas. However, the areas in which different “RS group indices” are simultaneously used can be under certain conditions also overlapping. This implies that RSs defined by (some of the) “RS group indices” may coexist, e.g., if they are separated in time, frequency, beam, antenna or code.

The UE uses the instructed RS scheme until it receives a new instruction by the BS. The decision updates of the BS are based on measurements ($\mathcal{M}_i$) and location information provided by the UE and all other UEs to the BS.

In order to allow for channel estimation between UEs served by different BSs (cell edge), RS assignments have to be jointly agreed by BSs before being provided to UEs.

**Example (6 vehicles)**

Fig. B.11.2 illustrates the proposed method using an example with 3 links (transmitter/receiver pairs).

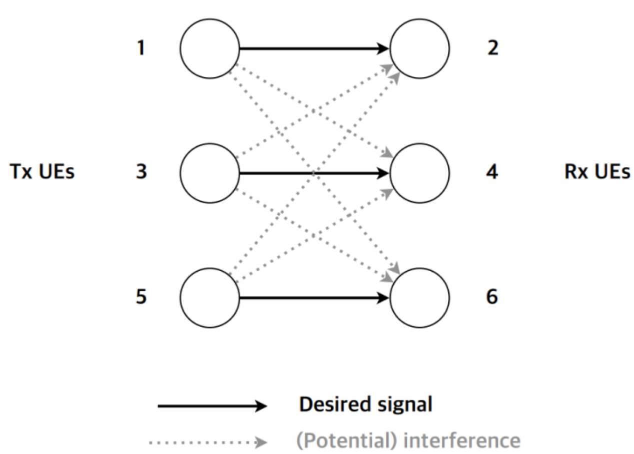



**Figure B.11.2: Example with 3 antennas per vehicle – receiving UEs use fixed rank-one receive filters.**

Given the nulling sets

$$Z_{12} = \{4\} \qquad Z_{21} = \{5\}$$
$$Z_{34} = \{2,6\} \qquad Z_{43} = \{\,\}$$
$$Z_{56} = \{4\} \qquad Z_{65} = \{\,\}$$

the same radio resource may be allocated to links $(1,2)$ and $(3,4)$, or to links $(3,4)$ and $(5,6)$, but not to links $(1,2)$ and $(5,6)$. This is because UE $1$ is unable to null UE $6$ and vice versa.

## B.12 Reference Signals Design for Direct V2X Communication

### Illustrative numerical results

This section presents some initial numerical results evaluating the performance of the NR eMBB DMRS (introduced in Section 3.3.5) in the V2X environment, which will give us some insight into the DMRS structure for V2X.

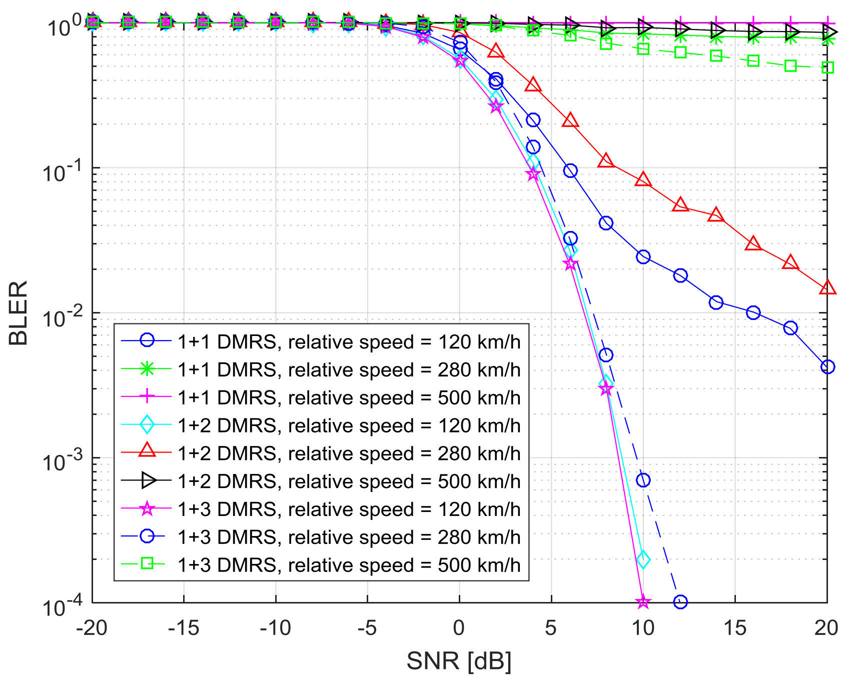



**Figure B.12.1*:* BLER vs. SNR for single link V2V channel, QPSK modulation and code rate ½, with different NR eMBB DMRS structures and different relative speeds between the transmitter and the receiver. '1+n DMRS' denotes 1 front-loaded DMRS symbol and n additional DMRS symbols (n= 1,2,3).**

We first explore the performance of the current NR eMBB DMRS design under V2V conditions. Figure B.12.1 shows initial simulation results using the V2V channel model of Release 14/15 LTE V2X [3GPP-36885], which can temporarily be used for our 5G V2X channel model under 6 GHz. In this simulation we assume that the first 2 symbols in a 14-symbol slot are not used for data transmission, and the last symbol is used for guard period. The modulation is QPSK and code rate is 0.5. The carrier frequency is 6 GHz and the LTE numerology is used. We assume no frequency offset in these simulations.

It can be observed from the simulation results that at high relative speed of 280 km/h and 500 km/h (absolute speed of 140 km/h and 250 km/h respectively) it is very challenging to obtain good channel estimation, not to mention that the frequency offset due to hardware impairments have not been considered in the simulation. It is expected that at higher carrier frequencies lower relative speeds will also become very challenging, because both Doppler spread, carrier frequency offset, and phase error will become more severe. On top of that, higher coding and modulation order (MCS) will further degrade the BLER vs. SNR performance. These challenges will be addressed in the next phase of the project.

## B.13 Radio Resource Management in 5G Enabled Vehicular Networks

### Illustrative Numerical Results of Technical Component in Section 3.3.8

In this section, we present some evaluation results of RRM solution described in Section 3.3.8. More specifically, we compare the performance of the proposed framework to 1) a state-of-the-art reference scheme [BSF+15], and 2) a near-optimal benchmark solution to the optimization problem of the first stage, which is obtained by a branch and bound method based on the commercial software Gurobi 6.5.

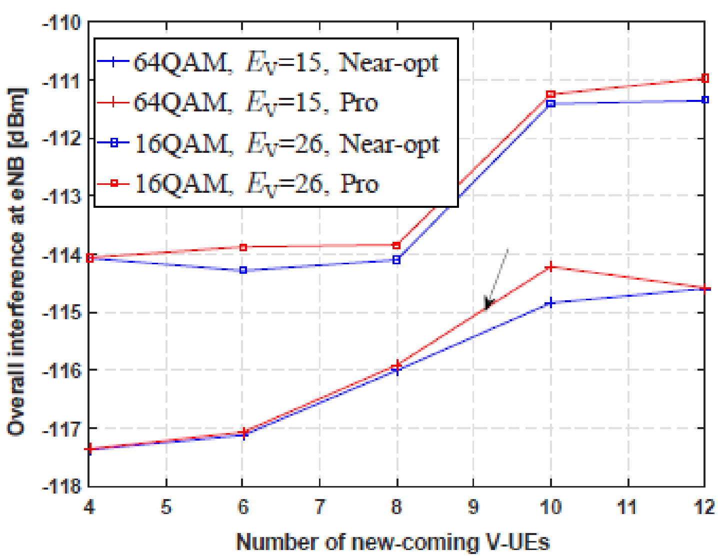



**Figure B.13.1 Overall interference at the BS, with one TTI message transmission. Here new-coming V-UEs denote the V-UEs whose messages transmission starts from the current time.**

Fig.B.13.1 compares the proposed stage-1 RRM algorithm with the near-optimal solution to the stage-1 optimization problem in terms of the overall interference at the BS, which is calculated as the summation of the interference over all the 100 RBs allocated to UL transmissions. The near-optimal solution is obtained by solving the stage-1 optimization problem via a branch and bound method. Here only large-scale fading is considered in the simulated channel models. In Fig.B.13.1 and Fig. B.13.2, $E_V$ denotes the number of RBs allocated to each V-UE per TTI. As shown by the simulation results, the performance gaps between the two schemes are very small, which validates the effectiveness of the proposed heuristic algorithm.

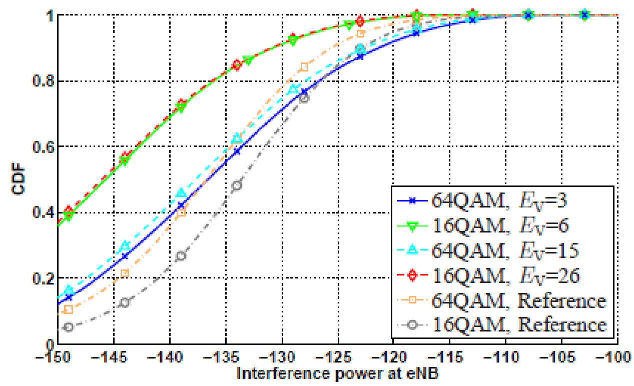



**Figure B.13.2. Except from the CDF of the measured interference power per RB at the BS**

Fig.B.13.2 evaluates the CDF of the measured interference power at the BS. Note that the CDF only contains samples for RBs that are allocated simultaneously in the primary network and the V2V underlay. As shown by Fig.B.13.2, the interference at the BS due to the reuse of resources in the V2X underlay is in many cases negligible. The interference power exceeds -120 dBm in only 3% of the collected samples when considering 64QAM and never reaches this value when 16QAM is applied in the V2V underlay. The reference scheme, on the other hand, does not aim to minimize the interference to the BS and therefore show poorer performance in this regard. These observations imply the promising usage of underlay D2D layer to integrate vehicular network under the proposed RRM framework and algorithm.

## B.14 Cognitive Full Duplex Communications in V2X Networks

### Illustrative Numerical Results of Technical Component in Section 3.3.9

Probability of collision and collision duration with incumbent (cellular) users are important metrics in any cognitive radio network. It is claimed that the cognitive method of sharing cellular spectrum for D2D communication will result in less interference and shorter collisions with primary users, compared to that in traditional underlay D2D connections controlled by gNBs. Fig. B.14.1 shows the probability of collision in this scheme for different levels of secondary's transmission power ($\alpha$) and compared to conventional method of listen-before-talk (LBT) of sensing. Fig. B.14.2 depicts the average collision duration of D2D transmission with cellular users for different levels of secondary's transmission power. It is seen that the collision duration would be shorter for lower transmission powers which implies shorter range of D2D communications. However, this scheme always offers shorter collision durations compared to conventional LBT schemes.

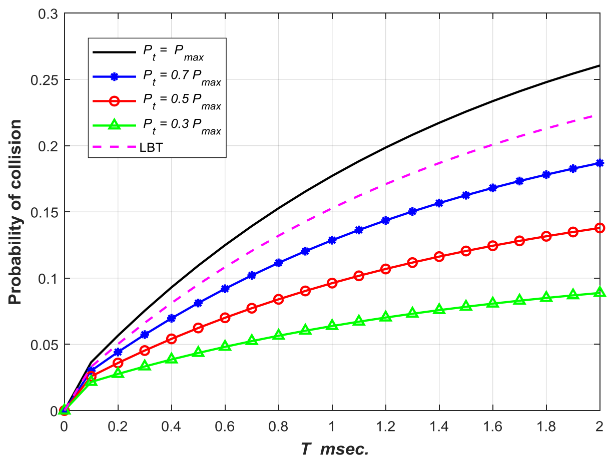


**Figure B.14.1*: Probability of collision of D2D users with cellular users vs. SUs' frame time, for different levels of SUs' power.***

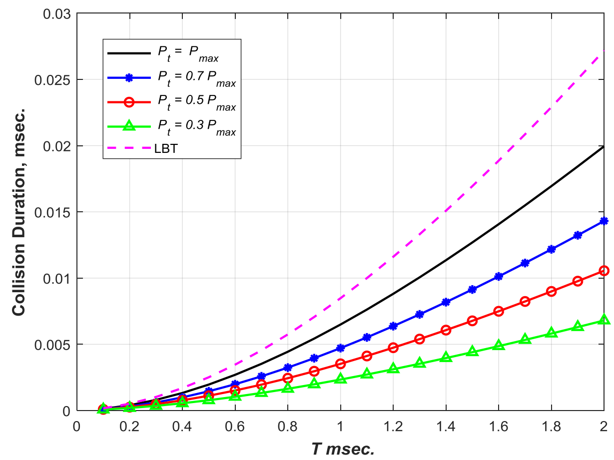


**Figure B.14.2*: collision duration vs. SUs' frame time, for different levels of SUs' power.***

In the next two figures the throughput of D2D connection has been considered and evaluated. Fig. B.14.3 depicts the normalized throughput for synchronous and asynchronous transmission vs. secondary's frame duration. It is seen that asynchronous transmission enhances D2D throughput due to better collision detection and shorter collision durations.

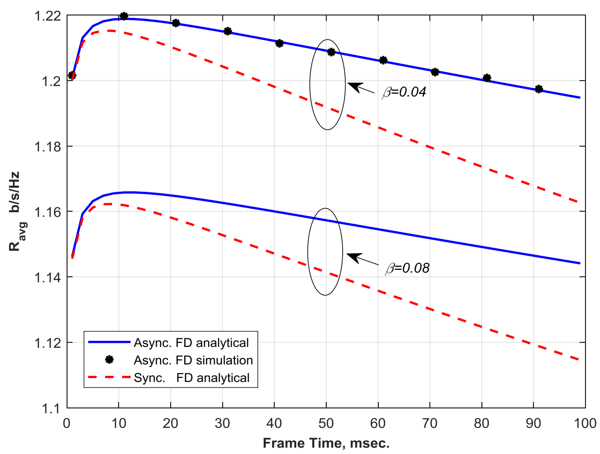


**Figure B.14.3*: normalized throughput for synchronous and asynchronous transmission vs. secondary's frame duration.***

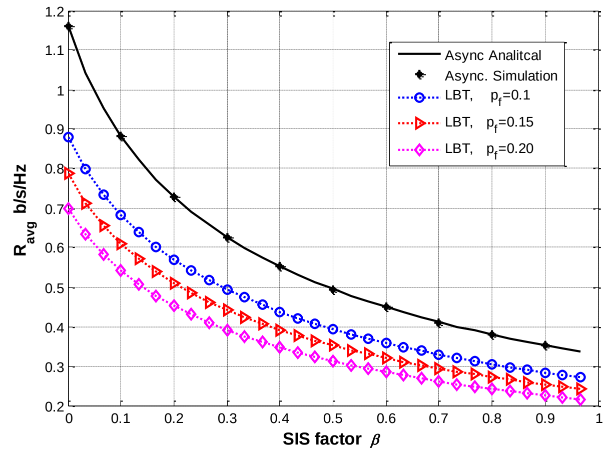


**Figure B.14.4 variation of D2D throughput against different self-interference suppression capability of OBUs.**

And Figure B.14.4 shows the variation of D2D throughput against different self-interference suppression capability of OBUs. We see that the proposed scheme outperforms conventional methods of sensing in terms of secondary's throughput.

**Disclaimer**: This 5GCAR D3.1 deliverable is not yet approved nor rejected, neither financially nor content-wise by the European Commission. The approval/rejection decision of work and resources will take place at the next Review Meeting planned in September 2018, after the monitoring process involving experts has come to an end.