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Medium Access Control for Cellular-based Vehicular Ad-Hoc Networks

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ABSTRACT

Vehicle to Vehicle (V2V) communications represent a critical enabler for safety of life applications such as Highly Autonomous Driving (HAD), which are subject to stringent reliability constraints. 802.11p is the current de-facto standard for V2V, formalized by European Telecommunications Standard Institute (ETSI) in the EU and the Federal Communication Commission (FCC) in the USA. Fast evolving cellular technologies such as 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE) are also working towards V2V support. Differently from 802.11p, however, LTE has a strict centralized communication scheduling, which is a limiting factor for the specific traffic patterns, network topology, and safety criticality requirements of V2V. Very recent evolutions of the LTE standard, enabling direct Device-to-Device (D2D) operations, open the path towards making it a viable candidate to coexist with 802.11p, thus providing a technological redundancy desirable for safety-of-life systems. D2D LTE, currently referred to as the Proximity Services (ProSe), retains nonetheless a strong centralized structure, with unsupervised operations being enabled only for Public Safety UEs. As a matter of fact, none of the currently available technologies has been specifically designed for the traffic patterns and requirements of V2V communications. V2V over LTE D2D, specifically, requires careful analysis, as many questions need to be answered: how can the control of the transmissions shift from a central entity (basestation) to many, distributed, actors? How it is possible to exploit LTE's channel structure to enable broadcast, cross-cell, pan-operator communications?

This thesis shows that unsupervised operations, currently loosely specified in ProSe, are essential for V2V. A proposition is made to address V2V needs, by splitting Medium Access Control (MAC) layer analysis into two separate entities: the resource reservation and the distributed channel access, of which only the former is performed by the network. A periodical, semi static-resource reservation scheme, based on a shared resource pool, was identified as the key to address the communication pattern requirements and to minimize the network involvement. A slotted and periodical channel organization pattern is proposed, which allows the scheduling to be treated as a TDMA-like system, wherein slots are distributed in both time and frequency. Two different approaches are then considered for distributed channel access: Optical Orthogonal Codes (OOC) which performs is according to an enhanced random mechanism, and Self-Organizing TDMA (STDMA), which exploits the knowledge of concurrent users' transmission patterns. The effect of the proposed channel configuration, and channel access algorithms is evaluated analytically and by means of simulation.

The cellular V2V mechanism proposed in this thesis enables cross-cell broadcast, for in-band as well as out-of-band deployment. The flexible channel structure allows coexistence with 802.11p, which proves challenging due to the substantially different channel access techniques. It is shown that OOC can outperform 802.11p while only being marginally affected by the half duplex impairment introduced by the time / frequency disposition of transmission

slots, but its performance degrades with increasing channel load because of its blind access scheme. STDMA, on the other hand, allows for more stable performance, but its re-reservation mechanism is more significantly affected by losses due to half duplex, thus requiring modifications to adapt to the proposed channel structure.

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1 INTRODUCTION

1.1 THE CONNECTED VEHICLE

Future tenses will soon be no longer necessary when talking about connected vehicles, since they are quickly becoming part of the everyday reality. For more than a decade in fact, companies, universities, governments, and standardization bodies have been putting huge efforts into creating a common framework for vehicles to communicate and interact with each other and with an infrastructure surrounding them. These efforts are continuing nowadays stronger than ever, even though the motivations that fuel them has significantly evolved over time.

In the earliest stages, the focus was on traffic safety and optimization applications: connectivity had the main function of electronically extending the horizon of each vehicle beyond what could have been achieved by onboard sensors alone. The benefits brought by this approach are twofold: firstly, drivers (and, at a later stage, advanced driving assistance systems), are fed with more complete and reliable information. Secondly, it adds a cooperative dimension to traffic safety and optimization, wherein communications enable decision making based on information sourced by peers and infrastructure in proximity; the outcome of the decisions is meant to benefit not only a single driver/vehicle, but the entire traffic in their vicinity alike. These applications are defined Intelligent Transportation System (ITS) by the US Department of Transportation [1], and Cooperative Intelligent Transportation System (C-ITS) by the the European Commission [2] and by the European Telecommunications Standard Institute (ETSI) [3], with these latter putting the accent on the cooperative aspect.

The initial set of applications, scheduled for the first round of commercial deployment, is commonly referred to as "day 1 applications" [2]. Day 1 applications (or services) include forward collision avoidance, green light optimum speed advisory and in-vehicle signage.

In more recent times, the breakthrough technical evolution both in the telecommunications and in the automotive industries, as well as the entrance of new stakeholders in the automotive ecosystem, has generated an expansion and a diversification in the applications related to vehicular connectivity. Vehicles are no longer just means of transportation: instead, they are now being considered players in a much wider environment of connected entities that interact with each other. These new players include many other categories of road users, such as pedestrians, and cyclists, commonly referred to as Vulnerable Road Users (VRUs). The concept of infrastructure is extended to smart sensors, urban furniture, and in general to every device called "thing" in the wider paradigm of the Internet of Things (IoT). Connectivity hence becomes more complex, and so do the challenges it brings: a new, *vertical* dimension is added, which connects road users to the network, and therefore to internet and to cloud-based services. New set of applications are being developed, starting from "day 1.5" and "day 2" traffic safety and efficiency to IoT deployments, each with new sets of requirements and constraint on the underlying technology adopted for connectivity.

In this following part of this section, the different approaches to vehicular connectivity will be presented, as well as the challenges they present for both horizontal and vertical connectivity. The three approaches are:

1. the Car-2-Car Communications Consortium (C2C-CC) approach;
2. the 3rd Generation Partnership Project (3GPP) approach, and
3. the IoT approach.

The challenges introduced by these increasingly complex connectivity models will be highlighted as a motivation for this work.

1.1.1 *The Car-2-Car Communications Consortium approach*

The C2C-CC (`http://www.car-2-car.org`) is an entity founded in 2002, which defines itself as a *"nonprofit, industry driven organization initiated by European vehicle manufacturers and supported by equipment manufacturers, research organizations and other partners"*, and is one of the very first bodies created to foster the development, the standardization and the harmonization of vehicular communications. The vision and mission of the C2C-CC are summarized in its manifesto, which was finalized back in 2007 [4], which traced the direction for the European research and development of vehicular communications for the next decade. The manifesto describes in detail the envisioned scenarios (§2), system architecture (§4), and applications (§5). In the seminal document, three main actors are considered for Car-2-Everything Communications (C2X) communications:

— **drivers**: who benefit (directly or indirectly) from the warning messages and road recommendations;
— **road operators**: who can mine data from the traffic and exploit it to improve traffic control;
— **hotspot / internet service providers**: who can equip urban infrastructure in order to support C2X communications.

Three types of scenarios wherein the aforementioned actors can gain benefit from C2X communications are identified, namely *traffic safety*, *traffic efficiency*, and *infotainment*: for each of them, a set of envisioned "day 1" applications is targeted.

Traffic safety applications include *cooperative forward collision warning*, *pre-crash sensing / warning*, and *hazardous location notification*. Forward Collision Warning is based on state information sharing among vehicles: each vehicle, in fact, periodically transmits information about its position, speed and heading, and receives the corresponding information from neighboring vehicles. This mechanism allows vehicles to be aware of the traffic situation in its surrounding, which constitutes a complementary source of information to the on board sensors. Exploiting this extended information, vehicles can detect imminent collisions risk and warn drivers on time, dramatically reducing the risk of collision. Pre-crash Sensing and Warning is a service that intervenes in those situation wherein the collision avoidance system is no longer able to prevent a crash. Its objective is to inform upcoming vehicles that a crash is about to happen, or has already happened. This serves multiple purposes: avoid the propagation of the accident, and, in combination with traffic efficiency application, trigger the re-routing of traffic in order to circumvent the affected area. Hazardous Location Notification, finally, is a way for connected vehicle to share information about potentially hazardous road condition with other vehicles in their surroundings. Any anomaly of the road surface detected by on board systems of the preceding vehicles, for instance, can be exploited by the following ones to adopt better driving decisions, improving both safety and comfort of drivers and passengers.

Traffic efficiency applications serve the purpose of improving circulation by exploiting awareness of other vehicles' state and travel plan. This application class includes Enhanced Route Guidance and Navigation, Green Light Optima Speed Advisory (GLOSA), and V2V Merging Assistance. All of these exploit information available via direct short range communications to perform local-scale optimization of the road circulation. GLOSA, for instance, exploits the knowledge of a vehicle's travel and traffic light timing information to recommend the optimal speed to catch a green wave. Similarly, V2V Merging Assistance, regulates the speed of vehicles about to merge into a traffic flow as well as the speed of the traffic flow itself in order to have a smooth insertion in traffic.

Finally, **infotainment** applications are essentially aimed at providing internet connectivity to drivers and passengers. This can be achieved by providing the infrastructure nodes with two networks interfaces: a network connection to the internet and a wireless Infrastructure-to-Vehicle (I2V) link to serve the vehicles in its vicinity.

The architecture designed by the C2C-CC is inherently flat and based on local, short range communications. Two classes of equipment are defined: On Board Units (OBUs), which are installed onto the equipped vehicles, and the Road Side Units (RSUs), which are infrastructure nodes. OBUs and RSUs are identical throughout the whole protocol stack, except for the application layer, where they support different functionalities. Different protocol stacks are necessary to support local scope applications and applications that require Internet connectivity ([4], Fig. 8).

The core architectural requirement at the foundation of the C2C-CC is that safety applications must be supported by a free technology, on a dedicated yet unlicensed band.

1.1.2 *The 3rd Generation Partnership Project approach*

The 3GPP is the entity responsible for the definition and standardization of the mobile networking systems based on the Global System for Mobile communications (GSM). Despite still having a reference to the 3rd generation in its name, the 3GPP is also developing and maintaining Long Term Evolution (LTE), the 4th and current generation, and working towards the specification of the upcoming 5th generation, currently referred to as "5G".

Every new generation brings, along with performance improvements, extended support for providing advanced connectivity to new application and scenarios. For 5G, the 5G Private Public Partnership (5G-PPP), a joint European initiative of public and private stakeholders, has been very active in defining new scenarios and identifying the directions for the technology to improve on.

This resulted in a series of whitepapers covering sectors such e-health, energy, future factory, and, most importantly for this work, the Automotive vertical sector [5].

The white paper [5] contains the vision of the 5G-PPP for the automotive sector. The document builds on top of the set of requirements defined by the C2C-CC for road safety and traffic efficiency, which are indeed supposed to be supported by 4G/5G as well. The scope of the 5G-PPP, however, is much wider, and reflects the technology advancements and evolution of business models that have occurred in the years following the redaction of [4].

From a technological standpoint, 3GPP stands on the vantage point of already having a network infrastructure widely deployed and functional. This means that Internet and cloud applications already have the means to be supported out of the box. On the other hand, the technology needs extensions to support the direct, ultra low latency communications between vehicles. In [5], the available technologies for this purpose are compared, in order to highlight their strengths and weaknesses, in order to properly direct the research efforts towards improving 3GPP technologies.

1.1.3 *The Internet of Things approach*

The IoT is a much wider concept than the connected vehicle, that however envisions to include connected vehicles under its umbrella. The idea at the base of the IoT paradigm is to have a ubiquitous, pervasive connectivity of billions of "things" to the internet; things have the ability to sense the environment and / or act on the environment, while at the same time producing data conveyed to the Internet, and reacting based on similar data produced by other things.

"Things" is a purposely generic word, which assumes a different meaning based on the considered scenario. In [6], the IEEE IoT Society collected the 100 most meaningful definition for IoT paradigm itself and for the concept of "thing", which differ according to the considered perspective. For the purpose of this thesis, the the definitions provided by the Internet Engineering Task Force (IETF) are of particular relevance:

> *"In the vision of IoT, 'things' are very various such as computers, sensors, people, actuators, refrigerators, TVs, vehicles, mobile phones, clothes, food, medicine, books, etc. These things are classified as three scopes: people, machine (for example, sensor, actuator, etc.) and information (for example, clothes, food, medicine, books, etc.). These 'things' should be identified by one unique way of identification for the capability of addressing and communicating with each other and verifying their identities."*

The IETF thus includes vehicles directly into the very definition of IoT, as a matter of fact recognizing them as one of the foundation blocks of the paradigm. Vehicular communications also fit in the wider definition of Internet provided by the IETF, which states the following:

> *"In the viewpoint of IoT, the 'Internet' considers the TCP/IP suite and non TCP/IP suite at the same time".*

This is particularly relevant, given that vehicular applications adopt both of them: the former for Internet connectivity, and the latter for direct Vehicle to

Vehicle (V2V) and/or Vehicle to Infrastructure (V2I) communications. This duality reflects one of the major architectural implications that the IETF identifies for the IoT, which is indeed relevant for vehicular applications when considered as a part of it: the "Vertical vs. Horizontal" challenge [7, §5.1]. IoT and vehicular communications alike need to perform direct proximity communications between things and/or vehicles, and network-supported communications to and from the Internet and the cloud. This challenge is one of the motivators for this thesis, as it will be detailed in the remainder of this section.

1.1.4 *Harmonizing the different approaches*

The three previously described connectivity paradigms provide some important insights on the future of the vehicular connectivity:

— communications shall not be limited to motor vehicles; instead, all of the possible categories of road users should be included. This includes VRUs, but also public transportation on rails, which in several cities (especially in Europe) share the roads with cars;

— connected vehicle will arguably not be living alone in their own world: instead, they will deeply integrate into wider paradigms such as the Internet of Vehicles (IoV) and, by extension, the IoT;

— as a consequence of the former, vehicular connectivity is not inherently horizontal or vertical; instead, the users and the applications will benefit from a technology able to seamlessly offer both operation modes.

This is the scenario in which this thesis is positioned: connected vehicles will ultimately require a complex and diverse connectivity pattern, wherein vertical connectivity to the network and ultra low latency horizontal communications will need to live side by side. Furthermore, horizontal connectivity must support different application classes, and consequently, transmission patterns. Awareness-based applications, such as forward collision warning, require the support of broadcast of beacon packets, whereas others, such as the Cooperative Adaptive Cruise Control (CACC) are based on unicast transmissions.

Having a unique technology to support all of these communication needs is desirable for multiple reasons: first of all, it eases the standardization operations, by avoiding conflicts between multiple competing entities, with the result of focusing the efforts of the stakeholders into a unified, common objective. It then eases the adoption of the technology by multiple categories of users: for larger devices such as vehicles, embedding multiple communication front-ends is less problematic than for smaller, battery powered and size constrained devices such as smartphones and sensors. These latter would arguably be forced to equip only one of these, resulting in a partial integration, which is not desirable, especially when dealing with safety of life applications.

Since IoT is an higher level paradigm, for which no transmission layer has been specified, we will focus on the C2C-CC and 3GPP approaches, which need to deal with this challenge from diametrically opposite perspectives, given the opposite premises they started from. The C2C-CC, who advocated for a free and fully distributed architecture, is based on 802.11p, an amendment of the WiFi standard that operates outside of the context of a basic service set, allowing for connectionless short range transmissions. RSUs, the infrastructure nodes, are also part of the horizontal plane, except for when they serve as Internet access points: in this latter case however, a different flavor of WiFi is adopted, such as 802.11a or 802.11n. On the other hand, the 3GPP LTE was conceived as a inherently vertical, strictly centralized, infrastructure-based communication system, wherein all the communications are scheduled by and pass through the network.

In order to satisfy the communication needs of connected vehicles, these two approaches must thus move in opposite directions: 802.11p already provides horizontal connectivity, but it needs the deploy an infrastructure to provide vertical support; as opposed to this, LTE already offers a widely deployed vertical infrastructure, but it needs to be extended so to allow direct Device-to-Device (D2D) communications that support both one-to-one and one-to-many transmissions, with the strict requirements and particular traffic patterns generated by vehicular applications. This is where the works in this thesis are positioned: LTE-based D2D communications prove to be scientifically interesting, as they force researchers to face a number of challenges. This was particularly true in 2013, when this work described in this thesis began, and standardization of D2D communication underlying LTE were in a very early study phase.

1.2 METHODOLOGY

The purpose of this work is the exploration of the possibilities offered by the ongoing 3GPP standardization, so to find the directions for standard extensions that enable horizontal connectivity for vehicular connectivity. For this reason, throughout the whole duration of the thesis, the study of the standards, both on the 3GPP side and on the ETSI ITS side, has covered an important role. The evolution of the LTE standard played an important role in the development in the thesis, and is reflected in the results presented in it. At the very beginning of it, in fact, discussions on the D2D operations were at a very early stage, and no publicly available document suggested upcoming developments to support Vehicle to Everything (V2X). These were taken in consideration as far as specifications were issued, as it can be specifically observed in section 3.2, concerning the resource reservation mechanism. As far as new tools were made available by the 3GPP, we introduced novelties in our proposal to exploit them.

In this work, we start with a qualitative analysis of the challenges imposed by V2X over LTE D2D, which is necessary in order to propose adequate protocols. The aim is to evaluate their performance, with particular emphasis on the effect that the system parameters have on them. To do so, we first modeled the performance by means of mathematical equations. In this way, despite requiring some abstraction to maintain tractability, it was possible to isolate each parameter and study its effect.

On a later phase of the work, we modeled such protocol by means of simulation. Our custom-developed simulator allows us to both recreate some idealistic condition, that validate the results obtained analytically, and insert some elements of realism, such as propagation effects (namely path loss and fading) and mobility.

1.3 APPLICABILITY

The concepts presented in this thesis are beneficial for applicability in several domains of vehicular connectivity, involving multiple categories of road users.

This work was initially developed within the French national research project Système Télécom pour les Transports Urbains du Futur (SYSTUF) [8], whose purpose was to *"demonstrate the feasibility of using a single communication technology based on LTE (Long term Evolution) to meet the Quality of Service requirements of critical (control and command also called Communication-Based Train Control (CBTC)) and non vital (also called Closed Circuit Television (CCTV)) applications simultaneously and to enable the development of innovative services contributing to seamless mobility which meets the growing demand for "smart and environment-friendly mobility."* Within the SYSTUF project, the role of LTE-D2D is to ensure direct connectivity between trams, trains and all of the other road occupants, such as pedestrians, VRUs, and the cellular network. For this, the LTE technology is essential: despite OBUs to connect cars, and trains equipped with Dedicated Short Range Communications (DSRC) are already available, there is currently no foreseeable plan to achieve widespread Internet, RSU connectivity or connectivity with handheld devices, carried by pedestrians and VRUs. On the other hand, these devices already come with LTE connectivity, which in future releases of the standard will support D2D direct connectivity. In this way, any type of road user will be connected to each other, to RSUs, and to the Internet via the installed LTE network. Direct connectivity between road users will extend the safety services supported by periodical position reporting messages, with the result of offering all of them a much more complete awareness of the surrounding traffic.

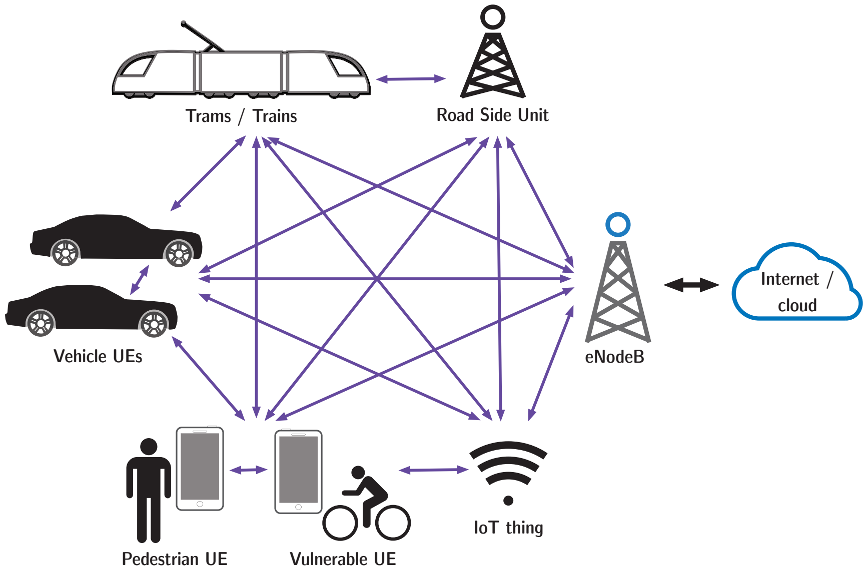


Figure 1 – Connectivity offered by LTE plus LTE-V2X

A further, noteworthy application of the work presented in this thesis is accurate positioning. In its second phase, this work was included in the framework of the European High precision Positioning for Cooperative-ITS (HIGHTS) project [9], whose aim is to improve position accuracy exploiting V2V communications. It is specifically important to achieve reliable, ultra low latency communications with a selected group of neighboring users, denominated *positioning anchors*, which contribute to the achievement of a high accuracy position measurement.

Direct V2V communications are the foundation of Virtual Traffic Lights (VTL) [10], a paradigm wherein the function of traffic lights is decentralized and built directly into vehicles. Once reaching intersections, vehicles automatically coordinate between each other via V2V messages, with the result of the traffic getting self-organized. A part of the work presented in this thesis was performed within the team that invented, developed and patented this mechanism, lead by Prof. Ozan Tonguz at the Electrical and Computer Engineering department of Carnegie Mellon University, in Pittsburgh, PA, USA.

1.4 TECHNOLOGY OVERVIEW

1.4.1 *Packet types*

From a technology standpoint, the focus of the work presented in this thesis is on single hop broadcast transmissions, which serve the purpose of conveying periodical position report messages. As simply illustrated in Fig. 2, these messages are intended to being received by the road users in proximity of the transmitter, as they contain critical updates on the state of the vehicle. These

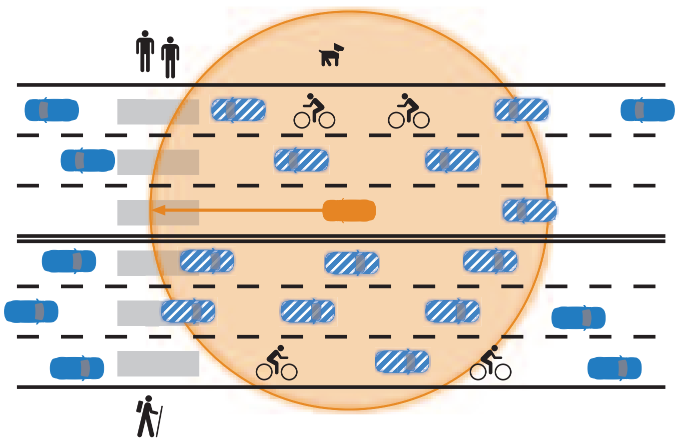


Figure 2 – Single hop broadcast communications

updates include accurate position, speed, heading, steering wheel angle, and many more. In order for such information to be available and exploitable by any manufacturer, standardization bodies have designed standard message types. In Europe, the ETSI defined the Cooperative Awareness Message (CAM) [11], which is supports two packet sizes, around 300 and 800 bytes, which are to be transmitted with a maximum periodicity of respectively 10 packets/s and 2 packets/s. In the US, this task was completed by the Society of Automotive Engineers (SAE), which defined the Basic Safety Message (BSM). Similarly to CAMs, multiple BSMs formats exist. A short format, meant for high frequency transmissions of 10 packets/s, BSM only contains the most crucial information, contained in the so-called "Part 1". A longer format is also defined, with more complete but less critical information, including also the "Part 2". Unlike CAMs, BSMs also serve as event-driven messages, which are transmitted in case of harmful or potentially harmful events, and propagated for multiple hops to spread awareness of the event. In Europe, a different type of message, named Decentralized Environmental Notification Message (DENM) [12], was specifically designed for the purpose. Among the reasons for this choice, is the fact that it produces a completely different traffic pattern than CAMs. This aspect is particularly relevant when these transmissions are conveyed over LTE, as it will be clearer at the end of this section.

1.4.2 *Frequency bands allocation*

Albeit with different structures, governments on both sides of the Atlantic have allocated dedicated spectrum to vehicular communications, as illustrated in Fig. 3. Both allocations are in the 5.9 GHz band, between 5855 and 5925 MHz. In the EU, 50 MHz were allocated [13], whereas in the US, the Federal Communication Commission (FCC) allocated 75 MHz of dedicated spectrum [14]. In both cases, the bands are partitioned into 10 MHz channels, with the

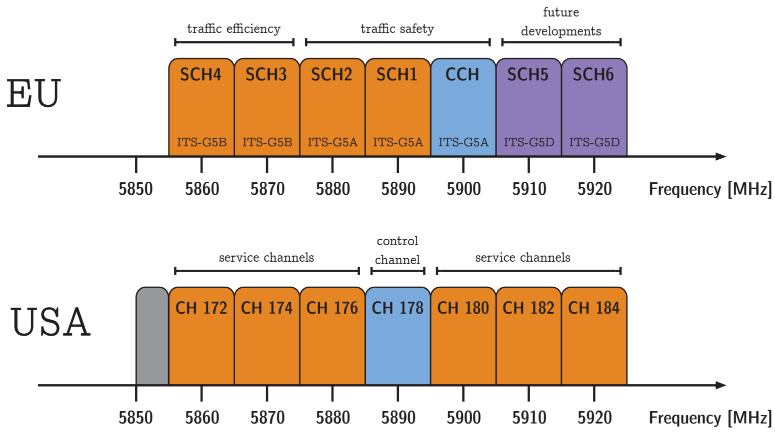


Figure 3 – Frequency allocation plans for ITS-G5 in the EU and DSRC in the USA

optional possibility of coalesce pairs of them, to obtain double width 20 MHz channels. Two types of channels are defined: the Control Channel (CCH) and the Service Channels (SCHs). The CCH is the reference channel, reserved for safety critical traffic, onto which all of the terminals should be tuned on by default. SCHs, on the other hand, can carry both safety critical and non safety critical traffic. The location of the CCH was operated in the EU and in the US according to different principles: as it can be observed in Fig. 3, in the US, the CCH is in central position with respect to the SCHs. A different choice was made in the EU, where it is one of the side channels: since transmissions on the CCH take place with higher power than on the SCHs, it this way the cross-channel interference is minimized.

In the EU, groups of channels are created to serve different purposes: The two SCHs closest to the CCH are in fact meant for traffic safety applications, whereas the remaining two others (SCH3 and SCH4), are dedicated to traffic efficiency services. These two groups of channels are respectively labeled as ITS-G5A and ITS-G5B. This means that, in the end, only 30 MHz of spectrum are available for traffic safety applications. An extra set of two channels (ITS-G5D) is reserved for future application.

1.4.3 *Transmission technology: 802.11p*

The particular traffic pattern imposed by CAM/BSM transmissions required the definition of a dedicated technology to support them. Both the US Department of Transportation and the ETSI in Europe agreed on adopting 802.11p as a foundation for DSRC and ITS-G5 respectively. 802.11p was an amendment of the WiFi standard designed to operate Outside the Context of a Basic Service Set (OCB). 802.11p hence does not require an access point to operate, and is designed to support non-Internet Protocol (IP) traffic. In 2012, it was finally integrated in the IEEE 802.11-2012 standard [15]: for notational convenience we will however continue referring to it as 802.11p in this document.

From a Physical (PHY) layer standpoint, 802.11p is designed to operate on three channel bandwidths: along the default 10 MHz configuration, 5 MHz and 20 MHz channel widths are supported. 802.11p shares the Orthogonal Frequency Division Multiplexing (OFDM) foundation of 802.11a, from which it is derived. 64 subcarriers are packed within the default 10 MHz wide channel, 48 of which carry data, 4 the pilot tones, and the remaining 10 are equally split on the edges of the band, transmitting no power thus acting as guard bands. With respect to 802.11a the subcarrier spacing is halved (which is 156.25 kHz, as opposed to 802.11a's 312.5 kHz), resulting in double symbol duration, which is necessary in the challenging vehicular propagation scenario. Modulation-wise, BPSK, QPSK, 16-QAM, and 64-QAM are supported, which according to the channel bandwidth provide one of the datarates listed in table 1.

Table 1 – Supported datarates in 802.11p [Mbps]

3	4.5	6	9	12	18	24	27
Configuration for CCH: 10 MHz BW, QPSK modulation							

The Medium Access Control (MAC) layer of 802.11p is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), which applies the Listen Before Talk (LBT) mechanism necessary for terminals to access the channel without a central coordinator. As it is designed specifically for broadcast communications, 802.11p lacks the tools to minimize some of the issues of CSMA/CA, as it will be detailed in section 2.4.1. 802.11p supports Quality of Service (QoS), by inheriting the Enhanced Distributed Channel Access (EDCA) from 802.11e, which supports four different priority classes in the contention process.

1.5 OBJECTIVE AND CONTRIBUTIONS

The aim of this thesis is exploring mechanisms and strategies for LTE to support horizontal connectivity, in order to provide support for vehicular safety critical transmissions. The contribution brought by this thesis are enumerated in the remainder of this section:

A comprehensive state of the art analysis is provided, covering the state of the standard, and the state of research activity, research projects, and business perspective. Such analysis is functional to justify the research presented in this work and its aims.

The definition of a novel resource reservation and allocation paradigm for LTE V2X, wherein channel is organized into semi-static pools, and the duty of scheduling their access is taken away from the evolved Node B (eNodeB) and distributed to the UEs. We refer to this paradigm as unsupervised, as opposed to the regular operations of LTE, wherein the eNodeB supervises the channel access.

Two different techniques are proposed to achieve the pool-based resource reservation. The first one, based on evolved Multimedia Broadcast Multicast Service (eMBMS), is based on a novel interpretation of an existing standard, which we adopted as a tool to support direct V2X communications. The second one is based on the sidelink, the new UE-to-UE interface defined by the 3GPP, which we first proposed to adopt for V2X. Furthermore, we highlight the challenges brought by such channel configuration, among which is the impairment due to half duplex mode of operations.

Two techniques were also examined for distributed channel access, each adopting a different approach: the first one, based on Optical Orthogonal Codes (OOC), a enhanced random access mechanism that provides reliability by protocol design. The second one is Self Organizing TDMA, which is a reservation-based location aware mechanism.

Analytical performance of OOC: the packet reception performance of OOC when applied to the LTE V2X channel, hence affected by HD impairment, are modeled analytically. They are then analytically compared against the reception performance of 802.11p. The model of 802.11p was found on literature, but was lacking the computation of the inter reception time, which we thus derived for the purpose.

Analytical performance of STDMA: a wide literature of research works is available on STDMA, all of which are performed by means of simulation, and which come to different and somehow contradicting conclusions. In the effort to deeply understand the reason of the protocol, we thus developed a novel analytical model for STDMA, where we compute the its packet reception, and slot occupation distribution performance.

STDMA protocol extensions: two protocol extensions for STDMA are proposed, in order to improve different aspects of its behavior when applied in LTE V2X channel, wherein transmission slots are spread both in time and in frequency.

Development of a custom simulation for LTE V2X: in order to validate the analytical results, and provide an evaluation with realistic channel propagation effects and mobility model, we developed a custom-made simulator, that provides the flexibility of testing MAC layer protocols over a LTE V2X channel allowing flexibility on the level of abstraction required for the PHY layer.

Performance evaluation by simulation: we evaluate the packet-level performance of OOC, STDMA and its proposed protocol extensions, both in static, ideal propagation conditions, with the focus of validating analytical results, and in a highway scenario, with realistic propagation and mobility models.

1.6 PUBLICATIONS

The work presented in this thesis resulted in the international publications listed in Table 2.

Table 2 – List of international publications

Conference Papers	Ref.
Laurent Gallo and Jérôme Härri - *"Short Paper: A LTE-Direct Broadcast Mechanism for Periodic Vehicular Safety Communications"*, VNC 2013, IEEE Vehicular Networking Conference, December 16-18, 2013, Boston, USA	[16]
Laurent Gallo and Jérôme Härri - *"Analytical Study of Self Organizing TDMA for V2X Communications"*, DVC 2015, 1st IEEE ICC Workshop on Dependable Vehicular Communications, 12 June 2015, London, United Kingdom	[17]

Journal Papers	Ref.
Laurent Gallo and Jérôme Härri - *"Unsupervised LTE D2D - Case study for safety - Critical V2X communications"*, IEEE Vehicular Technology Magazine, Special Issue on Emerging Technologies, Applications, and Standardizations for Connecting Vehicles, 2017	[18]
Laurent Gallo and Jérôme Härri - (under submission) *"Distributed Radio Resource Management (RRM) for Ad-Hoc LTE-V2X Automotive Safety Broadcast"*, submitted to the Elsevier Journal on Vehicular Communications	[-]

Research Reports	Ref.
Laurent Gallo and Jérôme Härri - *"Resource Allocation for LTE-Direct Broadcast of Periodic Vehicular Safety Messages"*, Research Report RR 13-290, October 2013	[19]
Laurent Gallo and Jérôme Härri - *"Analytic performance comparison of unsupervised LTE D2D and DSRC in a V2X safety context"*, Research report RR-14-298, December 2014	[20]

Laurent Gallo and Jérôme Härri - *"Vehicular safety critical communications: a case study for unsupervised LTE D2D "*, Research Report RR 16-327, November 2016	[21]
Laurent Gallo and Jérôme Härri - *"Self organizing TDMA over LTE sidelink"* Research Report RR-17-329	[22]

Posters	**Ref.**
Laurent Gallo and Jérôme Härri - *"Dedicated LTE communications for public transportations"* BMW-EURECOM-TUM Summer School on Smart Mobility 2020, 21-27 July 2013, Chiemsee Island, Germany	[23]
Laurent Gallo and Jérôme Härri - *"LTE-direct broadcast of periodic safety messages"*, BMW-EURECOM-TUM Summer School on Autonomous Driving in the Internet of Cars, July 27-August 1, 2014, Lake Tegernsee, Germany	[24]

White papers	**Ref.**
Jérôme Härri, Laurent Gallo and Friedbert Berens - *"Enhanced 11p Investigations and Proposal "* CAR 2 CAR Communication Consortium, 17 Feb 2017	[-]

1.7 OVERVIEW OF THE THESIS

The main body of this thesis is organized as follows:

Chapter 2: "State of the Art" presents a thorough description of the state of the art, under numerous perspectives. First, we provide an overview of the most relevant joint academia-industry research projects, which contributed to shaping nowadays context on vehicular networking. We then examine such context from the business perspective, which is now more likely than ever to play a critical role in determining which technology will be adopted for V2X communications. We then provide a detailed overview of the state of the standard, including an introduction to LTE, and a panoramic of the Proximity Services, which enabled D2D operations, and most recently evolved into LTE-based V2X, the upcoming official 3GPP support of V2X communications. The state of the research is then presented, detailing the research efforts in the domain of MAC algorithms, and LTE protocol and design extensions for vehicular networking. The limitations of the currently available approaches are finally highlighted, as a motivation for our work.

The first part of **Chapter 3: "Analysis and Problem Statement"** is dedicated to breaking down the global concept of LTE-V2X into simple requirements, in order to identify which of them is more important to be addressed. Specifically, we identify two major areas that need to be treated: the resource reservation, and the distributed scheduling. The following section of this chapter hence contains our propositions in these two aspects, along with a detailed description of the protocols that will be modeled in the next section.

As anticipated, **Chapter 4: "Modeling"** is dedicated to the modeling of the performance metrics of the protocols introduced in the previous chapter. The first half of the chapter focuses on the static evaluation, wherein the analytical model for the performance of OOC over the LTE-V2X channel are derived. Furthermore, details are provided on the custom simulator we developed, and how we utilized it to evaluate the static performance of the protocols. In the second part of this chapter, we extend such evaluation to a more realistic scenario, wherein path loss, fading and mobility are considered.

Chapter 5: "Results" is dedicated to illustrate, compare, and discuss the performance models and metrics derived in the previous chapter.

Finally, **Chapter 6: "Conclusion and Perspectives"** (unsurprisingly) concludes this work and opens to some possible future extensions of the concepts we introduced with this thesis.

2 STATE OF THE ART

This chapter provides a comprehensive overview of the state of the art of vehicular communications, which is presented as seen from multiple perspectives. First of all, we will present the most relevant *projects*, joint industrial and academic collaborations which have contributed, over several decades, to tracing the direction for the research and development of vehicular connected applications. Secondly, the *business* perspective will be treated: over the years in fact, the scenario of vehicular applications, and by consequence of the communication technologies to support them has profoundly changed. The economic motivation that push their development have thus mutated as a result, as well as the industries and stakeholders involved.

In the next section, the *state of the standard* will be analyzed in detail, starting from the earliest activities related to V2V communications, up until the most recent developments released by the 3GPP. Since this last is the most relevant for this thesis, particular attention and detail will be put in the description of its evolution, which has seen an increasing attention to V2X in the very recent years. The state of the standard will then be followed by a detailed *state of the research*, wherein the research efforts related to V2X communications over LTE will be presented, organized by methodology. This will be functional to introduce the reasons that motivated the work presented in this thesis

2.1 PROJECTS

Projects are partnership between the industry and the academia, which unite the efforts with the purpose of financing and fostering research activities. Projects are typically funded by governments or supra-national organizations such as the United States of America (USA) or the European Union (EU).

2.1.1 *European projects*

In the EU, one of the first and largest project in the domain of connected vehicles was PROgraM for a European Traffic system with Highest Efficiency and Unprecedented Safety (PROMETHEUS) [25], which lasted 96 months between 1987 and 1995. PROMETHEUS focused on the development of car design and microelectronics, with the aim of increasing vehicle safety and reduce their environmental impact, involving car manufacturers from 6 different nations, as well as further industrial members, research institutions and university from as much as 19 European countries. Vehicular communications had a significant role in the project, to which an entire program named PRO-NET was dedicated. The deliverable [26] already in 1988 presented a detailed description of application scenarios, as well as communication and processing requirements for autonomous vehicles.

PROMETHEUS, however, was confined to remain a study because of the target frequency bands at 63-64 GHz, which meant limited transmission range and considerable costs for equipment. It however opened to path to a multitude of projects on vehicular telematics that started in the following years. Among these, the CARTALK 2000 project was funded by the EU 5^{th} Framework Programme (FP5) in 2001, with the objective of developing cooperative driver assistance systems based on inter-vehicle communications. The paradigm envisioned by CARTALK 2000 combined a self-organizing system for communications between highly mobile vehicles (V2V) and between vehicles and infrastructure (V2I). In the same years, the FleetNet project [27, 28] was underway in Germany, aiming at developing of a common platform for inter-vehicle communications. The focus was on supporting three classes of applications and services: *(i)* cooperative driver-assistance (safety-related), *(ii)* local floating car data, and *(iii)* user communication and information services, each with different communication requirements in terms of delay, range, and reliability. Concerning the radio interface, FleetNet's choice was to exploit existing interfaces and adapt them to the challenging vehicular scenario, such as 802.11 and the Time Division Duplexing (TDD) operational mode of the UMTS Terrestrial Radio Access (UTRA). In [29], the final deliverable for the project, among the others are discussed issues which are still very relevant nowadays, such as the suitability of an air interface designed for cellular usage to support V2V and V2I communications, as well as synchronization in ad-hoc networks.

The successor to FleetNet is Network on Wheels (NoW) [30], a project sponsored from 2004 by the German Ministry of Education and Research, as a cooperation between car manufacturers, telecommunication companies and universities. As opposed to the previous projects, NoW's aim was to develop an open communication system that did not require any centralized control. Two separate protocol stacks were defined for horizontal and vertical connectivity, respectively based on 802.11p and 802.11a/b/g. The studies performed during NoW, both from the technical standpoint and from the market research one, contributed to the efforts of C2C-CC.

As opposed to the previously mentioned ones, which mostly concerned passenger vehicles, the project CHAUFFEUR [31] focused on the optimization of freight traffic. CHAUFFEUR, which started in 1996, was the first initiative to propose a platooning model for trucks, wherein the first of the line was conventionally driven by a human driver (the chauffeur), while the following one was electronically driven, closely following the former. This concept, formerly limited to freight trucks, is nowadays one of the dominant ways being developed to reduce fuel consumption in highway drives, for automated human passenger cars.

The ITS CORRIDOR project is a cooperation between Austria, Germany and The Netherlands [32], which contributed to the establishment of a highway corridor between Vienna and Rotterdam. The purpose is the collection, treatment of traffic information, which is used to produce pieces of advice and information to be fed back to the drivers, in order to improve traffic flow and safety.

Safe and Intelligent Mobility Test Field Germany (SIM^{TD}) is very relevant project on Cooperative ITS [33], Funded by the German Federal Ministry of Economics and Technology. The vision of the project is threefold: firstly, to connect vehicles to extend their awareness horizon, in order to achieve accident-free driving. Secondly, vehicles may be used for data acquisition, with V2X communications enabling the transmission of the sensed information, which will enable improving traffic efficiency. Lastly, directly creating value for the road users, by feeding them with customized and tailored information and services on board vehicles.

Preparation for Driving Implementation and Evaluation of C2X Communication Technology (PRE-DRIVE C2X) [34] and DRIVE C2X [35] are a project, both funded by the European 7th Framework Programme (FP7), respectively running from 2008 to 2010, and from 2011 to 2014, involving 34 different partners including automakers, electronics suppliers, research institutes and road operators. The purpose of PRE-DRIVE C2X was to prove the feasibility of traffic efficiency application via C2X communications, which were then developed, and tested on a large scale in DRIVE C2X.

SCOOP@F is a project co-financed by the European Commission and the French Ministry which planned the deployment of 3000 connected vehicles over 2000 km of French and European highways, to serve a multitude of purposes. Among these, improve road safety, exploiting real time information exchanged via communications between vehicles and the infrastructure; optimize traffic, so to reduce carbon dioxide emissions; and lay the foundations for the vehicle of tomorrow. The deployment was foreseen to happen in two phases: the first, between 2014 and 2017, is focused on basic services over ITS-G5 communications. The second phase, very relevant to the work presented in this thesis, aims at achieving, between 2016 and 2018, the implementation of more innovative classes of services, based on a novel hybrid architecture that operates on both ITS-G5 and cellular communications.

2.1.2 *US Projects*

Over on the western side of the Atlantic Ocean alike, the Automotive community has been very active in the last three decades. It is worth mentioning that the idea of automated driving was first proposed in the 1939 Wold Fair, during the exhibition named "Futurama". Its creator, General Motors showcased the idea of a safe, automated and fast travel based on telecommunications. Back then, these innovations were foreseen as available 20 years in the future: history told us that way longer than that will be needed, but the concept is still very up to date almost a century later.

In 1986 the California Partners for Advanced Transit and Highways (PATH) was founded, a research and development program of the University of California, Berkeley [1], which has been a leader in ITS ever since. Already in 1997, they were able to build and showcase a prototype of autonomous vehicle (named "PATH 2007") running on the I-15 near San Diego, California.

In 1997, the Intelligent Vehicle Initiative (IVI) was launched by the US Department of Transportation (DoT), with the purpose of developing Human Centered Smart Vehicles [36].

The late 90's were crucial for the future development of vehicular communications, with the FCC introducing 75 MHz of dedicated bandwidth to DSRC

1. www.path.berkeley.edu

in 1999. Two years later, in 2001, the American Society for Testing and Materials (ASTM) formalized 802.11a as a founding technology to build 802.11p, the amendment of the WiFi standard which then became the de facto standard technology for V2X until present days.

In late 2003, the Vehicle Infrastructure Integration (VII) initiative has been launched by the US DoT, successively renamed *IntelliDrive* [2], with three major purposes. First, improving *safety* by providing vehicles with all round awareness; second, to provide travelers and transport managers with information about multi-modal mobility; third, to reduce the environmental footprint, by reducing by selecting more efficient and eco-friendly routes.

The Crash Avoidance Metrics Partnership (CAMP) is a partnership between automakers in the US, united to find a common DSRC-based platform to improve traffic efficiency and reduce collision risk, by using the on board Global Navigation Satellite System (GNSS) and communications as a new sensing source.

2.2 BUSINESS PERSPECTIVE

Vehicular connectivity is a critical enabler for numerous new automotive functions and applications, which represent new market opportunities. The first wave of day one applications, however, only managed to involve the automotive industry and companies that historically worked closely with the automotive or mass transport manufacturers. Safety position reporting messages, in fact, were meant to be conveyed via WiFi over a unlicensed band, free of charge. The traffic efficiency and infotainment applications over 802.11 are reliant on the connectivity provided by a network of installed RSUs. Over the past years, multiple research deployments of such RSUs have seen the light, but no plan for widespread and commercially exploitable deployment.

LTE, on the other hand, is already a well established, widespread, and available technology (cfr. for instance the coverage information in [37]), whose continuous growth is pushing for even wider development in the coming years. The cellular network enabled a multitude of mobile services, ranging from customized advertising, to infotainment, data collection, and social networking. Vehicle manufacturers are already selling vehicles equipped with LTE connectivity in order to provide their users with customized services, real time digital map updates, and, at the same time, collect data which is fundamental both for the continuous improvement of their Advanced Driving Assistance Systems (ADAS) and beneficial to other users. For this to be possible, connectivity to the manufacturer's cloud is fundamental, and that would be impossible with today's plans of deployment for 802.11. LTE thus is a very attractive technology for vehicular connectivity, which motivates the research on technology extensions to support direct V2V communications, which would arguably include new user categories into the vehicular services, such as pedestrians (Vehicle to Pedestrian (V2P)), via their handheld connected devices.

Aside of the efforts and results of the research community, a fundamental role in determining the success of either technology is played by the industry. One of the company which made the most effort in developing 802.11 is NXP,

2. the name *IntelliDrive* was subsequently abandoned in 2011

which strongly supported its superiority against any LTE-based solution [38]. However, NXP was recently acquired by Qualcomm [39], one of the larges players in the LTE business, which might completely change future scenarios. LTE-based V2X, which seemed unnecessary a few years ago, will likely be inevitable in the near future.

2.3 STATE OF THE STANDARD

In this section, we provide a quick introduction to LTE, then review the current state of the standard concerning D2D and V2X operations, which we claim in this thesis being the operational mode that best suits the needs of vehicular networks and their periodical traffic patterns.

2.3.1 *Introduction to LTE*

In this section, a brief introduction on LTE is provided, with a particular focus on the air interface, given its relevance to the work presented in this thesis.

LTE is a centralized cellular telecommunications system, wherein by design all of the transmissions are scheduled by the installed network via the base stations, named eNodeBs. The system is profoundly asymmetric, which is why in the original Release 8, two channels were defined: the Downlink (DL), wherein the eNodeB is the sole transmitter and the mobile terminals, referred to as UEs are the receivers, and the Uplink (UL) channel, wherein the UEs are the transmitters, and the eNodeB is the unique receiver. This asymmetry is reflected in the choice of adopting two different air interfaces for the DL and UL channels. In fact, while eNodeBs are generally complex devices, constantly connected to a power supply, UEs are in general more simple devices, that have to cope with the power limitations due to battery power. For this reason, Orthogonal Frequency Division Multiple Access (OFDMA) was choosen for the DL channel, in order to maximize the achievable data rate, and Single Carrier Frequency division Multiple Access (SC-FDMA) for the UL, which allows for a simpler amplifier design thanks to its lower Peak to Average Power Ratio (PAPR) when compared to OFDMA. A desirable property of this is that SC-FDMA waveforms can be obtained by the same transmission chain as OFDMA, with the addition of a final Discrete time Fourier Transform (DFT) spreading block. Similarly, the decoding chain is identical, with the addition of a leading DFT de-spreading block. Since this is a very technical discussion on PHY layer implementation detail which are outside the scope of this work, we invite the reader to refer to notoriously detailed resources such as [40] and [41]. This relation, however, means that signals can be generated (and logically represented) in the same way for DL and UL, since the differentiation between the two waveforms takes place at the very end of the transmission chain. The illustration of the channel structure of LTE in Figure 4 hence represents the air interface for the DL channel, but is also holds for the UL one with the addition of the additional DFT block. In order to maximize the efficiency with which the radio resource is exploited, LTE adopts a strict time synchronous paradigm, where the time reference is dictated by the eNodeB. As illustrated

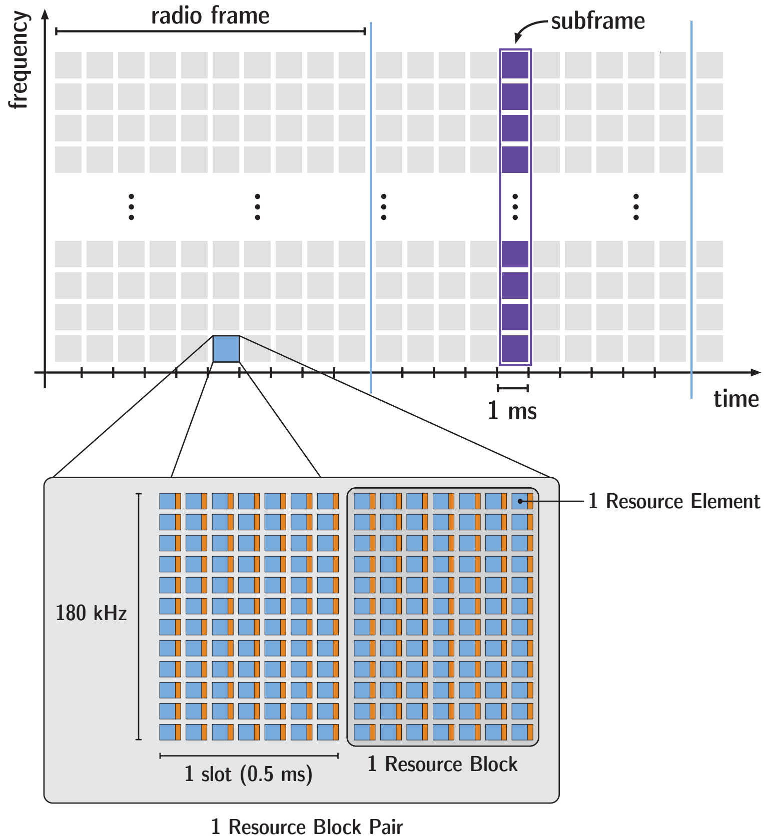


Figure 4 – LTE DL air interface nomenclature

in Figure 4, the channel time and frequency resources are partitioned into a grid of Resource Block Pairs (RBPs), each spanning over 180 MHz of BW for a Transmission Time Interval (TTI) equal to 1 ms. Within the 180 MHz there are 12 subcarriers, with 15 kHz spacing between each other. Internally, RBP are indeed composed by a pair of Resource Block (RB), including all of the 12 subcarriers for a time duration of 0.5 ms, referred to as *"slot"* in LTE terminology. One can observe, in Figure 4, that within the RBs, each of the subcarriers is divided into Resource Elements (REs), the most elementary channel partition unit in LTE. As a matter of fact, a RE corresponds to a modulation symbol (carrying a number of bits dependent on the selected modulation) plus a Cyclic Prefix (CP) tail, which protect against inter symbol interference due to multi path propagation. Two configurations of the CP are defined, a normal one and an extended one, which eventually determine the number of RBs. The extended configuration, wherein the CP is 16.67 μs long is designed for the eMBMS service (see section 3.2.3 for more details), wherein the multipath aspect is particularly critical, since UEs might receive the same signal at the same time from multiple eNodeBs. On the other hand, for regular scenarios a *"normal"* CP configuration is specified, wherein the CP duration is 4.7 μs. In this configuration, each subcarrier supports 7 REs per RB, whereas only 6 can be held per subcarrier when the extended CP is used.

Since RB / RBP are the basic building blocks of LTE air interface configurations, the specified channel bandwidths can both be expressed in MHz and in RBs, with the correspondence as in Table 3. Please observe that measures in RBs do not include the mandatory guard intervals on the sides of each channel. On the time domain, the set RBPs within the same 1 ms TTI covering

Table 3 – Supported bandwidths in LTE in MHz and corresponding values in RBPs

BW [MHz]	1.4	3	5	10	15	20
BW [RBs]	6	15	25	50	75	100

the whole bandwidth is denominated a *"subframe"*; similarly, a periodically repeated group of 10 consecutive subframes is named a *"frame"* or radio frame.

2.3.2 *Proximity Services*

D2D communications are a critical enabler for the support of V2X services over LTE. Standardization works on D2D links started in the early stages of the Rel. 12 under the name of ProSe with [42] and [43], respectively from 2012 and 2013. The former document represents the preliminary study of the scenarios and use cases, whereas the latter explores the architecture and protocol extensions to support them. The results of these studies originated [44], which is the current reference specification for ProSe, containing the architecture definitions for both roaming and non roaming scenarios, the procedures for discovery and communication (both for public safety and non public safety UEs), and the description of the novel interfaces at Evolved Packet Core (EPC) (i.e. the core network) and Evolved Universal Terrestrial Radio Access (E-UTRA) (i.e. the radio interface) level. Among the novelties introduced, the most relevant for this work is the PC5 Sidelink radio interface, described in more detail in the following part of this section.

ProSe offers proximity UE Discovery and Communication services: discovery can either be functional to enabling communications or be offered as a standalone service [44, §5.3.1.1]. The discovery services can be handled by the core network (EPC-level discovery, [44, §5.5]) or directly between ProSe-enabled UEs (direct discovery, [44, §5.3]). This latter is the configuration of interest for this work, as it minimizes the dependence on the installed network. From a radio resource management perspective, [45, §8] defines the two allocation procedures supported for ProSe direct discovery: autonomous resource selection (Type 1) and scheduled resource allocation (Type 2B). Autonomous Resource Selection requires the definition of a novel channel structure based on semi-static resource pools, whose PHY layer characteristics are specified by [46, §14.3.3] and described in more detail in section 2.3.2 of this paper. Type 2 resource allocation, on the other hand, controls discovery channel resources via dedicated Radio Resource Control (RRC) signaling.

From the communication standpoint, both broadcast and unicast paradigms are envisioned, although the former is currently loosely specified, and reserved to Public Safety UEs. Chapter 4 in [47] (*"From DMO to D2D"*) discusses the use of LTE D2D for public safety applications, and provides a more detailed description of the Sidelink operations.

Similarly to discovery, two resource allocation paradigms are supported for direct communications, as standardized in [45, §9.1.2]: scheduled resource allocation (Mode 1), and autonomous resource selection (Mode 2). The scheduled mode (Mode 1) does not require the allocation of a semi static communication resource pool: channel resources SL transmissions are in fact individually allocated by the eNodeB. A specific Downlink Control Information (DCI) format 5 ([48, §5.3.3.1.9]) and a specific Sidelink Control Information (SCI) format 0 ([48, §5.4.3.1]) are defined for this purpose. Mode 2, on the other hand, requires the definition of a shared Physical Sidelink Shared Channel (PSSCH) resource pool as in [46, §14.1.3]; a policy for UEs to select transmission resources within the pool, however, is not specified in detail. The definition of such a policy, in a broadcast vehicular safety scenario, is one of the main contributions of this work.

In order to support proximity-based discovery, communication and applications, ProSe introduced a novel D2D extension to the legacy LTE architecture. Figure 5 illustrates this extension for the general case, where the communicating UEs are attached to different Public Land Mobile Networks (PLMNs).

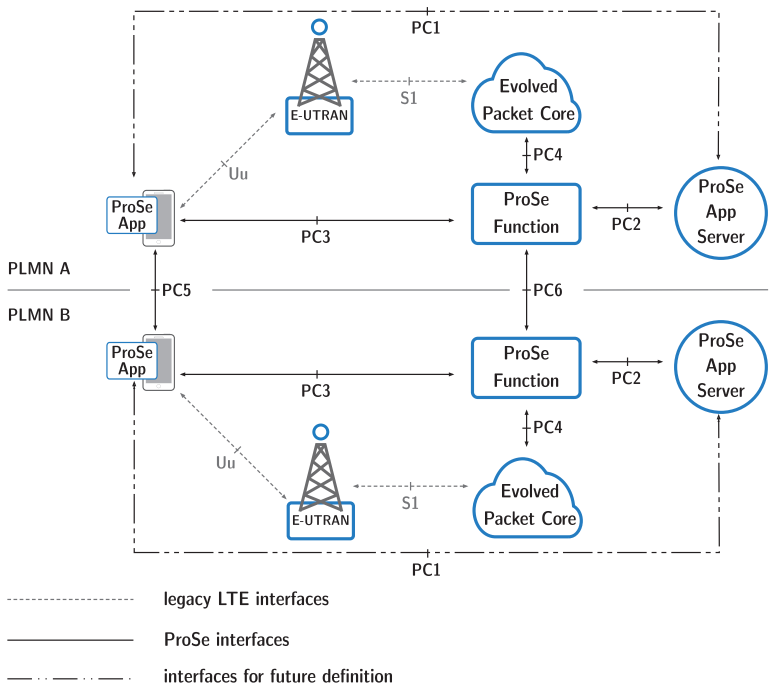


Figure 5 – ProSe architectural extension - adapted from [44, §4.2]

Alongside the legacy interfaces such as the User to UTRAN (Uu) connecting an UE to the eNodeB, a new set of reference points has been introduced to interconnect all functional blocks introduced by the specification. While Table 4 provides a brief overview of these new reference points and their role to the network entities, an interested reader can find a complete description in [44], §4.3 and §4.4 respectively. This work mainly focuses on the PC5 interface, directly connecting ProSe-enabled UEs.

In the LTE terminology this UE-to-UE link is denominated SL, as opposed to the conventional Uplink (UE-to-eNodeB) and Downlink (eNodeB-to-UE). The SL is defined as a subset of the Uplink resources [3], where D2D communications can take place; in the current specification it is allowed to operate within the frequency bands listed in [49, Table 5.5D-1]. The bandwidths that can be

3. In the current 3GPP specification, Uplink resources have been preferred for SL due to their lower PAPR.

Table 4 – ProSe: description of interfaces and entities

Entity	Description
ProSe App	the Application being served by ProSe
ProSe App Server	stores and manages Application IDs, and manages permissions
ProSe Function	logical function that is used for network related actions required for ProSe
Interface	**Description**
PC1	introduced but not yet specified in the current release
PC2	defines the interactions for Direct Discovery and EPC-level ProSe Discovery
PC3	used to authorize discovery functions, perform allocation of Application Codes and User IDs used for discovery, and define the authorization policies for discovery
PC4	provides geolocation and EPC-related user data
PC5	the interface carrying the SL user plane and control plane communications
PC6	connects ProSe Functions of different PLMNs, when ProSe-enabled UEs are attached to different cellular networks

allocated to SL differ based on the function: up to 20 MHz can be reserved for discovery, whereas 10 MHz is the maximum for communication and control (see [49, §A6.2 - §A6.5]).

As illustrated in Figure 6, the allocation of Sidelink resources is based on Resource Pools, formed by:

— a "subframe pool" in time domain, including all subframes carrying the SL.

— a "resource blocks pool" in frequency domain, the subset of resource blocks within the subframe pool that are actually assigned to the SL.

In time domain, subframe pools are laid out according to a periodical pattern, determined by a bitmap (`subframeBitmap-r12` within `SL-FR-ResourceConfig` in [50, §6.3.8]). The length of the bitmap is fixed to 40 subframes in Frequency Division Duplexing (FDD) deployments, whereas it varies from 4 to 42 according to the configuration in TDD. The period itself (for communication) is defined by `SL-PeriodComm`, which currently supports selected values between 40 and 320 subframes. In frequency domain, the resource pool occupies a subset of the resource blocks within these subframes, as determined by three parameters [50, §6.3.8]:

— `prb-start`, which determines the index of the Physical Resource Block (PRB) in correspondence to which the SL starts, starting from PRB #0;

— `prb-end`, which determines the index of the PRB in correspondence to which the SL ends, with respect to PRB #0;

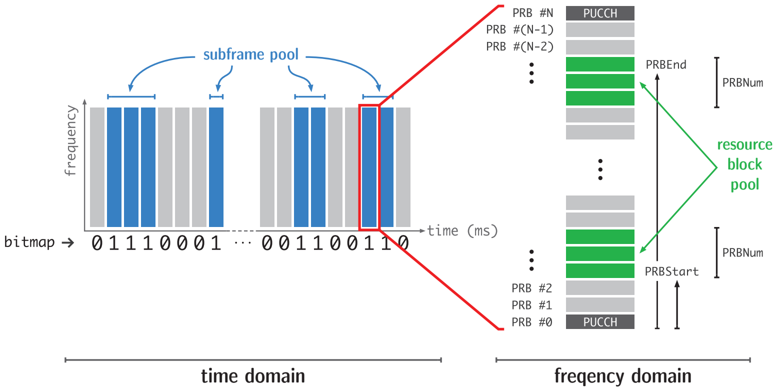


Figure 6 – Resource Allocation in time/frequency domain - Subframe and Resource Block pools

— `prb-num`, which determines the number of PRBs after `prb-start` and before `prb-end` that are assigned to the SL.

This results in the two-striped structure illustrated in Figure 6. All the parameters for the resource pool allocation are periodically broadcast by the eNodeB enclosed within the System Information Block (SIB) 18 for communications and SIB19 for discovery [50, §6.3.1], which are accessible by UEs in both `RRC_CONNECTED` and `RRC_IDLE` states.

Two types of resource pools are defined for transmission and reception: for UEs to correctly be able to transmit, the *RX pool* of the receiver must be aligned to the *TX pool* of the transmitter. UEs can support multiple resource pools interleaved in time domain: up to 16 in Reception (RX) and up to 4 in Transmitter (TX) (`max-SL-RXPool` and `max-SL-TXPool` in [50, §6.4]). Separate resource pools are created to support newly defined PHY layer channels:

— Physical Sidelink Broadcast Channel (PSBCH), used for the UE to UEs broadcast of control signals;
— Physical Sidelink Control Channel (PSCCH), dedicated to the transmission of the Sidelink Control Information;
— Physical Sidelink Discovery Channel (PSDCH), used by UEs to discover the presence of other UEs in proximity;
— Physical Sidelink Shared Channel (PSSCH), which carries the UE to UE data transmissions.

A detailed description how these PHY channels are mapped onto transport and logical channels is available in [51], in sections 5.3.1 and 6.1.3.3 respectively.

In ProSe, Discovery and Communication functions can take place, one following the other, or independently from each other: discovery, for instance, can either be functional to set up a communication or be a service by itself. Two major discovery modes are supported using uniquely LTE: network assisted ("EPC-level ProSe discovery", whose procedures in non-roaming scenarios are detailed in [44, §5.5]) and direct discovery, with this latter not involving the network directly for the discovery operation, thus being the case of interest for this work. Two resource allocation schemes are defined for direct discovery [46, §14.3.2]: "type 1" (autonomous resource selection) or "type 2B" (scheduled resource allocation). In type 2B, the resources for an UE to transmit a discovery message are assigned by the network via a transmission grant, whereas in type 1 they are randomly chosen by the UE from within the discovery pool [52, §5.15.1.1].

Direct communications over the LTE air interface similarly support two allocation schemes concerning the resources dedicated to the transmission of control and data information:

— **Mode 1 - scheduled resource allocation:** transmissions on the Sidelink are authorized by the network, which provides the transmitting UE with PSCCH resources wherein to transmit the SCI (see [48, §5.4.3]), and PSSCH resources to transmit data. A shared communication resource pool is not necessary, since the resources for the PSSCH are specifically allocated by the eNodeB for every transmission request. A shared control pool, on the other hand, is still required, as it needs to be checked by ProSe UE to detect upcoming transmissions.

— **Mode 2 - autonomous resource selection:** UEs autonomously select channel resources within the control pool for the transmission of the SCI and resources within the transmission pool for the messages carrying user plane data. As no coordinator is available to assign resources, they are statically allocated. This mode, in the current specification, is reserved for Public Safety UEs.

The allocation of SL resources for D2D transmissions differs according to the selected transmission Mode. A detailed description of these procedures is provided in Appendix A. Visually, a Sidelink implementation for transmission mode 2 would result in a channel organization such as the one in Figure 7, wherein the (different) periods of control/communication and discovery services are highlighted.

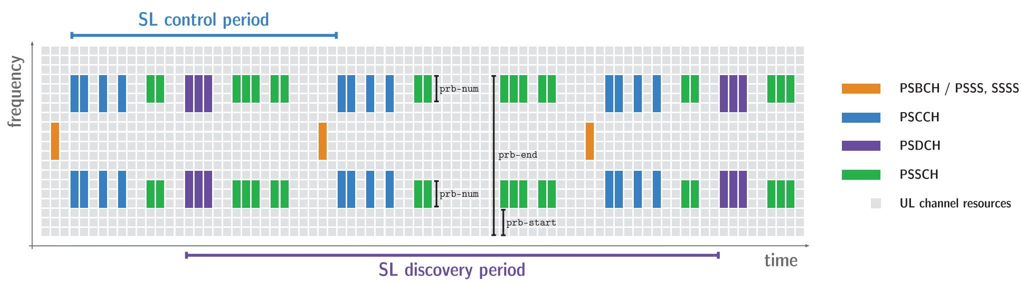


Figure 7 – Example of SL channel structure for transmission mode 2

2.3.3 *LTE-based V2X*

Very recently, 3GPP started issuing specifications for supporting LTE-based V2X applications, by defining a novel architecture extension depicted in Figure 8. Direct V2V, V2P and V2I communications are carried by the same PC5 sidelink interface as defined in ProSe, although with some extensions are found to be necessary to adapt it to the V2X communication requirements (listed in [53]). Said extensions include the support for non IP messages (such as CAMs and BSMs) [54, §4.4.2], and the support for one-to-many communications [55, §6.2.2] and autonomous resource selection [56, §5.1.1.2] for non public safety UEs. Alike ProSe, two new transmission mode are introduces, namely mode 3 (scheduling assisted by the eNodeB), and mode 4, wherein RRM is distributed.

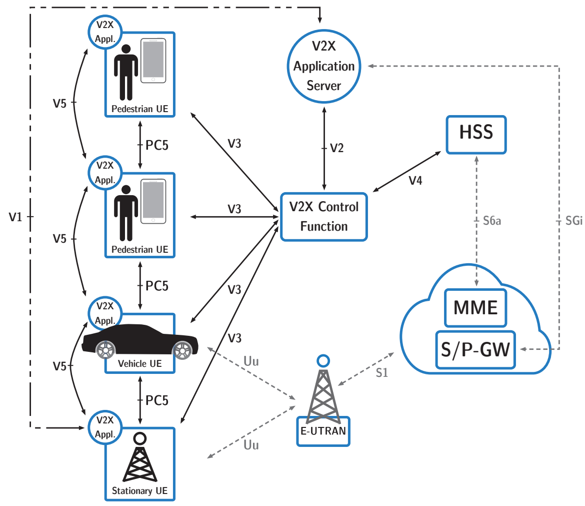


Figure 8 – LTE V2X reference architecture for non-roaming scenario. Adapted from Figure 4.2.1.1-1 in [54]. We invite the reader to refer to [54] and references therein for a detailed description of all the represented interfaces and entities. Black solid lines indicate newly defined LTE V2X interfaces, whereas gray dashed lines are legacy LTE ones. The V1 interface (black dash-dot line) is defined but not specified yet.

Support of V2X applications over D2D LTE is currently at a very early stage, wherein most of the items are for future study. In Table 5, are listed all of the 3GPP Technical reports (TR) and Technical Specifications (TS) concerning LTE-based V2X and the future perspectives on 5G.

Radio resource management is however clearly identified as a key challenge, as the legacy centralized architecture of LTE poorly adapts to V2X system requirements. V2X enabled UEs shall thus be able to select transmission resources in a distributed fashion, in order to achieve lower end-to-end latency. The main contribution of this work is therefore the proposition of a standard compliant channel organization based on the Sidelink and of a distributed resource access scheme that performs *enhanced random resource selection*, a resource control scheme that provides gains according to [56, §5.1.1.2].

2.3.4 *The PC5 Sidelink Interface*

LTE support of D2D direct communications required the specification of a novel UE-to-UE link, denominated Sidelink, which complements Uplink and Downlink. In ProSe, the SL air interface lies in a subset of the resources assigned to the UL, within frequency bands and with channel widths specified in [49]. LTE-based V2X extends the support to external carriers, such as the 5.9 GHz ITS band.

The PC5 SL resource allocation is based on the concept of resource pool, which is a set of channel resources allocated for a specific functions such as control, discovery, and/or communication. In time domain, resource pools follow a periodical pattern, as illustrated in Figure 7, wherein the period of the control resource pool and the period of a discovery pool are highlighted. Within each period, only a subset of the available UL subframes are occupied, according to specific bitmaps as in [50, §6.3.8]. As shown in the picture, dis-

Table 5 – Standard documents on LTE-based V2X

Technical Reports		
Document number	**Title**	**Ref.**
+ TR 22.886	Study on enhancement of 3GPP support for 5G V2X services	[57]
+ TR 22.885	Study on LTE support for Vehicle to Everything (V2X) services	[58]
+ TR 23.785	Study on architecture enhancements for LTE support of V2X services	[55]
*TR 33.885	Study on security aspects for LTE support of V2X services	[59]
*TR 36.786	V2X Services based on LTE; User Equipment (UE) radio transmission and reception	[60]
+ TR 36.885	Study on LTE-based V2X services	[56]

Technical Specification		
Document number	**Title**	**Ref.**
+ TS 22.185	Service requirements for V2X services	[53]
*TS 29.387	V2X Control Function to V2X Application Server aspects (V2); Stage 3	[61]
*TS 29.388	V2X Control Function to Home Subscriber Server (HSS) aspects (V4); Stage 3	[62]
*TS 29.389	Inter-V2X Control Function Signalling aspects (V6); Stage 3	[63]
*TS 24.385	V2X services Management Object (MO)	[64]
*TS 24.386	V2X enabled User Equipment (UE) to V2X Control Function aspects (V3); Stage 3	[65]
+ TS 23.285	Architecture enhancements for V2X services	[54]

Note: The documents labeled with a "+" sign have already been issued by the 3GPP, i.e. their version numbers are in the form 14.x.x or 15.x.x. On the other hand, documents labeled with a "*" are still in preliminary phase, with version numbers in the form 0.x.x, 1.x.x, or 2.x.x.

covery and control period might have different lengths, according to the application needs. In frequency domain, the resource pool occupies a subset of the resource blocks within these subframes, as determined by three parameters [50, §6.3.8]:

— `prb-start`, which determines the index of the PRB in correspondence to which the SL starts, starting from PRB #0;

— `prb-end`, which determines the index of the PRB in correspondence to which the SL ends, with respect to PRB #0;
— `prb-num`, which determines the number of PRBs after `prb-start` and before `prb-end` that are assigned to the SL.

Resource pools are created to support a newly defined set of physical layer channels ([51, §5]), as illustrated in Figure 7:

— PSBCH, used for the UE to UEs broadcast of control signals;
— PSCCH, dedicated to the transmission of the Sidelink Control Information;
— PSDCH, used by UEs to discover the presence of other UEs in proximity;
— Physical Sidelink Shared Channel, which carries the UE to UE data transmissions.

The way these channels map onto transport-level and logical-level channels is defined by [51] (§5.3.1, and §6.1.3.3 respectively).

The allocation of SL resources for D2D transmissions differs according to the selected transmission Mode. A detailed description of these procedures is provided in Appendix A. Considering the communication service, only Mode 2 - Autonomous Resource Selection - requires the reservation of a dedicated PSSCH resource pool (as in Figure 7), whereas in Mode 1 the resources for D2D data transmissions are dynamically allocated by the eNodeB upon request. As a result, UEs in in Mode 2 do not need to be is state RRC_CONNECTED in order to transmit on the SL, whereas in mode 1 the transmitter is required to stay in connected state.

2.4 STATE OF THE RESEARCH

In this section, comprehensive review of the research literature on vehicular connectivity will be provided. First, an overview will be provided of the MAC algorithms that have been developed by the research community over the years. These algorithms were specifically developed for 802.11p, the de facto standard for V2X communications. In the following, the LTE-based techniques are presented, first by introducing those that rely on the infrastructure mode, then the D2D-based solutions. To conclude this section, a discussion on the limitations of all these techniques is presented, along with the motivation of the work presented in this thesis.

2.4.1 *MAC Algorithms for V2X*

MAC is an essential layer to performance of vehicular network, since it has to deal with high speed terminals, complex mobility patterns and ever-changing topology. In the very early stages of their development, Vehicular Ad-hoc Networks (VANETs) took inspiration from the MAC layer of Mobile Ad-hoc Networks (MANETs), which previously already had to cope with similar challenges [66]. Many surveys have been dedicated to this topic over the years, each representing the evolution in research and standardization, such as [66] in 2006, [67] in 2011, [68] from 2012 which focuses on multi channel deployments, and more recently [69] in 2015, which focuses on TDMA. The vast majority of available access for MANETs and VANETs belongs to the following categories (in alphabetical order):

— Code Division Multiple Access (CDMA);
— Carrier Sense Multiple Access (CSMA);
— Frequency Division Multiple Access (FDMA);
— Time Division Multiple Access (TDMA);
— Space Division Multiple Access (SDMA)

in some cases, as it will be shown later in this section, techniques that combine multiple of the previous were presented.

Code Division Multiple Access (CDMA)

CDMA is a widespread multiple access technique, adopted by 3GPP in Universal Mobile Telecommunication System (UMTS) (the cellular generation preceding LTE) and by GNSS systems such as the Global Positioning System (GPS) and GALILEO. In CDMA systems, each transmitter is assigned a different code, also referred to as Pseudo Noise (PN), which is used to spread the signal over the whole available bandwidth. The PN code are instances of a base sequence (such as Gold codes, or Hadamard codes) which have a desirable correlation property: different instances have a negligible cross-correlation (ideally 0), whereas the auto-correlation (i.e. an instance correlated with a replica of it) is a value much bigger than 0. This property allows terminals to simultaneously use the whole available bandwidth, thus allowing a virtually zero-delay channel access. On the receiving side, terminals can mathematically extract transmissions by generating locally every possible instance of PN and correlating it with the incoming signal: thanks to the aforementioned correlation properties, this operation will isolate the component (transmission) spread with that specific instance of the PN.

Both *synchronous* and *asynchronous* CDMA systems exist: in the former, all PN sequences are transmitted from the same point, hence are perfectly time-aligned, such as in the DL channel of UMTS. In this case, sequences can be perfectly orthogonal, with cross-correlation equal to 0. On the other hand, MANETs and VANETs are asynchronous, which means that the effects of the non-zero cross-correlation at the receivers cannot be neglected. This problem, known in literature as *near-far problem*, is studied for MANETs in [70], where the authors also propose a protocol solution to it.

The adoption of CDMA-based MAC for vehicular networks has been considered in [71], thanks to its ability of providing real time channel access. To this, the resistance to jamming (both intended and unintended), and the possibility of reusing the same channel resources simultaneously for multiple transmission must be added to the strengths of CDMA. However, the authors in [71] rule it out as a viable candidate because of the effects of near-far problem, which are particularly relevant for highly mobile and potentially dense networks such as VANETs. Furthermore, from a research perspective, they also highlight the fact that CSMA requires far more complex processing than other schemes such as CSMA or TDMA: this does not represent an issue for the practical implementation, since off the shelf hardware is available that is capable of doing it. However, this might be a barrier for the development of accurate simulation tools for its evaluation, which were not available at the time the paper was written.

Carrier Sense Multiple Access (CSMA)

CSMA is an extremely popular medium access scheme, because of its simplicity and its effectiveness in achieving distributed coordination. For this reason, it was chosen as the basis for the 802.11 standard. In CSMA, terminals apply the LBT paradigm to perform channel access, which implies that before transmitting a packet, terminals must check the state of the channel occupancy.

WiFi adopts a CSMA/CA mechanism, wherein terminals transmit only when the channel is appropriately sensed idle. The basic function, named Distributed Coordination Function (DCF), is well described in [72], the seminal paper of Bianchi, wherein an analytic model for the computation of its performance is proposed. DCF is a contention-based technique in which terminals sense the channel before performing a transmission. The channel might either be idle (i.e the average power sensed over a slot time is lower than a predetermined Clear Channel Assessment (CCA) level) or busy. Channel access is regulated according to a multi-stage backoff mechanism, which represents the collision avoidance component of the protocol. The transmitter randomly generates a Contention Window (CW), i.e. an integer value in the range $[0, CW_{min}]$, wherein CW_i is the maximum CW value of r the i^{th} stage, to which a backoff counter is initialized. Before transmitting, the terminal senses the channel for a slot duration: if the channel is idle, the backoff counter is reduced by one unit, then the process repeated in the next slot time. Otherwise, if the channel is busy, the backoff process is frozen for a time equal to DCF Inter Frame Space (DIFS), after which the channel is sensed again. When the backoff counter reaches 0 the packet is transmitted.

On the RX side, the terminal must sends back an Acknowledgment (ACK) packet immediately after reception, plus a delay equal to a Short Inter Frame Space (SIFS). The SIFS is properly designed to be shorter than the DIFS, so that other terminals cannot sense the channel free until the end of the ACK. The transmitter waits for this ACK: if it is correctly received, the process ends. Otherwise, the transmitter enters the next backoff phase, by:

1. increasing the maximum width of the CW as $CW_i = 2^i CW_0$, wherein i is the current stage of backoff;
2. randomly picking a new CW $\in [0, CW_i]$;
3. repeating the aforedescribed backoff procedure.

If the ACK fails to be received once again, this mechanism is repeated until $CW_i = CW_{max}$, after which the packet is dropped. On the RX side, if the system operates in acknowledged mode, the terminal must sends back an ACK packet immediately after reception, plus a delay equal to a SIFS. The SIFS is properly designed to be shorter than the DIFS, so that other terminals cannot sense the channel free until the end of the ACK.

Despite providing a distributed access coordination, this procedure suffers from a few problem:

1. sensitivity to jamming;
2. unbounded channel access for high channel load;

3. the *hidden terminal* problem;
4. the *exposed terminal* problem.

The first two points are different incarnations of the same problem: the access mechanism based on sensing will get stuck into backoff mode if the channel is jammed or highly utilized, with most transmission getting dropped.

The *hidden terminal* is a well known phenomenon that might occur when two terminals (named for convenience "TX_1" and "TX_2") not within respective sensing range attempt to communicate with a third terminal (we will refer to as "RX") in range of both of them. TX_1 and TX_2 cannot detect each other, which could lead their transmissions to overlap, causing a collision to RX. The hidden terminal problem is tackled by the Institute of Electrical and Electronics Engineering (IEEE) 802.11 Ready To Send (RTS) / Clear To Send (CTS) mechanism. Say TX_1 has a packet ready for RX: before transmitting it, it transmits a small RTS packet containing the identifier of RX. If RX is ready to receive it, it will then reply with a CTS packet containing the identifier of TX_1, which, upon reception, will start the contention procedure to transmit the intended packet. If at the same time TX_2 also needs to communicate with RX, two scenarios might happen: it either receives the CTS meant for TX_1, thus containing an identifier that does not match its one, or it transmits a CTS to RX which will remain unanswered, since RX is busy receiving from TX_1.

The *exposed terminal* is a dual problem to the *hidden terminal*, wherein the contention mechanism prevents transmissions from happening even when no collision to the receivers would be caused. Assume a pair of transmitters (TX_1 and TX_2) willing to transmit a message respectively to one of two transmitters RX_1 and RX_2. The two transmitters are in range of each other, whereas the two receivers are not: they only are in range of their respective transmitter. When one among TX_1 and TX_2 is transmitting, the other one will refrain from doing so, because of sensing the channel busy. This is one case in which the carrier sense mechanism fails, because had that second transmission occurred it would have collided with the first one in the transmission area, but both would correctly be received by the appropriate RX.

Vehicular networks, however, required the definition of a specific version of 802.11, commonly referred to as 802.11p[4]. From a MAC standpoint, in fact, vehicular network impose a set of challenges, and raise a set of requirements that were not being considered until then in the 802.11 design [73]. Differently from other flavors of 802.11, 802.11p only operates in broadcast mode when transmitting status and emergency messages, which implies that receptions of those packets cannot be acknowledged. This leads to a couple of consequences. First, the backoff process only consists in a single stage: if at the end of it the packet is not transmitted, it is dropped. Secondly, the RTS / CTS mechanism cannot be implemented, which means that in 802.11p is affected by the hidden terminal problem. The effect of it on the performance of 802.11p is evaluated in [74], where they are also compared against STDMA.

In order to ensure a certain degree of QoS, 802.11p adopts the EDCA from 802.11e [75], which assigns higher priority to different types of traffic in the transmit queue by choosing smaller maximum sizes for the CW.

4. 802.11p was the temporary name of the amendment, officially dropped after it became effectively part of the 802.11 standard in 2012. However, for notational convenience, and to align with the literature, we will keep referring to it as "802.11p" in this document.

Frequency Division Multiple Access (FDMA)

As the name suggests, in FDMA multiple access is achieved by assigning transmitters different frequency channels. This technique avoids spending bandwidth in the contention process, but imposes constraints that are hardly acceptable for vehicular networks, wherein safety-critical status packets are broadcast and destined to all of the vehicles in proximity. In FDMA it is in fact necessary for the transmitter and all the interested receivers to be tuned on the same channel. This operation increases the complexity and requires a further control channel for synchronization message exchange [69]. Despite being used in ITS-G5 for the transmission of messages on the SCHs, these limitations made FDMA a unsuitable choice for status packets. Some cases exist, wherein a mixed FDMA and TDMA is proposed [76], but to best of knowledge no pure FDMA solution for safety critical V2X communications has been proposed.

Space Division Multiplexing (SDMA)

SDMA exploits the spatial distribution of terminal to assign them (or having them choose) a different set of channel resources based on their geographical position. This class of solutions attracted the interest of the vehicular community, wherein terminals have access to accurate information about their position. The adoption of SDMA for vehicular network was made in [77], wherein the authors show how its flexibility allows for its use in conjunction with other multiple access systems such as CDMA, FDMA, and TDMA. In the referenced paper, authors assume a transmission rate of 50 packets/s (each of 100 bytes), and propose two techniques. The first is a basic implementation of SDMA, wherein a road is split into space divisions such that no more than one vehicle can be in the same division at the same time, which results in tiles 5 m long, for the whole width of a lane. This tiling is coupled with a TDMA approach, which associates a time slot to each tile, in such a way that the same time slot is not reused by tiles less than 500m apart. In the same paper, the authors also propose an improved version of the protocol, wherein a portion of the bandwidth is assigned to a control channel, which is used by vehicles to transmit their position, hence the timeslot they are assigned. The control channel is itself split into access slots, to access which terminals apply a contention model similar to 802.11. Despite sounding promising, no performance evaluation of the proposed techniques appears in the paper.

Years after, in 2008, the authors in [78] study the suitability of SDMA for vehicular communications, claiming that up until then no study was available that proved its realistic feasibility. In this paper, they analyze the challenges raised by SDMA, specifically regarding the Partitioning Function (P-FUNC) to partition space and the Mapping Function (M-FUNC) that assigns channel resource to each so-generated tile. Both these functions, in fact, are easy to generate in basic road configurations; in real world, there are however a multitude of complex road layouts to take into account. Moreover, such function would need to be stored in form of a database within vehicles, making them difficult to maintain updated following the numerous roadworks and modifications that affect the layout of the road network everyday. On the other hand, the authors prove that a global division, wherein the whole map is tiled rather than the roads only, would solve the aforementioned problems, but fail short to achieving a 100 ms inter packet transmission delay when coupled to a TDMA system. Overall, the authors identify 4 challenges whose solution is fundamental in order for SDMA to be uitable for vehicular communications: find a manageable way to (i) generate and (ii) maintain M-FUNC and P-FUNC; (iii) solve the border effect, which cause difficulties on choosing the proper channel when at the border between neighboring tiles; (iv) address the incertitude in position, which might lead to the wrong channel choice. This last point, however, is of great importance in a wider sense for highly automated vehicles.

In [79], the authors propose an enhanced version of SDMA, tackling the aforementioned issues by having RSUs dynamically perform P-FUNC and M-FUNC, based on traffic conditions, vehicle speed and reception performance.

Time Division Multiple Access (TDMA)

TDMA represents a very popular class of multiple access algorithms for wireless networks, and by far the one that attracted more research area for MAC protocols for vehicular networks. In TDMA systems, terminals exploit in turns the whole channel bandwidth for a predetermined amount of time.

In TDMA systems, MAC impairment is caused by packet collisions, of which two types of collisions are defined [80, §3.1.2]:

1. *access collisions*is experienced by terminals in range of two vehicles two hops from each other, choosing the same transmission slot;
2. *merging collisions* happen when vehicles not within TX/RX range, typically moving towards each other, reserve the same slot, and simultaneously transmit in it once they reach proximity.

The most basic declination of TDMA protocol is Additive Links On-line Hawaii Area (ALOHA) developed in the early 70's at the University of Hawaii [81]. ALOHA is so simple that can be described in one sentence: when a terminal has a packet ready for transmission, it transmits it. Collisions are dealt with by an acknowledgement / retransmission system. This solution, known as pure ALOHA, provides extremely easy implementation and has little requirements, but is proven to only be able to deliver a throughput equal to about 18 % of the available channel rate. An evolution of the protocol, call Slotted-ALOHA, halves the vulnerable time by imposing a time slotted system, wherein packets can only transmitted within predefined time intervals (slot). In this way, it is able to provide a throughput twice as high as pure ALOHA: this, however, is only equal to about 36 % of the available channel rate.

In recent years, many more sophisticated TDMA solutions have been proposed to specifically tackle the challenges raised by vehicular networks. Two most relevant categories of TDMA algorithms exist, based on whether they operate in a completely decentralized way, or they rely on a central coordinator.

Centralized algorithms can either be based on infrastructure, or on clustering of the users, with the channel resource assignment being performed by a subset of the users elected to be cluster heads. An example of the former is presented in [82], with the authors proposing a protocol wherein scheduling is performed by RSUs, based upon Channel State Information (CSI) information on every single V2V/V2I link collected from the terminals. The technique shows promising performance, but is affected by the shortcomings typical of infrastructure-based techniques, namely the fail-safety of the system being dependent on the installed network, and the very practical requirement of deploying the network itself. Another relevant, more recent, infrastructure-based MAC protocol is Centralized TDMA MAC (CTMAC), introduced in [83].

According to [69], cluster-based algorithms are getting increasing attention in recent times, due to their ability to reduce the overhead by concentrating the scheduling function into the cluster head. Examples of this include TDMA Cluster-based MAC (TCMAC) [84], and [85].

Decentralized algorithms, are because of their nature of particular interest for vehicular networks, and include Vehicular Self Organizing Ad Hoc Networks MAC (VeSOMAC) [86], Vehicular Ad Hoc Networks MAC (VeMAC) [87], Collision Free Reservation MAC (CFR-MAC) [88], Mobile Slotted Aloha (MS-ALOHA) [89], and STDMA [90].

VeSOMAC was introduced in 2007 as a TDMA solution to overcome some of the issues brought by CSMA/CA, such as unbounded channel access delay under heavy channel load, and packet losses due to collisions. It does that by defining mechanism to broadcast slot utilization information along with the packets, along an in band control procedure to account for the topology changes due to vehicular mobility. The time dimension of the channel is organized into periodical frames and slots, and the protocol is designed to operate both in synchronous and asynchronous mode, where only in the former users share the slots and frames time boundaries. VeSOMAC requires the satisfaction of a so-called "timing constraint", which states that no one-hop or two-hop slots must overlap, because they would respectively cause direct collisions and hidden collisions. This is done by including in each packet reservation information about the slots immediately before and after it, which can be utilized by receiving users to base their reservation upon. VeSOMAC shows significantly better performance in transferring files with respect to CSMA/CA-based 802.11, especially in multi-hop scenarios. Despite this latter not being relevant for the transmission of periodical messages, the base principle and the improvements it brought are noteworthy.

In 2011, the authors in [87] introduced VeMAC, a multichannel TDMA scheme which eliminates the hidden terminal problem to provide reliable one hop broadcast. Specifically, different sets of slots are assigned to vehicles traveling in opposite directions, which is beneficial to mitigate the effect of merging collisions. This solution is straightforward to implement for simple road configurations, but it can be challenging in complex real world scenarios, as previously discussed for SDMA.

CFR-MAC is a much more recent protocol presented in 2014, based on the aforedescribed VeMAC, which provides yet another solution for solving the hidden terminal problem. In CFR-MAC, vehicles include the Frame Information (FI) to every transmitted packet: the FI is a field including not only the status of each slot as perceived by the transmitting vehicle, but also information about the speed and acceleration of the transmitting node. This system provides users with an extended view of their two hop channel usage, which is the exploited for their own scheduling decisions. Similarly to VeMAC, disjoint sets of slots are assigned to users moving in opposite directions; these two sets, however, are further divided into three subsets each, depending on the relative speed between vehicles. CFR-MAC provides low channel access, and stable performance for increasing channel loads, which however comes at the cost of high overhead in each packet (increasing with the number slots per frame), and the difficulties of allocating slot sets in realistic road scenarios inherited from VeMAC.

MS-ALOHA and STDMA are exceptionally relevant protocols, first because they both have been object of intensive research, and second because they have been officially studied by the ETSI as potential alternatives to CSMA/CA [91, 92].

MS-ALOHA [93] is based on two previous MAC schemes, namely Reliable Reservation ALOHA (RR-ALOHA) and RR-ALOHA+ [94], the former of which was developed in the framework of the FleetNet project (as discussed in section 2.1.1) [95] for the UMTS air interface, but also adaptable to other PHY schemes. MS-ALOHA makes them scalable and more suitable to the vehicular environment. As in RR-ALOHA, a FI array of 12-bits fields, which describe how each slot in the current frame is perceived, is piggybacked to each packet. MS-ALOHA extends this concept by exploiting a unassigned state within the FI to implement a flag message which allows transmitters to control the propagation of such channel usage information, preventing busy slot flags to spread more than two hops. In this way, hidden terminal problem is averted, and the channel utilization is improved, by preventing slots from being labeled busy too far away from the transmitter actually occupying them. In this way MS-ALOHA provides a significantly improved packet reception performance with respect to RR-ALOHA+, especially at closer distances to the transmitter.

In [96], the authors of MS-ALOHA compare it by means of simulation against the CSMA/CA mechanism 802.11p is based upon, and against RR-ALOHA+, both in urban and in highway scenarios. It is shown that RR-ALOHA+ poorly adapts to situations where more nodes are present than channel slots available, which results in remarkable dips in packet reception probability. On the other hand, MS-ALOHA significantly reduces the occurrence of collisions, by providing an efficient slot allocation, which results in better packet reception statistics at ranges within 100 m when compared to both RR-ALOHA+ and 802.11p. 802.11p manages to provide shorter channel access delays than MS-ALOHA: however, the latter protocol is able to guarantee a bounded access latency under varying channel loads, whereas this is not the case 802.11p. A qualitative comparison between MS-ALOHA and STDMA can be found in [97].

STDMA is one of the protocols this thesis is focused on, hence it deserves a full, detailed description which can be found in section 3.5 of this document. Similarly to MS-ALOHA, STDMA is a protocol wherein users reserve their own transmission slots exploiting knowledge about the channel utilization in their surroundings. This information is attached to each transmitted packets, and, differently from MS-ALOHA, it only requires the addition of 2 values, namely the *timeout*, i.e. the number of consecutive frames for which the present slot is still reserved by the transmitter, and the *offset*, which indicates the offset to the newly reserved slot when a new one is chosen following a timeout expiration. STDMA provides an interesting mechanism to deal with situation wherein there are not enough available slots to satisfy the communication needs of all the users, by making users willingly reuse a convenient slot already being reserved by the terminal which is located as farthest away [5], so to guarantee a semi deterministic channel access while minimizing the effects of the resulting collision. Several works exist which compare STDMA against CSMA/CA, with interestingly different conclusions: in [98] and [99] the authors respectively show its ability to provide guaranteed channel access (hence real time communications support), and to operate also at high network density, while at the same time outperforming 802.11p also in scenarios wherein the channel is not saturated. On the other hand, in [100] it is shown that STDMA offers superior performance only in idealistic scenarios, while the same authors in [101] show that scenarios can be crafted to make one or the other protocol outperform the other one.

2.4.2 *LTE-based techniques for V2X*

In this section, we review the state of the art of research work concerning lte-based solutions to support V2X communications.

Infrastructure-based LTE V2X

Since its earliest release (Rel.8), LTE was designed to offer high capacity (above 100 Mbps in DL and 50 Mbps in UL), reduced latency (below 10 ms) and high reliability, representing a notable improvement compared to previous generations of mobile cellular technology. For this reasons, in recent years, the research community thus started to investigate the ability of LTE to support V2X communications. In 2013, the authors in [102] made a first survey covering the issue, which compares it against 3G and 802.11: among the others, one of the main concerns raised in the article is the lack of support of direct V2V mode, which would have caused all the traffic to be routed through the infrastructure. This represents an issue concerning the distribution of CAM/BSM packets, which are meant to be received by all the vehicles within TX/RX range. The centralized architecture of infrastructure-based LTE would require the establishment of backend servers and network entities to determine the set of receivers for each of the transmitted packets, which is challenging, especially considering the high TX rate per user.

Several research works analyzed the capacity of the LTE infrastructure to support V2X communications: in [103], the author develops an analytical model to evaluate whether the capacity of LTE network is sufficient for the purpose, concluding that it *"easily becomes overloaded even under [...] idealistic assumptions"*.

In [104], LTE is compared against UMTS and 802.11p as a mean to convey periodic safety messages at urban intersections, a scenario particularly relevant due to the challenging propagation and high network density. In this paper, the UL is handled via the regular standard procedure, whereas DL is performed via the eMBMS service [51, Section 15]. eMBMS is a broadcast service which improves resource usage efficiency, avoiding the scheduling of dedicated unicast DL resources for each users and each packet. The focus of the article is thus in the evaluation of the performance of the Random Access Channel (RACH), which represents the bottleneck of the system. The authors

5. please refer to section 3.5 for the detailed description of the slot reuse procedure

conclude that LTE is technically a capable technology to support V2X at intersection in the proposed configuration, but raise a concern about the cost that it would imply, since DSRC manages to provide comparable performance at no charge.

The monetary aspect is a key issue for the exploitation of the LTE network infrastructure, which is raised by all the works previously cited in this section. In [102] the authors conclude that *"[...] effective business models should be specified to support the widespread use of LTE for cooperative ITS applications. No one would agree to pay unless highly reliable safety services and attractive traffic applications can be provided"*. This problem is specifically addressed in [105], where the authors compute the cost associated to LTE for ITS applications over the lifetime of a car. They also observe that is unforeseeable for drivers to pay on a subscription-basis for the data exchange necessary for ITS applications. They thus propose to compute the costs in the average lifetime of a car, which is to be added to the vehicle's purchase price. From a technical standpoint, the authors also propose a eMBMS-based system, which is demonstrated providing lower resource usage and lower delay than dedicated unicast systems. The authors also address another key issue with the eMBMS system, which is the determination of the recipient. In eMBMS-based architectures, in fact, vehicles transmit CAMs/BSMs via the UL channel of the LTE; every 100 ms (or any regular time interval), the network bundles all of these packets in a unique, large, broadcast transmission that is received by all of the terminals in the eMBMS area. Determining the extension of this area, however, is a challenging problem. Small areas (the size of a cell) would be easy to implement, but be beneficial only to vehicles in their center, as those close to the cell edge would miss important transmissions coming from their neighbors lying on a different cell. Wide area would solve this issue, at a cost of very large bundles, that would contain information from vehicles too far away from each other, and increase the computational load. In the simulations in [105] the solution adopted is that all the CAMs transmitted in a cell are distributed by eNodeBs located to up to 362m away from it. This solution, however, might prove challenging to implement in practice, due to the complex geometry of the network.

A different approach on supporting infrastructure-based vehicular communication is the development scheduling algorithms adapted to the characteristics of vehicular users and traffic patterns. In [106] the authors analyze the impact of different scheduling algorithms on packet reception and delay performance in a realistic scenario, when vehicular transmissions are mixed with legacy voice and video transmissions. In [107] the authors present a Speed and Location Aware (SLA) LTE scheduler, suitable for vehicular applications.

D2D-based LTE V2X

A different part of the research community argues that vehicular communications over LTE should be supported via direct D2D links. In this section, we review the most relevant research activities on D2D LTE, with a specific focus on works that develop schemes that are designed to operate within a single cell, which have only been evaluated in such a scenario, and require extra work to achieve coordination in a multi cell scenario. Single-cell deployment is an assumption commonly made as a simplifying hypothesis when developing optimization algorithms, also for vehicular application. However, we claim that it is only partly reasonable, since in vehicular networks users are spread over a wide area, covered by multiple cells, and attached to multiple operators.

D2D communications underlying the LTE cellular network have been researched since the earliest stages of the specification [108]. [109] contains an extensive review of the literature on cellular D2D communications until 2014, classified by type: based on the type of spectrum they occupy, D2D communications can in fact be "inband" or "outband". In the former case, D2D transmission are assigned a subset of resources within a PLMN's frequency bands (typically the UL ones), whereas in the latter scenario they are operated in a separated band. Inband D2D can be further split into "overlay" and "underlay", with overlay D2D users being assigned orthogonal resources to the legacy cellular users, whereas the "underlay" paradigm has D2D users reutilize the same resources as cellular users. This latter paradigm has proven very attractive as RB reuse improves spectral efficiency by exploiting proximity gain. On the other hand, outband D2D can be of "controlled" or "autonomous" type: controlled D2D communications are scheduled by the basestation, despite physically taking place on a separate band. This is the case, for instance, when the basestation re-routes transmission between nearby UEs to a different interface, such as WiFi-direct on the Industrial, Scientific, and Medical (ISM) bands [110]. On the other hand, autonomous outband communications are completely self-organized by D2D-enabled UEs.

More recently, D2D cellular communications have attracted increasing attention in the vehicular community, with several studies investigating their suitability to support automotive safety-critical applications. In [102], 3G and LTE cellular communications are compared to WiFi for vehicular networking, and LTE D2D is featured as an appealing solution. Radio Resource Management is stressed as the key aspect to ensure an adequate coexistence of legacy cellular and V2V communications. In [111] D2D for Intelligent Transportation Systems are studied in terms of spectral efficiency, concluding that the inband underlay paradigm is a better option. The same work also addresses the problem of unavailability of full state information, due to high terminal mobility, proposing a predictive resource allocation algorithm. The same problem is discussed in [112], in which the authors advocate the concept of "pay for safety", i.e. the use of licensed technologies such as LTE for safety applications. In this scenario, V2X transmissions need to be considered primary links in order to be able to respect QoS requirements, and not to be limited to very short ranges (in the order of 10m). The same authors also suggest that a hybrid solution, integrating both cellular D2D and 802.11p, is viable for V2X to extend safety safety communications classes of devices (smartphones, IoT *things*) other than vehicles. In [113] the authors evaluate the influence that V2V specific PHY and MAC configuration, and traffic patterns have on the performances of LTE D2D, reaching the conclusion that LTE D2D offers adequate performances (in upper bound) to support this type of traffic. In [114], the performance evaluation focuses entirely on the PHY layer, using multiple Multi Input Multi Output (MIMO) modes: based on analytic channel models, the authors confirm the feasibility of LTE D2D-based V2V in terms of achievable throughput. The book chapter [115] takes a detailed view on all the flavors of LTE (both legacy and ProSe) for both safety and non-safety vehicular communications, which concludes discussing the challenges for 5G to become an enabler for Vehicle-to-Device Communications.

Several works propose techniques to improve cellular D2D to specifically support vehicular communications focusing on RRM and power control. In [116], the authors develop an algorithm for separate RB allocation and power control in an inband underlay scenario, wherein Vehicular UEs (V-UEs) are the primary users: pairs of V-UEs share RBs with Cellular UEs (C-UEs), with the goal of maximizing C-UEs sum rate while satisfying the V-UEs reliability and latency constraints. The optimization is made considering unicast V2V link, with broadcast being supported by considering the receiving V-UEs with the least favorable channel in the model. The same authors improved the paradigm in [117], this time allowing multiple V-UEs pairs to share the same RBs with a cellular link, by grouping V-UEs into clusters. In both models, however, the optimization is performed at the basestation, and a single cell deployment is considered. The authors in [118] designed a centralized RB allocation scheme for inband, underlay, broadcast D2D wherein cellular users are the primary users, based on the location of the vehicular UEs: the cell area is partitioned into sectors, and vehicular UEs in each of them are assigned resources differently. By simulations it is shown that, for a single cell scenario, the coexistence of cellular and vehicular D2D is possible, while ensuring the strict reliability requirements of V2V with a limited overhead. However, a scheme so dependent on a regular shape of cells is interesting but might prove difficult to implement in realistic scenarios: according to [119], in fact *"referring to average coverage area shapes as circles, squares or hexagons [...] surrounding radio ports is a largely academic exercise"*. Further, according to the references cited in the same paper, only about half of the users in residential areas are connected to the closest basestation. The same authors extended and improved the paradigm to a multicell deployment in [120], which is however still very reliant on a geometrical partitioning of cells.

The knowledge of geographic position of vehicular UEs is also exploited in [121], wherein an inband underlay scenario is considered, with vehicular UEs being primary users and one single cellular UE as a secondary one. The proposed resource selection and power control schemes are distributed, apply to V2V unicast only and are evaluated by means of simulation for a single cell deployment, with one stretch of road crossing the cell. The same authors in [122] apply vehicle UEs clustering and refine the power control algorithm to relax the full channel state information knowledge requirement.

Discussion on available D2D LTE for V2X

Numerous of the techniques available in literature rely on the installed network to perform the scheduling of direct V2X transmissions. This enable remarkable performance, as the network has a global view of the traffic conditions, and can operate optimal decisions. However, the reliance on the network also originates several issues. First of all, the functioning of the whole system is tied to the functioning of the network, which represents a single point of failure, that is not desirable on safety of life applications. A further hypothesis common in research literature is that all of the UEs are in `RRC_CONNECTED` state and connected to the same eNodeB. This implies a series of undesirable consequences: first, all the UEs must be connected to the same Public Land Mobile Network Operator (PLMNO), which is questionable on real life deployments. Second, the optimization techniques are proposed for single cell deployments: this hypothesis simplifies the problem, but again is far from reality, wherein vehicular UEs are usually spread over wide areas, and served by different eNodeBs. Extending the scheduling of broadcast transmission to multiple eNodeBs would require complex network-side coordination alongside the complexity added by the scheduling algorithms. Finally, maintaining highly mobile users in `RRC_CONNECTED` state would prove stressful for the network, due to the massive number of contemporary handover procedures to be handled.

Transmission mode is also crucial: most of the network-based D2D scheduling techniques focus on unicast transmissions, which poorly adapt to the broadcast periodical transmissions required by CAM/BSM packets. In some cases, such as [117], broadcast transmissions are supported by optimizing for the worst unicast channel between the transmitting vehicular UE and any of the intended receivers. It remains unclear, however, how precisely this is representative of the state of the channel. Furthermore, the basestation will need to constantly receive updates on the CSI of all the D2D links, which represents a further load for the radio channel.

Techniques that exploit the position of the UEs to assign them different channel resources provide a viable technique to achieve distributed coordination, which however is not free of issues. One of these is, as also discussed when dealing with SDMA, to find a proper way to partition the map, providing the best compromise between the number of partitions and the availability of channel resources to match them. Furthermore, optimized areas might require very precise positioning information, and cause collisions in case of errors in the position measurement.

The purpose of this work, is to overcome these limitations, by providing a LTE-based mechanism to support distributed, unsupervised, cross-cell and multi operator communications for road users to perform broadcast periodical communications. The focus of this work, as it will be discussed in detail in chapter 3, is on periodical broadcast safety messages, since event-driven messages are suitable for being transmitted vis the network (legacy LTE transmissions) as well as infotainment. Unicast D2D transmissions between vehicles, on the other hand, are already supported by the ProSe standard, as described in Appendix A.

3 ANALYSIS AND PROBLEM STATEMENT

In this chapter, we analyze the requirements and the challenges brought by vehicular communications, that need to be addressed while supporting them over LTE-D2D. We then present our solution, which is organized into two independent phases: *Resource Reservation*, treated in section 3.2, and *Distributed Scheduling*, as treated in section 3.3. They respectively serve the function of preparing the pool of channel resources to be reserved to V2X transmissions, and to provide SBS User Equipments (SBS-UEs) a mean to independently select which subset of said resources to utilize for each transmission.

3.1 SERVICE REQUIREMENTS AND CHALLENGES

Supporting vehicular safety communications via D2D communications underlying the cellular network proves to be particularly challenging task. Vehicular safety communications, in fact, have a distinct traffic pattern and network topology, which have been the subject of intensive research in the past decade. On the other hand, cellular systems such as LTE have a very well defined architecture, which was not designed to fit vehicular traffic. The first challenge stands in establishing a resource reservation procedure able to live in the intersection of these two worlds. Vehicular safety communications have the following communication requirements, which we state starting from the most critical one:

local broadcast transmissions - the purpose of vehicular safety transmissions is to convey awareness, which is the ability for a vehicle to detect the presence of, and be detected by, neighboring road users. To do so, status update messages are transmitted, which contain information about the transmitter's current position, speed, and heading. These messages are known as CAMs in the EU, and BSMs in the US. The area of interest of these messages is the proximity of their transmitters: their intended receivers are thus all of the neighboring road users that can possibly be reached. The most efficient way to do so, is by broadcast transmissions.

low latency - position, speed, and heading are quickly changing variables in vehicular networks. For this reason, the information contained in CAM / BSM becomes stale very quickly. Vehicular communications thus impose strict requirements in terms of end-to-end latency, which shall be minimized, in order for packets to be received as quickly after being generated as possible. Day one applications require end-to-end delay lower than 100 ms, while day 2 applications (such as platooning, or the CACC) aim at latency lower than 10 ms [5].

distributed operations - centralized scheduling is not suitable for vehicular safety transmissions. This derives directly from the local nature of the vehicular safety information: centralized scheduling algorithms, in fact, assume knowledge of the set of intended receivers of each packet. This however is very difficult to predetermine, as it is dependent on the transmitter's position, the surrounding traffic, and the geography of the location. It is thus fundamental for road users to be able to transmit CAMs/BSMs without the centralized management entity. Parameters such as transmission frequency and transmission power shall be selected by the transmitter locally, based on locally available information.

Furthermore, a centralized architecture is undesirable when it comes to safety critical requirements, since eNodeBs are single points of failure, which would prevent all the communications within their coverage area in case of technical issues.

periodical Machine Type Communications (MTC)-like transmissions - CAMs and BSMs contain the instantaneous state of their transmitter, which is very short-lived information. In order to maintain a high quality of awareness, these messages need to be transmitted periodically. The transmission rate is selected as a compromise between several constraints. It needs to be sufficiently high to enable accurate tracking of fast moving vehicles, but not too high to cause uncontrolled collisions when the network density increases. For these reasons, the periodicity ranges between a minimum of 1 Hz and a maximum of 10 Hz [123] for day 1 applications, according to the context: following EU specifications, in fact, it is envisioned to be constantly regulated by the Decentralized Congestion Control (DCC) as in [124]. Day 2 applications such as Highly Autonomous Driving (HAD) or platooning, which will require knowledge about the surrounding traffic with higher precision, will arguably require higher transmission rates, up to 20 Hz.

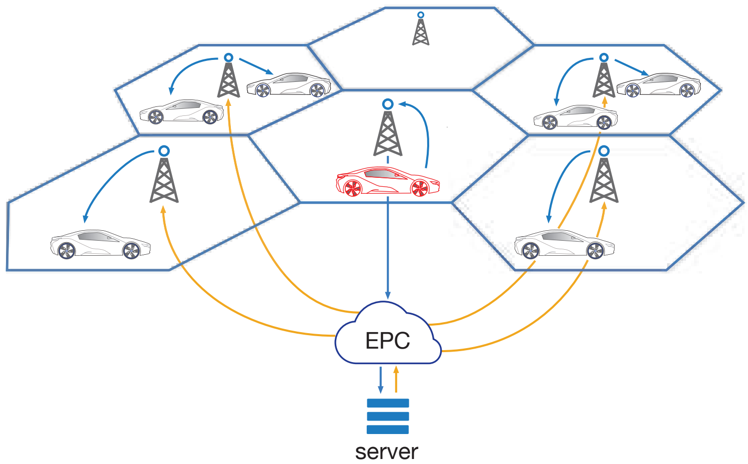
The aforementioned requirements, however, are not straightforward to be met within the LTE reference architecture, which is characterized by the following design constraints:

centralized architecture - in LTE, terminals must be subscribed, and maintain a connected state to the network infrastructure in order to be able to transmit; the scheduling procedure is strictly controlled by the basestation (named eNodeB in the LTE terminology). Transmissions performed by Path Losss (PLs) are unicast only, and happen only towards the eNodeB. Each transmission must thus pass through the core network (EPC) before reaching the endpoint, and must be authorized by the eNodeB via a scheduling grant.

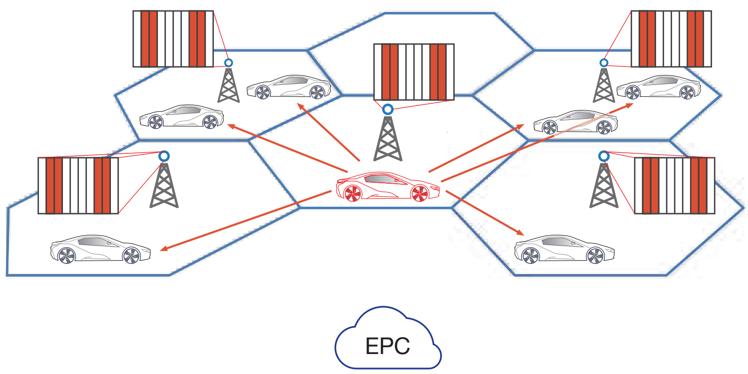
This procedure does not fit the vehicular safety requirements, as illustrated in the example of Figure 9a, which shows the path that a packet transmitted by a target TX (in red, in the middle) needs to cross before reaching its recipients, represented by the other vehicles in the surroundings. The packet needs to be transmitted on the UL channel to the eNodeB the TX is connected to. It then needs to cross the EPC up to when it reaches a dedicated server, which serves the purpose of determining to which other SBS-UEs the packet is meant for. The server needs then to create a copy of the packet for each of those, which needs to cross the EPC one more time up to the eNodeB to which the recipient is attached. The path is even longer when any of the recipients is subscribed to a different operator, and is particularly unsustainable for periodical, high frequency transmissions.

On the other hand, in Figure 9b a direct unsupervised system is illustrated. In it, a share pool of channel resources (highlighted in red, with the same resource pattern being allocated by all of the neighboring eNodeBs) is reserved. In this way, the data path does not cross the eNodeB.

cell-based resource management - in LTE, channel resources are allocated by the eNodeB on a per-transmission basis, via scheduling grants, and on a cell-basis. This is noticeable in Figure 9: in the connected case (Figure 9a), a dedicated set of unicast resources must be allocated by each eNodeB first in UL, then in DL once per each of the intended receivers, which results in an extremely inefficient utilization of channel resources. On the other hand, in this work we propose a unsupervised configuration (Figure 9b), wherein each packet is only broadcast once within the resource pool, without requiring dedicated scheduling from the network.



(a) Cell-based connected LTE operations



(b) Connection-less cross-cell LTE V2X

Figure 9 – Comparison of LTE operation modes: centralized, supervised, cell-based (9a) vs. distributed, unsupervised, cross-cell (9b)

3.2 RESOURCE RESERVATION

The resource reservation phase is performed by the network, with the purpose of dedicating a proper set of channel resources to support direct V2V, V2I, and V2P transmissions. In this section we present two reservation paradigms: the eMBMS-like, and Sidelink-based mechanisms.

Problem analysis

As previously mentioned, resource allocation for D2D communications underlying the LTE air interface is a complex issue, as it conceptually conflicts with LTE's eNodeB-centric structure. V2X communications, on the other hand, break this paradigm by enabling direct UE-to-UE data paths, which require a completely different approach to managing channel resources.

In the base architecture, all of the outgoing packets from a UE perspective are sent to the eNodeB via the UL channel, regardless of the location of the intended final receiver. Similarly, all of the transmissions incoming the UEs are channeled through the DL. In both cases, the eNodeB reserves a dedicated set of channel resources upon need.

The DL channel also supports multicast and broadcast transmissions, but are essentially equivalent to the network instructing multiple UEs, or groups thereof, to decode the same set of DL resources.

As a result of this structure, when in `RRC_CONNECTED` state, UEs tune their receiver front-end to the DL channel and the transmitter to the UL channel. UEs constantly monitor the DL control channel, where they receive from the basestation both the DCI that points to the DL transmissions directed to them, and the scheduling grants that point at the UL channel resources to be used for their transmissions. This paradigm represents a limitation for the introduction of D2D operations, for several reasons.

First of all, a common waveform is to be agreed on for D2D communications. As introduced in section 2.3.1, in fact, LTE adopts two different waveforms for DL and the UL, respectively OFDMA and SC-FDMA. It was established by the 3GPP to adopt the latter as a waveform for D2D since the definition of ProSe, namely because of its better peak to average power ratio. This means that the radio front end of the UEs needs to be modified to support D2D: in addition to the OFDMA receiver for the DL, and the SC-FDMA transmitter for the UL, UEs will require the installation of a SC-FDMA receiver for the SL.

Secondly, a UE-to-UE data path means that the receiving UE needs to tune its receiver to the transmitter's SL band: the RX hence needs to be made aware of the presence of the transmitter, and of its SL frequency band, before the communication can start. This is a non-trivial issue within the base architecture, especially in the case wherein the transmitter and the receiver are not subscribed to the same operator. The specification of the supervised mode of ProSe (which the 3GPP released while this thesis was on development) provides support for this scenario, albeit limited to unicast, burst-traffic transmissions. This can be observed in the architecture scheme in Figure 5, wherein the PC5 interface may connect ProSe-enabled UEs in proximity attached to different PLMNs. However, since the transmission is scheduled by the eNodeB to which the TX is attached, it will take place on the transmitter's SL band. The receiving UE thus needs to be instructed by its operator to tune into the SL channel of the transmitter, in order to be able to receive the control information and the subsequent data transmission. This is done following the procedure we described in Appendix A, wherein the full table of available frequency bands for ProSe can also be found.

This procedure, however, is not suitable the traffic pattern imposed by vehicular safety messages, which is neither bursty nor unicast, but is periodical and broadcast instead, with vehicular UEs continuously switching between being transmitters and receivers. The transmission range required by such applications can reach several hundred meters: this is particularly problematic because in high network density scenarios such as in cities, a single transmission is likely to reach multiple UEs attached to different eNodeBs belonging to different operators. At any point in time, it thus becomes really challenging to establish for each UE which band to tune into. To do so, it is furthermore required for UEs to already be aware of the presence of a transmitter: this however is a unreasonable assumption, since advertising the transmitter's presence to UEs in proximity is one of the reasons that CAMs/BSMs are transmitted in the first place. A network-based scheduler would require overly complex multi-operator coordination, force UEs to continuous frequency hops, and introduce scheduling delays of multiple milliseconds per packet, which cannot be afforded by delay sensitive safety critical messages.

For the aforementioned reasons, we claim that a network-supervised resource reservation, wherein a set of channel resources is assigned by each operator to the UEs subscribed to it, is extremely unpractical. We thus propose to use a unique channel for LTE V2X, which is exploited directly by all of the vehicular UEs, without needing the supervision of a network. In this way, we introduce LTE V2X as a new declination of LTE, similar to what 802.11p outside the context of the BSS represents to 802.11, illustrated in Table 6.

Table 6 – Parallelism: 802.11 OCB vs LTE V2X

802.11 OCB	LTE V2X
does not require an Access Point (AP) for communications	does not require a eNodeB for communications
no scanning to find the AP	no network coordination to find V2X channel
dedicated band (ITS 5.9 GHz)	dedicated pool of channel resources
No AP synchronization	Limited/absent eNodeB synchronization
Authentication and security delegated to upper layers	
Direct and dedicated communications between terminals, with no infrastructure involvement	

Despite the similarities, this process is more difficult for LTE than it is for 802.11: as opposed to it, in LTE resources are in fact managed by the network, and new standard extensions must be aware of it, in order to provide retro-compatibility. In LTE it is thus necessary to have a dedicated set of resources that is reserved by the network, but whose utilization is not supervised by it.

In order to enable its utilization for broadcast communications in a vehicular scenario, wherein users are spread over an area covered by different eNodeBs belonging to different PLMNs, we need to introduce a dedicated wide area for resource reservation, as described in the following section.

3.2.1 *Cross-cell wide area resource reservation*

One of the advantages of the LTE over 802.11-based technologies are the different transmission modes it supports, which can all be exploited in vehicular communications. Vehicle to Network (V2N) and V2I transmissions can be supported by legacy unicast UL and DL transmissions, which prove efficient in conveying infotainment traffic, mapping data, and DENM messages. Non-safety direct V2V messages can efficiently be supported by ProSe, described in detail in section 2.3.2 and in Appendix A. The purpose of this thesis is to address periodical safety messages, for which no efficient mechanism exists yet.

The first crucial step in enabling cellular-based broadcast cross-cell transmissions is the definition of a high-level safety service, which we will refer to as Safety Broadcast Service (SBS) from now on. The UEs which are subscribed to such service are denominated SBS-UEs. The SBS is offered on a wide area, covering multiple neighboring cells, which we denominate Safety Broadcast Area (SBA), as illustrated in Figure 10.

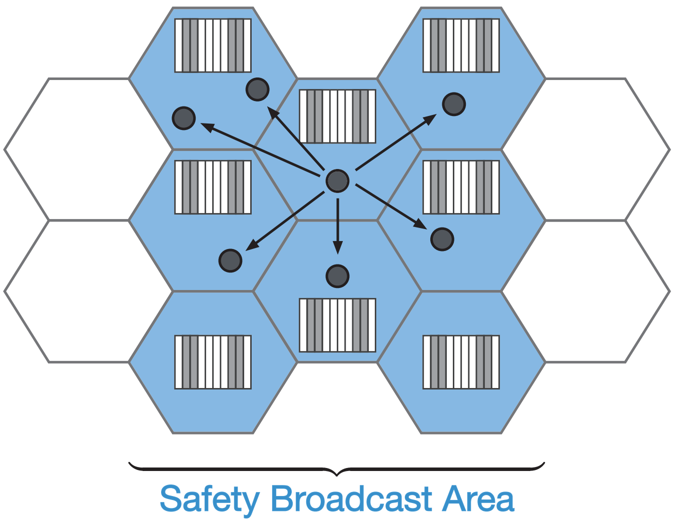


Figure 10 – Safety Broadcast Area. It is shown how a SBS-UE in the SBA can transmit broadcast messages to other SBS-UEs within the same area, but in the covering area of different cells. In the cells within the SBA a sample radio frame is illustrated, showing a constant set of resources, uniformly allocated all throughout the SBA.

Within the SBA, it is necessary to dedicate channel resources for SBS-UEs to be able to transmit safety messages. The reservation process must be carefully designed in order to comply with the requirements we identified in section 3.1. Broadcast transmissions, united with SBS-UEs being spread over multiple neighboring cells, require the same resources to be available for each transmitter on all the cells covered by its transmission range. The periodical and high transmission rate of safety messages, furthermore, united with the potentially very high number of concurrently transmitting users, make it really hard for the network to achieve the necessary level of coordination to reserve these resources on a per-transmission basis. Even if achievable, such coordination would come at the price a huge overhead for the network, and make the whole system dependent on it, which fails to comply with the distributed operations requirements that we previously defined. In this work, we hence claim that a semi-static resource reservation paradigm is necessary. This paradigm, is based on the definition of a *resource pool*, common to all the eNodeBs within the SBA, which is shared by all the SBS-UEs. We will also refer to this pool as SBS-pool.

The aim of this work is to make the reservation policy of the resource pool comply as closely as possible with the LTE standard. Furthermore, we propose a resource pool which consists in set of pre-determined resources periodical in time. The periodicity brings several benefits:

— it minimizes the signaling necessary for the network to communicate the coordinates of the resource pool to the SBS-UEs: RRC messages containing this information will in fact only be broadcast periodically. Furthermore, a SBS-UE needs to receive such information only once, until the time allocation pattern of the resource pool changes;

— it provides resilience to network failure, as a corollary to the previous point. In case of temporary absence of coverage, in fact, SBS-UEs which have already received the resource pool coordinates may be able to continue exploiting the same resources, assuming (reasonably) they have sufficiently accurate and stable time synchronization and frequency tuning. This applies both in case of eNodeB failure and when SBS-UEs move into areas outside coverage.

— it provides means to optimize the system's energy efficiency, by applying Discontinuous Transmission (DTx)/Discontinuous Reception (DRx). During radio frames that are not assigned to the resource pool, in fact, SBS-UEs can enter power saving mode, knowing exactly when to wake up again, at the occurrence of the next radio frame containing RBs reserved to the SBS pool.

In the following of this section, we will present in detail two different propositions made in the past years, the first based on eMBMS in section 3.2.3, while the second is based on the PC5 Sidelink, and is illustrated in section 3.2.4.

3.2.2 *Timeline of propositions*

The development of this thesis proceeded in parallel with the release, by the 3GPP, of technical reports and novel standard extensions to support vehicular communications. It is thus important for us to highlight the temporal timeline of our work, in order to highlight the fact that the propositions contained in this work preceded the release of similar concepts by the 3GPP. We first identified the need for a common resource pool dedicated to LTE V2X in October 2013 [19], then published it, along with the eMBMS-based resource reservation mechanism, in December 2013 [16]. The eMBMS allocation process was not adopted by the 3GPP.

The specification for the Sidelink were released with Release 12 of LTE, in March 2014 [44], and our proposition to adopt it for the support of V2X communications was first published in the research report [20], which dates a few months later, and its subsequent updates. The official support of LTE V2X using the SL was only publicly announced by the 3GPP in 2016 [56].

3.2.3 *eMBMS-like resource reservation*

We proposed the first resource reservation technique in 2013, when ProSe were in a early stage of their specification for unicast transmissions, and only started to consider broadcast communications, which were strictly reserved to public safety UEs. Said mechanism, first published in [16], is based on eMBMS. Despite not being suitable for D2D communications right away, eMBMS was at that time well defined and established in the LTE standard, and it provided the means to perform a multi-cell, periodical, semi-static resource allocation.

As a further benefit, eMBMS also provides a well desired retro-compatibility with Rel. 8 terminals. According to the standard, in fact, UEs continuously scan the channel for the Cell-Specific Reference Signals (CRS), the pilot signals used for DL demodulation as well as for determining the cell ID. Since eMBMS uses different pilot signals from the DL channel, UEs are pre-configured, since Rel. 8, not to scan for CRS in subframes reserved to eMBMS. A similar situation will apply when eMBMS is used to reserve resources for V2V transmissions, wherein the DL CRS are not needed, hence not transmitted. This will prevent non-SBS-UEs from trying to retrieve CRS from subframes used by V2V communications.

In the remainder of this section, an introduction to the basic principles of eMBMS is provided, to which follows a description of the adaptations needed for supporting V2V broadcast communications.

Introduction to eMBMS

eMBMS is the LTE implementation of the Multimedia Broadcast Multicast Service (MBMS) available since UMTS rel. 6, which allows the network to broadcast or multicast multimedia content over a wide area. eMBMS transmissions take place over a Multicast Broadcast Single Frequency Network (MBSFN), meaning that the set of resources dedicated to them has to be the constant all over the area of interest, as illustrated in figure 11. Inside each cell belonging to the eMBMS area, a sample LTE radio frame is depicted: the dashed subframes put into evidence the identical set of dedicated resources.

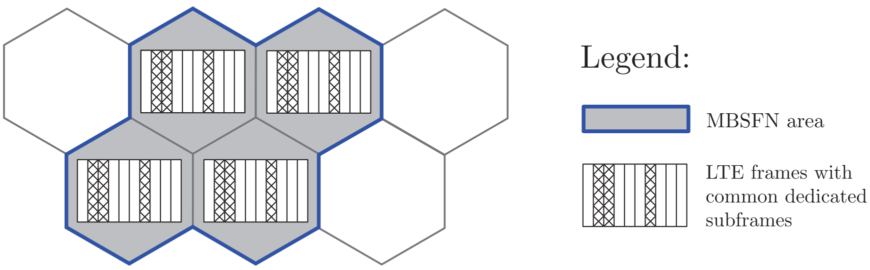


Figure 11 – MBSFN area over multiple cells with common allocated resources.

eNodeBs can allocate from 10% up to 50% (for TDD LTE) or 60% (for FDD) of their total DL resources to eMBMS. Within these resources up to 8 logical time multiplexed channels Multicast Channels (MCHs) (named MCH1 to MCH8) can coexist, each corresponding to a different multimedia content.

MCH channels are organized according to a periodic scheme as illustrated in figure 12.

The base period is the Common Subframe Allocation (CSA) which corresponds to the minimum time lapse during which all the services are scheduled, one after the other and without overlapping. CSA can be set from a minimum of 80 ms to a maximum of 10.24 s. In the example in Figure 12 it is set equal to 80 ms. Within the CSA period, services are time multiplexed according to the CSA pattern: in the figure, MCH1 occupies the first 3 frames of the CSA period, while MCH2 is assigned the following two.

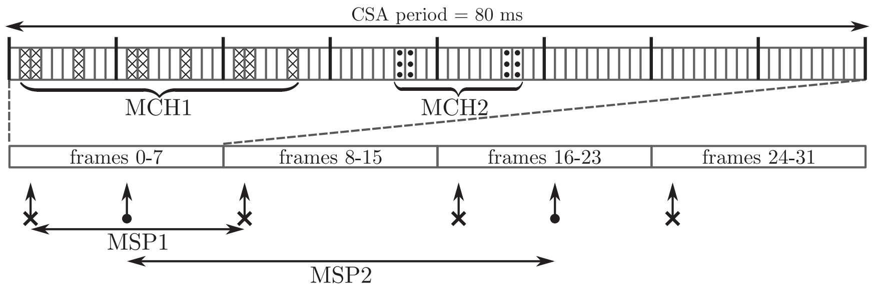


Figure 12 – Time distribution of eMBMS services.

The set of subframes to be assigned to a specific service is specified in the MCH Scheduling Information (MSI): in figure 12, MCH1 occupies three subframe (number 1,2,6 and) per frame, while MCH2 takes place over subframes 6 and 7.

The MCH Scheduling Period (MSP) defines the frequency of a given service: contents more demanding in terms of data rate may need to be scheduled in every CSA period, while less demanding ones can be allocated more sporadically.

UEs can acquire the location of the MCH channels by reading the SIB13 periodically transmitted by the eNodeBs. In Table 7 are listed the operations every UEs must perform to receive an eMBMS service of interest (for further details please refer to [41, chapter 15]).

Table 7 – UE procedure to receive an eMBMS service

1:	Synchronize to the eNodeB using Primary Synchronization Signal (PSS) and Secondary Synchronization Signal (SSS);
2:	Decode the Master Information Block (MIB), to find the location of SIBs;
3:	Read SIB13 to find the location of Multicast Channels;
4:	Receive the MCH of interest.

The most important aspect of the described procedure is that *no protocol procedure to set up a connection with the eNodeB is required*. Furthermore, since the resource allocation is uniform all over the MBSFN area, no handling of mobility by the network is necessary. These are the key points we aim to exploit to allocate resources for the broadcast LTE V2X transmissions.

eMBMS procedure for V2V

The technique we propose in this section is designed to exploit the resource reservation mechanism of eMBMS: it is evident however that some modifications are required to it, since the eMBMS service was in origin designed to support DL broadcast transmission. In eMBMS, in fact, the eNodeBs are the only transmitters and the UEs are the receivers. On the other hand, in our proposed system:

— **the eNodeB only reserves the resources, but does not transmit in them**: its purpose is in fact just to reserve a sub-set of the available resources. This is a fundamental difference withh classic eMBMS: in V2V, the eNodeB is never part of the data path; on the other hand, the set of the reserved resources will be considered by the SBS-UEs as a resource pool for direct V2X transmissions, which they will exploit by applying a distributed scheduling algorithm as discussed in section 3.2.6

— **V2V transmissions adopt LTE's UL waveform**: this is the case despite eMBMS allocating resources on the DL channel. It is in fact widely recognized that SC-FDMA is the reference choice for D2D communications, thanks to its better PAPR than OFDMA. This indeed implies that UEs need to be modified to also feature a SC-FDMA receiver;

— **the resource pool coordinates can be preloaded** in devices. Under the reasonable assumption that coordinates of the resource pool remain constant over time, the coordinates of the resource pool can be stored into devices rather than being periodically broadcast via SIB.

3.2.4 *Sidelink-based resource reservation*

Recently, the 3GPP has very rapidly progressed in issuing standard to support D2D communications, the keystone of which is the introduction of the PC5 interface, also known as Sidelink. Starting from 2015, the standard hence provided the tools for defining a direct D2D interface, which in the latest available version of the standard is limited to unicast transmissions supervised by the network. We provide information on the channel structure of the SL in section 2.3.2, and a comprehensive description of the available frequency bands and resource allocation mechanism for unicast transmissions in Appendix A.

While ProSe provides the flexibility to allocate the SBS-resource pool either *inband* or *outband*, as respectively illustrated in Figure 13a and 13b, in this work we will only consider the outband mode. Specifically, the SBS-pool can be allocated in the dedicated 5.9 GHz ITS band, which has recently been labeled by the 3GPP as the LTE band 47. This configuration brings several benefits:

— it does not require the reassignment of commercial UL resources;

— it allows the coexistence with other V2V communications technologies, such as 802.11p, by time sharing the channel, as illustrated in Figure 13b.

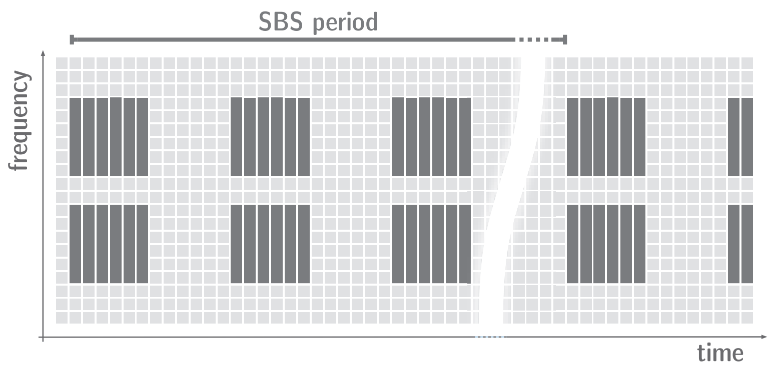
— it allows, when adopting a distributed scheduling technique, the coexistence of UEs subscribed to multiple operators.

Such allocation can happen following different patterns:
- — it can be done in the 5.9 GHz ITS band;
- — it can take place in a common, unlicensed ISM band;
- — it can partially exploit the commercial infrastructure (like for instance the 3.5 GHz LTE band) as an anchor for synchronization and the reception of broadcast information, and utilize the 5.9 GHz ITS band for the CAM/BSM transmissions.

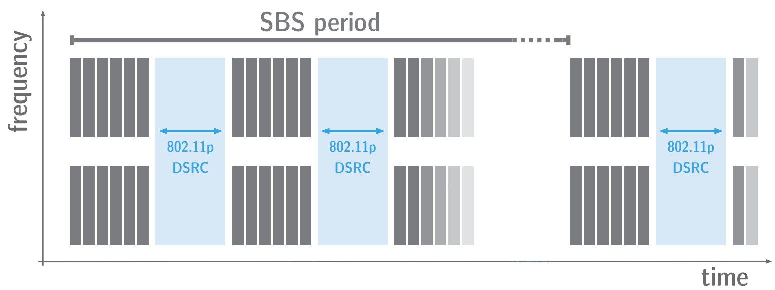
In the first two cases, the UEs operate in full ad-hoc mode, whereas in the third case, the network can be used as a fall back solution when the 5.9 GHz band is not available (due for instance to extreme congestion or malicious jamming).

Either way, resources are allocated following a periodical pattern, whose period we unsurprisingly refer to as SBS-period. The SBS-period determines the maximum transmission rate to be supported by the SBS: for instance, in order to achieve a standard maximum transmission rate of 10 Hz, it is convenient to set it equal to 100 ms. The same allocation pattern must indeed be followed by all of the eNodeB covering the SBA.

It is worth noting that the role of the installed network is again limited to the definition of the set of channel resources, and it is not part of the data path between SBS-UEs.



(a) Inband deployment: commercial UL band sharing



(b) Outband deployment: dedicated 5.9 GHz ITS band (LTE band 47)

Figure 13 – SBS resource pool reservation modes. The darkened RBPs are those assigned to the SBS resource pool.

Among the previously mentioned advantages brought by the outband mode, the last one is of particular relevance, as it allows to drop the unrealistic hypothesis, frequently found in literature, that all of the UEs are subscribed to the same operator.

3.2.5 *Synchronization*

Synchronization is an important challenge to be solved in V2V underlying the LTE air interface. In D2D-type communications, in fact, synchronization is a even more critical issue than in the legacy LTE architecture. First of all, UEs are normally all synchronized to the operator they are attached to. Most importantly, though, synchronization in cellular networks is a *"subjective"* matter, as the time reference is set by the basestation to which each UE is connected to. On the DL channel, in fact, the eNodeB is the only transmitter, and all of the UEs synchronize their receivers on the synchronization signals transmitted by it. The starting instant of each subframe, is thus perceived differently by each UE, as it depends on the propagation delay, which in turn depends on the geographical distance between it and the eNodeB. This issue is even more complicated on the UL channel, wherein the eNodeB is the only receiver, and the UEs are the transmitters. In this case, the UL transmissions must all be carefully timed, so that they all get to the eNodeB synchronized, and fitting the timing of the basestation. In order for this to happen, the eNodeB provides each UEs with a *timing advance*, which compensates for the propagation delay.

In V2V applications, however, each SBS-UE is in turn a transmitter and a receiver within the same resource pool. Hence, a unique time reference must be shared by all of the UEs. As it is illustrated in Figure 14, different operators' time references are likely to not be aligned to each other: for this reason, synchronization must be achieved from an external source shared by all of the UEs, independently from the operator they are subscribed to. We hence propose to achieve synchronization exploiting GNSS, similarly to ITS-G5, in which is fair to assume all of the SBS-UEs are equipped with. Synchronization issues might however happen in areas wherein the GNSS coverage is insufficient such as in urban canyons and tunnels. This can be partially solved by operators, by attaching to the proper SIB message a field containing the timing difference between the network timing and the SBS pool timing. The details of such procedure, as well as the solution for the problem in edge cases wherein neither the GNSS nor the cellular coverage are available, are outside the scope of this work. In the remainder of this work, we will assume the SBS-UEs are synchronized.

As illustrated in Figure 14, the start and end instants of the i^th batch of consecutive subframes, are respectively labeled as t_{si} and t_{ei}. These time instants must be pre-determined, and expressed as Coordinated Universal Time (UTC) time values, which operators will then broadcast via SIB message. In this way, SBS-UEs are able to switch from their operators' band to the ITS band at the right time, as illustrated in Figure 15. Furthermore, since operators know the SBS-pool allocation pattern and the timing mismatch between it and their network, they can also retrieve the subframes during which SBS-UEs will be tuned to the ITS band. In this way, they are aware that legacy DL transmissions directed to SBS-UEs must take place in the time subframes where they need not to be tuned to the ITS band. On the other hand, if no DL transmission is scheduled for a given SBS-UE, it may enter idle mode to save energy.

The ideal characteristics of the subframe allocation pattern for the SBS-pool are to be investigated in a future work.

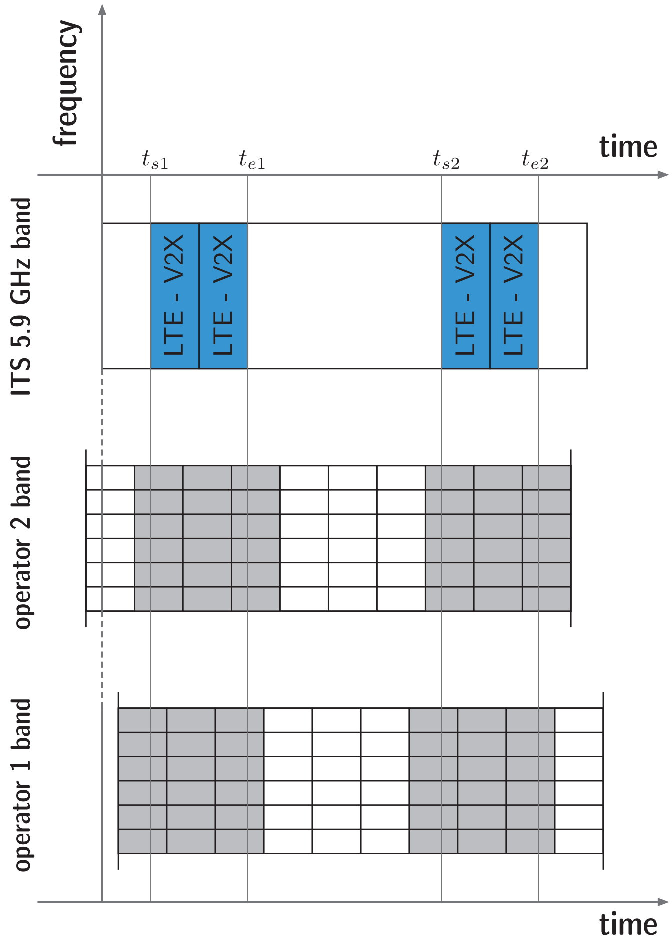


Figure 14 – Outband SBS resource pool: pan operator synchronization. It is shown how the stating time instants of each subframe are not aligned between different operators, and are not aligned to the subframes in the SBS pool. Within the operators' bands, the subframes that are co-located in time with the subframes belonging to the SBS-pool are highlighted in gray. A transceiver supporting both bands will thus only be able to tune to one of these bands at any give time.

3.2.6 *Resource pool partitioning*

Once the SBS resource pool is defined, SBS-UEs need to be able to efficiently exploit it for the transmission of CAM/BSM messages. The first step in doing this is to partition of the SBS resource pool into a pattern of packet-slots (or simply "slots"[1]), as illustrated in Figure 16. A packet slot is a continuous collection of RBPs within the same subframe, whose size is sufficient to host a CAM or a BSM packet. In the figure, L denotes the number of packet-slots available per SBS period. As it will be discussed in the next chapter, the value of L depends on parameters such as modulation and coding scheme chosen, channel bandwidth, and on N_{SBS}, the number subframes allocated to the SBS resource pool within the period.

1. In LTE terminology, the term *"slot"* indicates a 0.5 ms time division (cfr. Figure in section 2.3.1), which is never used in this work. We will thus use the word "slot" in its connotation of base element for a slotted MAC protocol

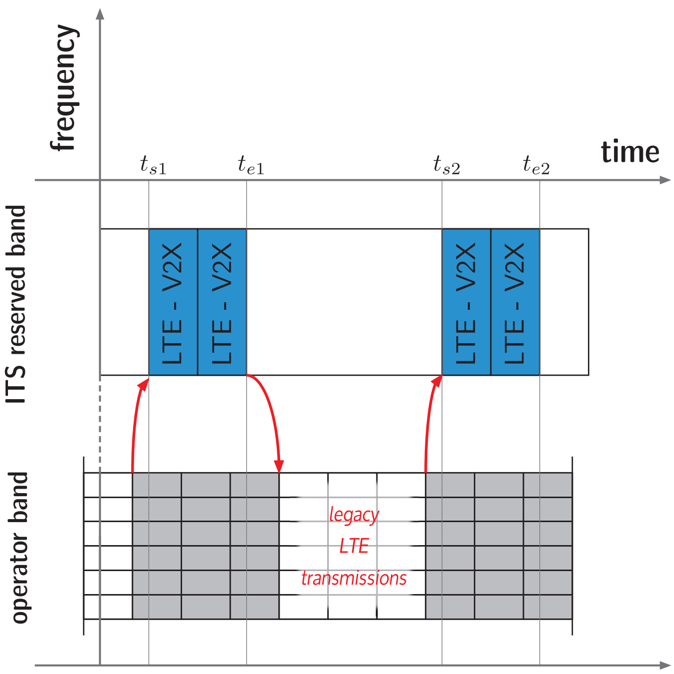


Figure 15 – Distributed Allocation: OOC-based access to slots

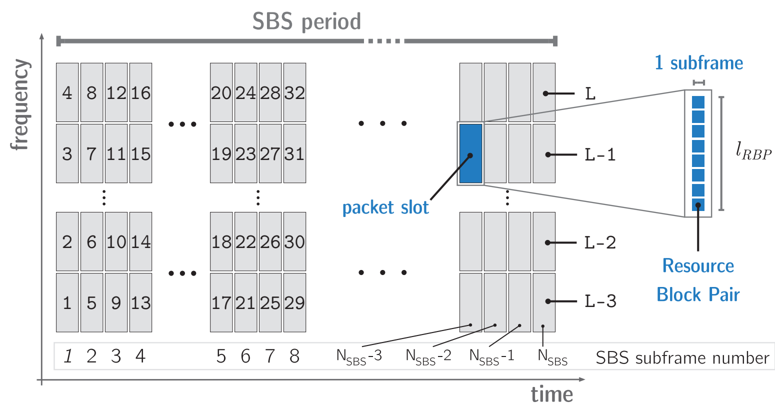


Figure 16 – Partition of the SBS resource pool into packet-slots

The assumption of SBS-UEs being synchronized, allows all of them to have aligned SBS-periods, i.e. the starting instant of a period is the same for all of the SBS-UEs. In this way, all of them can partition the SBS resource pool in the same way, which results in each packet-slot (labeled with a number from 1 to L in Figure 16) perfectly overlapping for all of the users. The most important result of this process is the fact that the channel access in LTE-V2X is now reduced to a TDMA-like resource access problem, which is an already well known problem in literature. The specification TDMA-like is necessary due to the slots not only being distributed in the time dimension, but also in frequency, the effects of which will be evaluated and discussed in the remainder of this thesis.

Half duplex impairment

The large bandwidths (up to 20 Mhz) and the high spectral efficiency provided by LTE, allow for multiple packet-slots to be stacked within the same subframe. This clearly benefits the system, as it allows for either large number of available slots, or relatively lower amounts of slots, but concentrated into fewer subframes. This allows the SBS resource pool to occupy fewer subframes, hence allowing the SBS-UE to enter longer idle periods, saving power. On the other hand, current technology limits us on the fact that SBS-UEs can only operate on Half Duplex mode, which means that at any given time (i.e. in any given subframe) they can either be in TX or in RX mode. This means that, when transmitting a packet in a packet slot, a SBS-UE cannot receive transmissions that occur in slots located in the same subframe. This is an impairment that must be dealt with; the evaluation of its effects, as well as propositions to mitigate it will be presented in chapter 4. However, in the next paragraph it will be shown how the partitioning function may have deep influence on the entity of the HD impairment.

On the composition of packet-slots

Figure 17 illustrates different possible setups that can be obtained when partitioning the SBS-pool in order to form packet-slots. Specifically, three different configurations are shown, wherein each packet slots is composed by 8 RBPs, each represented by a colored square. Every configuration partitions the same set of of 4 subframes [2].

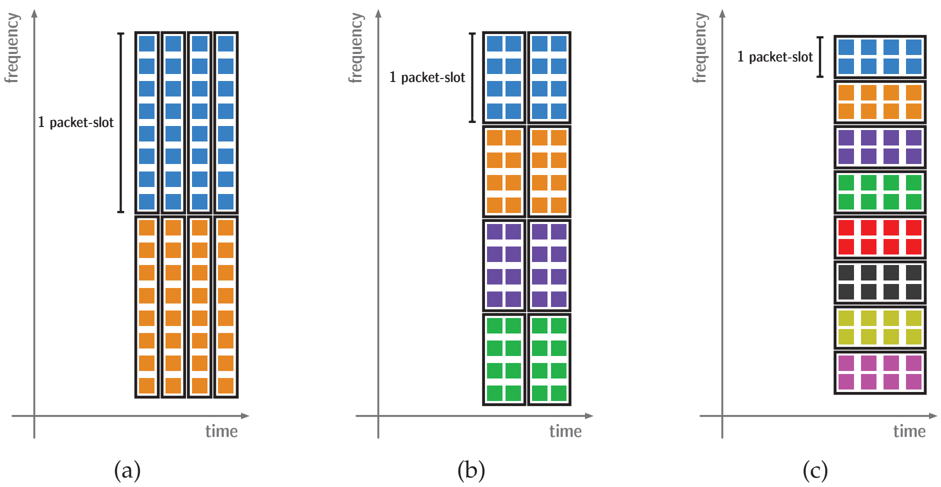


Figure 17 – Partition of the SBS resource pool into packet-slots: time vs. frequency disposition

Despite all of them managing to allocate the same number (8) of packet-slots within the same set of channel resources, their time-frequency disposition deeply affects the receiving performance. Due to half duplex constraint in fact, a SBS-UE transmitting in a subframe, cannot receive packets transmitted in other slots located within the same subframe. This is represented with different colors in Figure 17, where the PRBs forming the same packet-slot are surrounded by a black line. A SBS-UE transmitting in one of these packet-slots cannot receive the packet slots with different colors that are within the same subframe(s) it occupies.

2. please note that Figure 17 only serves a illustration function, as it does not represent an actual standard LTE bandwidth

In case 17a, slots are formed by PRBs all belonging to the same subframe, whereas in cases 17b and 17c they respectively span over 2 and 4 subframes. Despite the number of available slots remaining the same, the number of receivable slots does not. In fact, while in case 17a a SBS-UE transmitting in one slot loses one slot due to HD impairment, in cases 17b and 17c it would lose 3 of them, and all of the remaining 7 respectively.

3.3 DISTRIBUTED SCHEDULING

Once the SBS resource pool is defined, and partitioned into packet-slots, a mechanism is needed for SBS-UEs to access them in a decentralized fashion. In this work, we analyze two different techniques, and how they do behave in the LTE V2X channel we defined earlier on this section.

In the decentralized system we are proposing, the scheduling role is taken away from the eNodeB and distributed to the SBS-UEs. While providing all the advantages we discussed in detail in section 3.1, it poses a series of challenges: first of all, since SBS-UEs cannot have a global view as the eNodeB has, thus the allocation will be subject to collisions. It will hence be the SBS-UEs' duty to mitigate their negative effects, by adopting proper scheduling choices and controlling the transmission power: these aspects are the subject of the remainder of this chapter.

In [56], the 3GPP identifies three different types of channel access algorithms, which are proven to be provide gain, namely *collision avoidance based on sensing* (labeled as "P1"), *enhanced random resource selection* ("P2"), and *location-based resource selection* ("P3").

System based on *collision avoidance based on sensing* adopt CSMA types of channel access, which are unsuitable in synchronous systems such as LTE, although they can be found in the standard, for instance in the parts regarding Licensed Assisted Access (LAA). LAA is the LTE standard extension to allow LTE-based scheduled transmissions in unlicensed ISM bands [125]. In order to be able to access unlicensed bands, eNodeBs need to apply a CSMA/CA-like Listen Before Talk mechanism as specified in [46, §15], in order to coexist with other LBT-based channel access technologies such as 802.11. However, LTE transmissions are bound to start in correspondence of the start of a subframe [126]. This is challenging, since subframe start every millisecond, whereas 802.11 slots are in the microsecond order of magnitude. At the current state of specification, LAA transmission thus require the eNodeB to transmit a "reservation signal" once it completes the contention process. This signal serves the purpose of freezing the contention process of other competing terminal until the start of the next following subframe. While serving the purpose, reservation signals degrade the channel utilization efficiency. Techniques are being proposed to improve this aspect, such as modified frame structures as mentioned in [126]. However, this technique is designed for burst traffic, and poorly adapts to periodical, high rate transmissions such as the ones we consider in this work: for this reason, we ruled it out.

In the remainder of this section, we thus present two channel access mechanisms, each belonging to one of the two remaining paradigms. The first, in section 3.4, is based on Optical Orthogonal Codes (OOC), an *enhanced random resource selection*, wherein SBS-UEs blindly access the channel. Reliability and improved reception performance are provided by the intrinsic mathematical properties of the OOC codewords.

The latter technique, treated in section 3.5, is Self Organizing TDMA, which belongs to the P3 *location-based resource selection* category. STDMA is a reservation-based channel access scheme wherein terminals choose their transmission slots based on the choices made by concurrent users, which they can learn from the reservation information which is attached to each transmitted packet. The location-based dimension of STDMA lives in the way it handles high channel load scenarios, wherein, in case of lack of free slots to transmit in, users choose to cause a "controlled collision" with the transmission of the user located the farther away.

3.4 OPTICAL ORTHOGONAL CODES (OOC)

The solution proposed in this work and in [16] for the distributed allocation is based on Optical Orthogonal Codes [127], a multiple access technique that improves delivery reliability by having SBS-UEs perform multiple retransmissions of the same CAM/BSM message per SBS-period. The principle of reliability via retransmissions was already investigated in [128] in 2004, at the very early stages of research on vehicular communications.

OOC are sets of binary codewords (i.e. {0,1} sequences), that have already being investigated as a mechanism to regulate channel access [129, 130]. The definition, properties, and algorithm for their generation are described in detail in [127]. The most important property of OOC is that the correlation between pairs of codewords belonging to the same set is limited to a threshold value denoted with λ. Hence, considering any couple of codewords u and v, L bits long, belonging to the same OOC set, (1) holds true:

$$\sum_{j=1}^{L} u_j \cdot v_j \leq \lambda \quad \forall u \neq v. \tag{1}$$

Similarly to [129], the values of the bits of OOC codewords are associated to transceiver states: 0 bits correspond to the UE's RX mode, whereas 1 bits are related to the UE's TX mode. Before the beginning of each SBS period, SBS-UEs shall generate an L-bits long OOC codeword. Each of the bits is then associated in order to the slot in the same position within the SBS-period: the SBS-UE then transmits a packet in each of the slots corresponding to "1" bits, and sets itself in RX mode during all the slots associated to "0" bits, as illustrated in Figure 18. The Hamming weight w of the codewords corresponds to the number of retransmissions performed by the SBS-UE per SBS-period (which, for the scope of this work, we will assume being w exact replicas of the same packet), while λ is the maximum number of collisions that can happen, during a SBS period, between pairs of users within TX/RX range [3]. From a practical standpoint, this means that any couple of codes from a OOC codeset have at most λ "1s" in the same position. This means that any pair of transmitters can at most collide in λ out of their w transmission slots. By properly choosing

3. excluding the case in which multiple SBS-UEs generate the same codeword in the same SBS period. In this work we will focus on scenarios wherein parameters are such that this event is highly improbable, thus we will not consider it

$\lambda < w$, this property provides a boost in reception probability. As a matter of fact however, this property limits the number of codewords that can belong to the same OOC codeset, according to the choice of parameters L, λ and w: a closed-form expression to find the exact number is not available, although upper bounds can be computed, as described in [130].

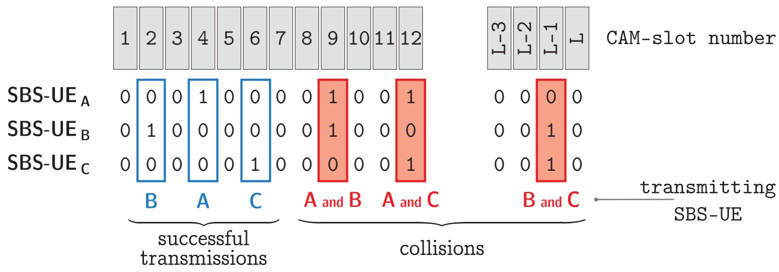


Figure 18 – Distributed Allocation: OOC-based access to slots

Figure 18 illustrates a basic example of the channel access mechanism, for a basic scenario with 3 SBS-UEs A, B, and C within respective TX/RX range, wherein $w = 3$ and $\lambda = 1$. Every SBS-UE thus transmits within 3 slots per period, and it collides at most in one of them with each of the other SBS-UEs. It can be observed that when only one of the SBS-UEs within respective range transmits in one slot, the transmission is successful. On the other hand, when multiple SBS-UEs independently select the same slot, a collision occurs. In this scenario, the properties of OOCs codes help by increasing the probability that at most one of the transmissions is successfully received, as evaluated in section 4.1.1.

3.5 SELF-ORGANIZING TDMA

STDMA is a MAC-layer distributed protocol that enables users to transmit periodical messages with a given transmission rate. To accomplish this, it adopts a slotted channel approach and a slot reservation system, wherein terminals reserve the slots for their transmissions. This reservation is made by keeping into account the slots reserved by other terminals in proximity, with the objective of minimizing the collisions that would lead to reception losses.

3.5.1 *Related Work*

STDMA is already commercially adopted for periodical position reporting in shipping [131] (with the name Automatic Identification System (AIS)) and airline [132] industries. Given its effectiveness proven on the field, and thanks to extensive research works such as [90] and [133], the ETSI considered STDMA as an alternate to CSMA/CA [91]. Numerous research studies have recently focused on STDMA, which has shown many properties desirable for safety-critical communications due to its synchronized nature. In [134], Sjöberg et al. show that STDMA offers better performances than 802.11p in terms of Packet Reception Probability (PRR), regardless of the presence of hidden terminals. In [99], the same authors also highlight the increased scalability of STDMA with respect to 802.11p, thanks to its virtual immunity against undesired packet collisions due to concurrent transmissions.

Another fundamental property of STDMA is the deterministic channel access delay, which is a quantity that in 802.11p could grow unbounded in highly loaded scenarios. In [133] Alonso and Mecklenbräuker study the stabilization time of STDMA, which is the time necessary for the protocol to reach a stable performance. 802.11p achieves better stabilization time than STDMA in lightly loaded scenarios, but it increases with growing channel loads, whereas STDMA offers stable performances in high density networks. On the other hand, Gaugel et al. [100] recently conducted an in-depth evaluation study of the structure of STDMA, showing that it offers better performance than 802.11p's CSMA/CA only in ideal scenarios, in which transmissions are not heavily affected by propagation induced errors. In [101], they further show that the superiority of any of the two protocol over the other is dependent on the considered scenarios.

All of the works currently available, including those cited in this section, analyze STDMA by means of simulation, hence subject to artifacts caused by the simulation scenario. A detailed, scenario-independent analytical study of STDMA would help understanding how every aspect of the protocol theoretically affects its performances. It is however still missing in literature, and is therefore the subject of this work.

3.5.2 *Protocol description*

STDMA is a slotted structured access mechanism, in which channel resources are organized into slots, each with time duration and bandwidth adequate to host a fixed size packet. For the purpose of this work, we consider CAMs packets [11], periodically transmitted by vehicles to report their instantaneous state, which includes position, speed and heading. The objective is for each terminal to transmit r CAM packets per second, where r stands for "report rate". The value of r can be individually decided by each user, according to its application needs. The flexible structure of STDMA enables the effortless coexistence of terminals with different report rates.

In order to support periodical message transmissions, the STDMA medium access policy based on periodical pattern, wherein all the slots within a predetermined time window are organized into a *frame*, as illustrated in Figure 19.

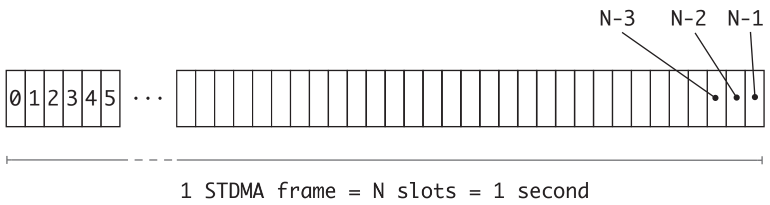


Figure 19 – STDMA: channel organization into slots and frames

Frames are repeated periodically, and have a duration of 1 second in vehicular applications [131], which are those considered in this thesis[4]. We refer

4. For reference, in shipborne applications (AIS) frames have a longer duration, equal to 1 minute.

to N as the number of slots that can be hosted within a frame. The value of N depends on the packet size and on the transmission parameters such as the modulation and coding scheme, and the bandwidth, which determine the available capacity. It is assumed that terminals, which from now on we will refer to as UEs to conform with LTE nomenclature, are slot synchronous, meaning that the starting and ending moment of each slot must be aligned for all UEs. Such time alignment can be achieved, for instance, with GNSS, which is fair to assume every transmitter is equipped with. Frame synchronization, on the other hand, is not required.

Protocol goal

The STDMA protocol is based on a slot reservation mechanism, in which all of the transceivers are assumed to be in turn transmitters and receivers. The final goal of the protocol is illustrated in Figure 20, which shows a sample one-second frame. In it, the transmitter allocates r slots ($r = 4$ in this very example)

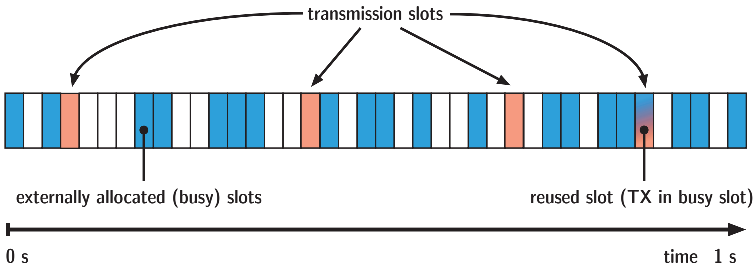


Figure 20 – STDMA: periodical transmission goal

for its CAM packets transmissions, approximately evenly distributed in time. The figure also illustrates how these transmission efficiently slots alternate in time with externally allocated slots, which are slots which the current terminal knows will be used for transmissions by other terminal within radio range. A reused slot is also shown: this represents the case wherein the current terminal willingly decides to allocate as a transmission slot one that is already being used by another user.

The procedure that each user needs to go through, after being started up, to achieve this goal, is articulated into the following 4 phases, which need to be performed in the order:

1. the **initialization phase**, during which the UE senses the state of the channel for exactly one frame duration, and builds an internal map representing which of the slots are already being allocated by other UEs;
2. the **network entry phase**, a short phase (less than one frame) during which the UE performs a one-time transmission of a special packet, to inform other UEs of the fact it is joining the network;
3. the **first frame phase**, during which the UE performs the first reservation of its r transmission slots in the first frame;
4. and finally the **continuous operations phase**, representing the steady state of the protocol, during which the UE utilizes the slots previously reserved for transmitting CAMs. Furthermore, in order to mitigate the

effect of merging collisions, the position of the transmission slots is periodically changed.

All the phases will be described in detail in the following of this section. For reference, the system parameters, along with their description, are summarized in Table 8.

Table 8 – STDMA system parameters: [131, Table 16, §3.3.4.4.2]

Symbol	Name	Description
Nominal Starting Slot (NSS)	Nominal Starting Slot	Slot around which is built the Selection Interval (SI) for the first Nominal Transmission Slot (NTS)
Nominal Slot (NS)	Nominal Slot	lot around which is built the SI for any NTS subsequent the first; NSS is, as a matter of fact, the first NS
Nominal Increment (NI)	Nominal Increment	Ideal inter-distance (in slots) between two consecutive transmissions. It is equal to the ratio between the number N of available slots per frame and the Report Rate (Rr)
r	Report Rate	Number of transmissions per second the current UE needs to perform
SI	Selection Interval	The set of slots surrounding the NTS or the NSs among which slots that compose the candidate set are chosen
NTS	Nominal Transmission Slot	The slot chosen by the UE to perform a packet transmission
t_{min}	Minimum timeout	Minimum value to which the timeout counter can be initialized
t_{max}	Maximum timeout	Maximum value to which the timeout counter can be initialized
w_{CSmin}	Minimum candidate set size	Minimum number of slots that need to be inserted in a candidate set
w_{CSne}	Number of slots in the candidate set for the network entry	Minimum number of slots that need to be inserted in the candidate set for the transmission of the Network Entry Packet

The initialization phase

The first phase UEs enter is the *initialization phase*, during which they listen to the channel for one entire frame. Since no frame synchronization is required, the starting point is random, and purely dictated by the instant of each UE's startup. In this process, the state of each slot is registered into an internal map. The possible states defined in [131] are:

— **Free**: the current slot is not used by any other UE within range;
— **Externally Allocated**: the current slot is used or reserved for transmission by another UE within range;
— **Internally Allocated**: the current slot is used or reserved for transmission by the current UE.
— **Unavailable**: a power level is detected higher than a given CCA threshold, but no information could be correctly decoded. This situation typically happens when multiple packets from UEs within range of the current UE collide, and the Signal to Interference and Noise Ratio (SINR) of either is too low to decode it. This state, which is not listed in [131] but proposed in [100], is necessary for implementation purpose.

Needless to say, internally allocated slots will not be encountered in the initialization phase, since none of them has been scheduled yet.

In Figure 21 a sample scenario is illustrated, wherein the *free* slots are in white, and the slots detected to be *externally allocated* are shaded in light blue. The initialization phase terminates when all of the N slots have been listened to, and a state has been assigned to each of them. Once this is done, the UE switches to the following phase, the *network entry phase*

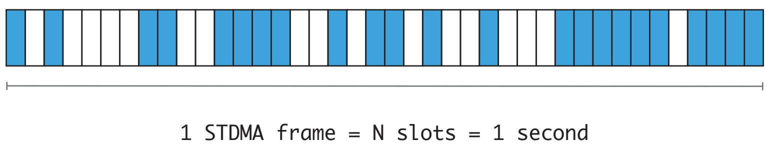


Figure 21 – STDMA: initialization phase. *Free* slots are colored in white, whereas **externally allocated** slots are shaded in light blue.

The network entry phase

The purpose of the network entry phase is for the current UE to transmit a Network Entry Packet (NEP), a one time special transmission to inform all the other UEs within range that it is about to join the network. The slot for the transmission of the NEP is chosen using a p-persistent mechanism based on the Random Access Time-Division Multiple Access (RATDMA) protocol, which is mandated *"when a station needs to allocate a slot, which has not been pre-announced"* [131]. The procedure is the following:

1. a candidate set is compiled, including all of the free slots among the first w_{CSne} slots, where w_{CSne} stands for the width of the candidate set for the network entry.

2. when in correspondence of the k^{th} slots belonging to the candidate set, the UE decides whether to transmit the network entry packet in that slot with probability $p(k)$, which is computed as in (2).

$$p(k) = \frac{k}{w_{CSne}} \quad (2)$$

This step is repeated until a transmission slot for the NEP is successfully chosen.

Before transmitting the NEP, the terminal needs to first select the location of the first of its NTSs, i.e. the slot wherein the first CAM packet will be transmitted. In this way, the time offset to it can be included into the NEP, which will thus inform other UEs in the network both of the presence of a new terminal and of the position of its first transmission slot.

The procedure to select the first NTS (the number 0), is the following:

1. a Nominal Interval (NI) is defined as $NI = \lfloor N/r \rfloor$, where r is the Report Rate, i.e. the number of transmissions that a terminal needs to perform per second. The NI represents the ideal interval between two consecutive transmitted packets;

2. a Nominal starting Slot (NSS) is randomly chosen among the free slots within the first NI ones. We denote this slot as σ_{nss};

3. a Selection Interval (SI) is defined as the set of all the slots around the NSS: its cardinality is determined by the parameter s, which represents the ratio between the width of the SI and the one of the NI, with $0 < s \leq 1$. Denoting with $\sigma_0, \ldots, \sigma_{N-1}$ the slots within each frame as numbered by the current terminal, the set of the slots belonging to the first SI (hence, with index 0) is given by (3), and illustrated in Figure 22.

$$\begin{aligned} SI_0 = \left\{ \sigma_{(j \mod N)} \right\}, \quad \text{where:} \\ \sigma_{nss} - \left\lfloor \frac{N}{2r} s \right\rfloor \quad \leq \quad j \quad \leq \quad \sigma_{nss} + \left\lfloor \frac{N}{2r} s \right\rfloor \end{aligned} \quad (3)$$

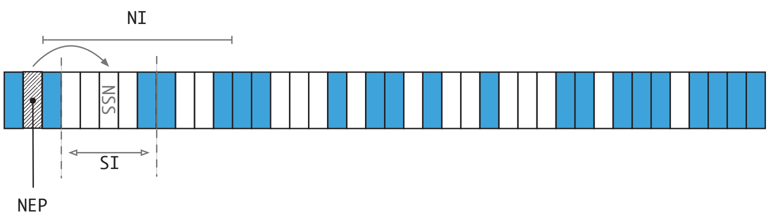


Figure 22 – STDMA: network entry phase: choice of the NEP slot and of the NSS. *Free* slots are colored in white, whereas *externally allocated* slots are shaded in light blue.

The parameter s is fixed to a value equal to 0.2 in AIS, whereas it is a variable system parameter for vehicular applications (see [100]).

4. within the so-defined selection interval, a candidate set is compiled, according to the following rules (and illustrated in Figure 23):
— *free* slots are automatically included in the candidate set;

— the minimum size for the candidate set is w_{CSmin}. If less than w_{CSmin} free slots are available in the SI, a suitable number of *externally allocated* ones must be included in the candidate set. These are selected starting from the ones allocated by the users more distant from the current transmitter;

— the designated slot for the first packet transmission, which we mark as σ_{nts_0} , is randomly chosen from the ones in the candidate set with uniform probability, regardless of its state.

In case the NTS is an externally allocated slot, the current terminal will not be able to reuse slots allocated by that same user in the current frame. For this reason, in [131] §3.1.6 the states *available* and *unavailable* for externally allocated slots are defined.

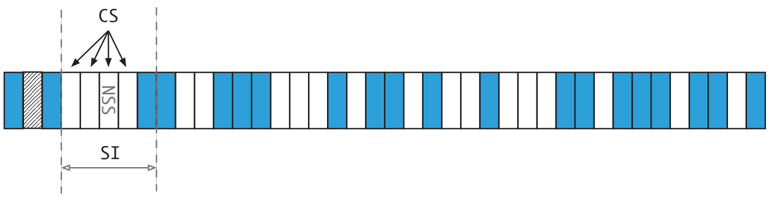


Figure 23 – STDMA, network entry phase: SI and candidate set compilation. *Free* slots are colored in white, *externally allocated* slots are shaded in light blue, and the NEP slot is filled with a dash pattern.

Finally, the UE transmits the NEP, to which it appends the offset between σ_{nep} (the next slot), and the σ_{nts_0}, as in Fig 24, where the offset is set equal to 2 slots. The UE subsequently waits for the σ_{nts_0}, then moves to the next phase, the *first frame phase*.

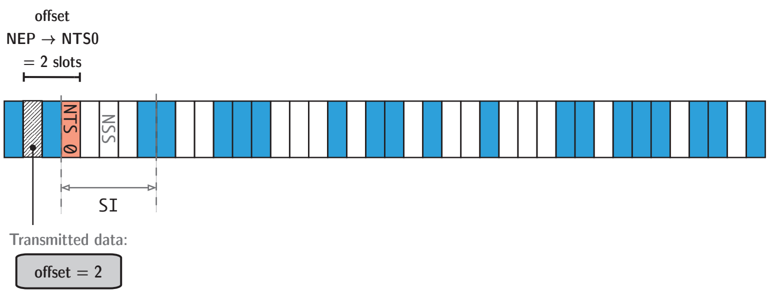


Figure 24 – STDMA, network entry phase: NTS selection and NEP transmission. *Free* slots are colored in white, *externally allocated* slots are shaded in light blue, the NTS 0 is shaded in red, and the NEP slot is filled with a dash pattern.

The first frame phase

The purpose of this phase is the reservation of the remaining $r-1$ NTSs beside the first one (NTS 0, reserved in the previous phase), in order to eventually allocate r transmission slots per frame.

The procedure to reserve NTS $i+1$ must be performed before transmitting the packet in the NTS i, in order to be able to include the reservation information related to NTS $i+1$ in it. This information includes two parameters, as illustrated in Figure 25:

1. the **offset** (in slots) between NTS i and NTS $i+1$;
2. the **timeout** t_i related to NTS i.

The offset indicates the number of slots that separates NTS $i+1$ from NTS i. The timeout value represents the number of consecutive frames for which a NTS occupies one given slot. STDMA, in fact, is designed for highly mobile terminal: the slots chosen as NTSs need thus to be periodically changed, in order to avoid merging collisions. In order for this to happen, each terminal associates one timeout counter to every NTS, which is initialized with a random integer value picked between t_{min} and t_{max}. Typical (ETSI standard) values are $t_{min} = 3$ and $t_{max} = 7$. This means that after using a slot as NTS for between 3 and 7 second, the reservation procedure must be repeated, and a new slot chosen to carry that NTS.

In order to reserve the next NTS, a procedure very similar to the one applied for NTS 0 is to be applied:

1. select a NS 1, NI slots after the NSS;
2. construct a SI around the NS, defined as:

$$SI_1 = \left\{\sigma_{(j \mod N)}\right\}, \quad \text{where:}$$
$$\sigma_{nss} + NI - \left\lfloor \frac{N}{2r} s \right\rfloor \leq j \leq \sigma_{nss} + NI + \left\lfloor \frac{N}{2r} s \right\rfloor \tag{4}$$

3. compile a candidate set from the slots within the SI following the same procedure as for the reservation of the first NTS in the network entry phase.
4. select the NTS #1 randomly among the slots within the candidate set

The packet in NTS # 0 is finally transmitted, containing:

— the timeout t_0 for NTS # 0
— the offset (in slots) between NTS # 0 and NTS # 1

These pieces of data will inform all the users receiving the CAM packet in NTS # 0 that that slot will be *externally allocated* for the next t_0 frames, and that the slot wherein NTS # 1 has been allocated will be as well, albeit for an unknown (for the moment) number of consecutive frames.

The procedure illustrated above is then repeated until all the r NTS have been successfully allocated, as illustrated in Figure 25.

In Figure 25 the reservation information transmitted in each of the NTSs is shown, specifically the timeout and the offset.

Once this is done, the UE moves to the *continuous operations phase*.

The continuous operations phase

The continuous operations phase represents the steady state of the STDMA protocol: terminals will stay in it indefinitely after they reach it. In this phase, terminals perform their r transmissions per frame in their previously allocated NTSs, and continuously listen to the channel. This is done in order to maintain the internal representation of the slots' states updated, which is a piece of information necessary to perform re-reservations. A re-reservation is the process with which a terminal selects and allocates a new slot for one of its NTS, after it has used it for a certain number of consecutive frames indicated by

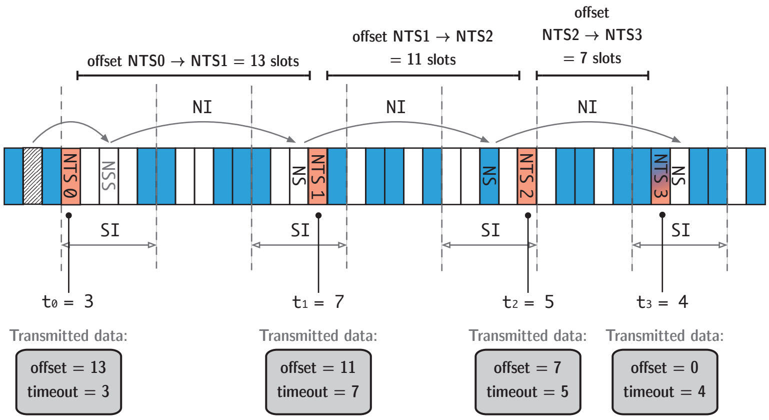


Figure 25 – STDMA, first frame phase: first reservation of the NTSs. *Free* slots are colored in white, *externally allocated* slots are shaded in light blue and the NTSs are shaded in red. In this specific example case, NTS #3 is shaded in both red and light blue, as it is a NTS located on a externally allocated slot.

the timeout value associated to each NTS. This operation is necessary to mitigate the effect of merging collisions, by making the NTS assignment change periodically. The re-reservation process is illustrated in Figure 26, and will be described in the following.

Figure 26 illustrates 6 frames stacked vertically, with the time axis continuing to the left side of the page after each of them. The first of these represents the internal state of a transmitter in the *first frame phase*, whereas the following 5 ones are the first 5 frames of the continuous operation phase. We consider the basic scenario (as for the previous phases) wherein each frame is made up of $L = 40$ slots, and the considered terminal must transmit $r = 4$ packets. Hence, the allocation of 4 NTSs is required, which we labeled as NTS 0 to NTS 3.

In the first frame phase, after choosing the slot for NTS 0, the terminal allocates the following one (NTS 1) 13 slots away from it. Furthermore, it randomly picks a value of $t_0 = 3$ for the NTS 0, which means that such slot is reserved to be the NTS 0 for the current frame, and the next 3 ones (until the counter reaches 0). The timeout and offset information are then attached to the CAM packet transmitted in NTS 0. This process is repeated for NTS 2 and NTS 3, each of which is respectively allocated 11 and 7 slots away from the previous one. Specifically, one can notice in Figure 26 that the slot carrying the NTS 3 is shaded in both blue and red: this is because an externally allocated slot was chose to carry it.

It is worth observing the change of meaning of the "offset" value in the first frame phase and in the continuous allocation phase. In the first frame phase, in fact, it serves the purpose of advertising to other users the position of the next NTS slot for the transmitter. On the other hand, after all of the NTSs are allocated, it indicates the offset between the position that NTS i occupies in the current frame, and the position NTS i itself will occupy on the next frame. This is used to inform other users when a re-reservation is performed, i.e. a new slot is chosen to carry NTS i. In Figure 26, this can be observed on the NTS 3 of the first frame phase. No further NTS needs to be allocated, and $t_3 = 4$, which means that NTS 3 will occupy the same slot for the current frame, and

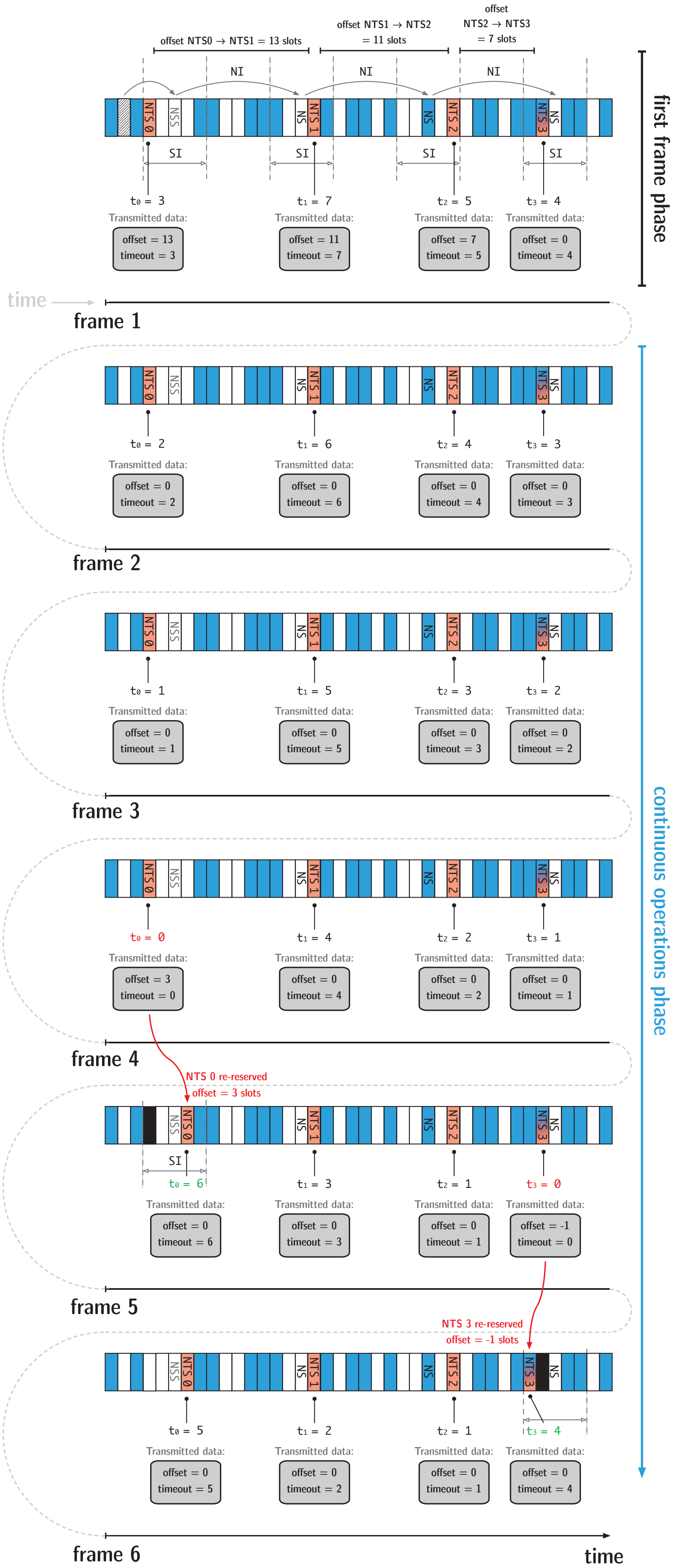


Figure 26 – STDMA, first frame phase and continuous operations phase.

the next 4 ones. Hence, the offset to its position on the next frame is 0. This is observable in frames 2 and 3 alike, during which all of the NTSs maintain their location. The respective timeout counters, on the other hand, are reduced by one unit at each frame.

On frame 4, the timeout counter of NTS 0 expires, hence the terminal must perform again the reservation process to choose a new location for it, which we remind it consists on the following steps:

— consider a Selection Interval (SI);
— compile a Candidate Set from slots within the SI;
— select a new location for the NTS by randomly choosing one of the slots in the candidate set.

Once this is done, a new timeout is chosen for the NTS ($t_0 = 6$ in our example). This timeout, along with the offset between the current NTS 0 location and the one of the newly chosen one (which is 3 slots later in our example), is attached to the last transmission performed in the old NTS 0 slot.

Similarly, the timeout for NTS 3 expires on frame 5: a new location for the NTS 3 is chosen 1 slots earlier with respect to its last location, which results in a transmitted offset value equal to -1.

In Figure 26 the old position is colored in marked in black just to help the reader identifying it with respect to the new one.

3.5.3 *Considerations on slot reuse*

The context aware reservation mechanism is the key to STDMA's performance: the knowledge of other UE's reservation patterns, in fact, allow for an optimized allocation of the available free slots. Understandably, this mechanism is challenged when the network density increases, and not enough free slots might be available to compile a complete candidate set. In this case, the solution adopted by STDMA is to progressively insert *externally allocated* slots to the candidate set up until when it contains w_{CSmin}, starting from the one allocated by the UE further away. It is commonly referred to as "*slot reuse*" when the current UE selects an already externally allocated slot for its transmission.

This is an effective way to handle higher Channel Load (CL), but it comes with some caveats:

— once added to the candidate set, the *externally allocated* slots have the same probability of being picked than any *free* slot in the candidate set;
— adding the externally allocated slots starting from the ones used by the farthest away UE, does not necessarily mean it is the farthest possible UE. Instead, it means it is the most distant UE that reserved a slot within the SI of the current one.
— the position of the so defined farthest UE must be correctly received, hence it must be within TX / RX range. A collision is thus inevitable, with UEs standing between transmitting UEs which might be able to decode one of the packets thanks to capture effect, should the SINR be high enough.

As it is shown in [100], packet losses in STDMA have a broader effect than just missing a generic CAM / BSM, i.e. some status information about the transmitting UE. They also imply the loss of reservation information, which will therefore affect the decisions taken by neighboring UEs. If a packet containing the offset to a new reservation is lost, another UE might choose the same exact slot at the same time, causing a collision. And since slots are reserved for at least t_{min} consecutive frames, this means that at least t_{min} consecutive collisions are caused, assuming the colliding UEs stay within range proximity for all that time.

3.6 PROTOCOL EXTENSIONS FOR STDMA OVER LTE-V2X

The STDMA reservation mechanism was not designed to operate in a channel configuration wherein packet receptions can be affected by half duplex impairment, such as the LTE-V2X one we presented in this thesis. In this section we will thus discuss two strategies to mitigate its effect. These strategies resulted in two protocol extensions, STDMA for OFDMA deployments (OSTDMA), and Selective Hiding STDMA (SH-STDMA), which are respectively presented in sections 3.6.1 and 3.6.2.

Both of them require the introduction of a new state that slots may assume, aside from "free", "internally" and "externally allocated", and "unavailable". This new state is "hidden", which is associated to slots that cannot be received by a given UE because one of its NTSs is located within the same subframe. Packets transmitted by other terminals in slots that are hidden to a certain UE are thus impossible to receive for that UE. Hidden slots are highlighted in Figure 27.

OSTDMA and SH-STDMA both retain the same protocol structure of STDMA, but alter the way the candidate set is compiled.

3.6.1 *OSTDMA*

Half duplex impairment prevents UEs from receiving packets transmitted in slots temporally co-located with their own transmission slots, which are hence labeled as "hidden" slots. Hidden slots are particularly critical for several reasons:

1. CAM packets transmitted in them by other UEs cannot be received;
2. the reservation information (timeout and offset) attached to the packets transmitted in them by other UEs cannot be received;
3. hidden slots are very likely within the boundaries of the selection interval, as it is illustrated in Figure 27.

This means that, because of hidden slots, UEs are missing awareness and reservation information about transmissions that might take place in the set of slots among which their own transmission slots are chosen. OSTDMA is thus conceived to mitigate the impairment caused by half duplex.

OSTDMA is identical to STDMA, except for the way the candidate set is compiled, which differs in the following way:

— hidden slots are excluded from the candidate set.

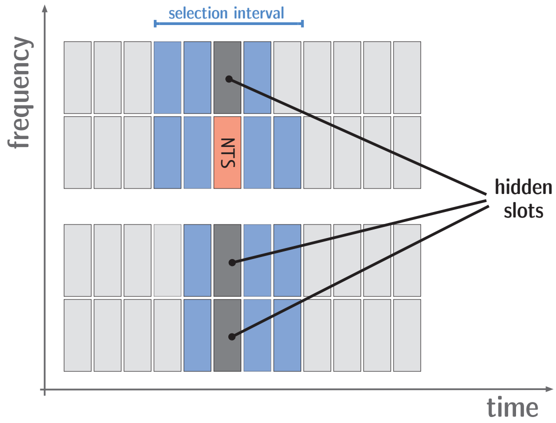


Figure 27 – OSTDMA base principle. Hidden slots, colored in dark gray, are excluded from the candidate set when re-reserving a new NTS

3.6.2 *SH-STDMA*

SH-STDMA takes a different approach to dealing with the half duplex impairment. The reception losses due to it cannot be avoided, since they are due to a technological limitation of the transceiver. The protocol, can however be extended to intelligently reduce its negative effects

SH-STDMA is conceived to selectively avoid hiding the NTS allocated by vehicles closer to the transmitter, the information transmitted by these being the most relevant. To do this, the procedure of compilation of the candidate set is modified as follows:

1. the selection interval is compiled as in STDMA
2. A penalty is assigned to all the LTE subframes involved in the SI, regardless of whether all the slots in it belong to the candidate set, or just a subset of them (this latter case might happen at the edges of the SI). By denoting with S_i the i^{th} in the SI, and with σ_j the j^{th} slot within a given subframe, the penalty P_i for the i^{th} subframe is computed as in

$$P_i = \sum_{j=0}^{n_s} g(d(\sigma_j)) \tag{5}$$

   where $g(x)$ is a function decreasing with x, and $d(\sigma_j)$ is the distance between the current UE and the one which reserved slot j. In case the slot j is free, $g(x)$ gets value 0.

3. a candidate set is compiled as follows:

   — it must contain exactly the number of slots w_{CSmin} (the minimum for STDMA)
   — free slots are added starting from the subframes with lower penalty P_i
   — if less than w_{CSmin} free slots are available in the SI, the remaining slots are picked by progressively choosing them from the subframes

with lower penalty, and choosing the one allocated by the farthest UEs first.[5]

In the evaluation on the next section, we adopted the following penalty function:

$$g(d(\sigma_j)) = \begin{cases} \frac{1}{d(\sigma_j)} & \text{if } \sigma_j \text{ is externally allocated} \\ 0 & \text{else} \end{cases} \quad (6)$$

Figure 28 illustrates the basic principle of SH-STDMA. On the left side, the selection interval is illustrated: in it, externally allocated slots are color-coded according to the distance between the UE reserving it and the current UE (the vehicle illustrated). A higher penalty is assigned to slots reserved by close by vehicles (in red).

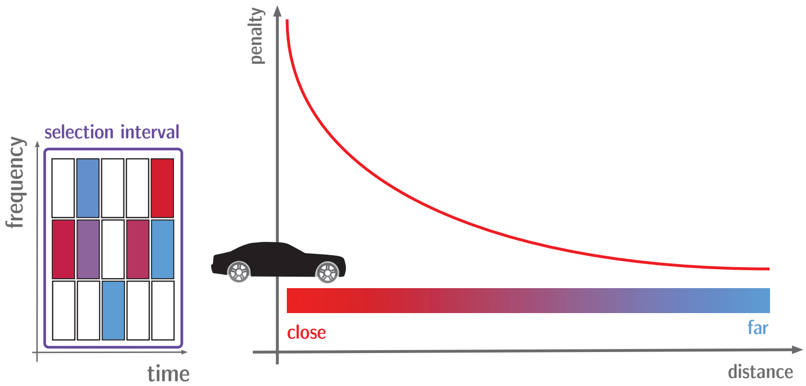


Figure 28 – SH-STDMA, basic working principle.

3.7 CONGESTION CONTROL

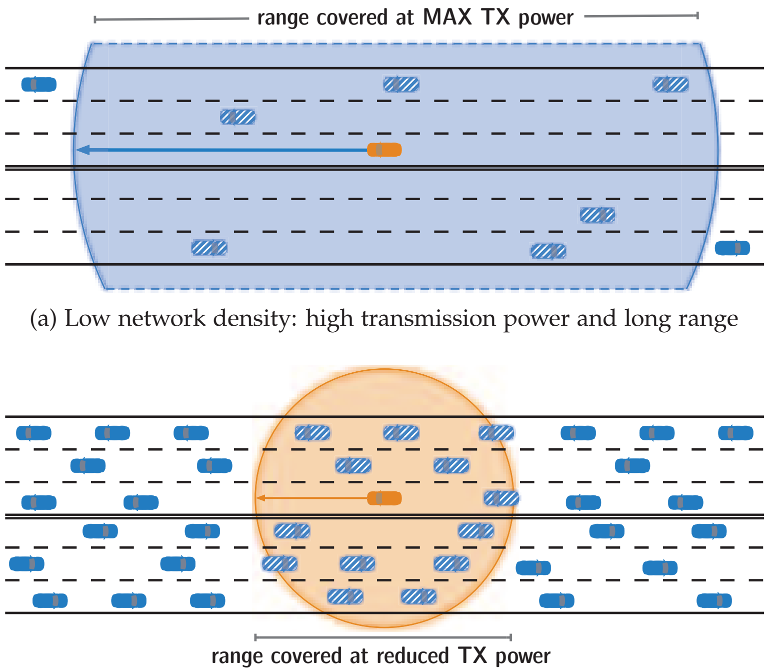
Congestion control is essential in decentralized systems, wherein the task of maintaining channel load under control is fully a responsibility of the terminals, since no centralized controller with a bird's eye view is available. In our proposed model of LTE V2X, in fact, substitute themselves to the eNodeB when it comes to scheduling.

Every channel access scheme, however, need to have a carefully designed congestion control mechanism, tailored on its based concept. For instance, the ETSI designed the Decentralized Congestion Control for the CSMA/CA-based ITS-G5 [124]. In [124] several different strategies are presented, including:

— Transmission Power Control (TPC), which is based on terminals choosing their transmission power level based on the expected attainable range. As illustrated in Figure 29, when the network density is low, terminals can afford high transmission power (Figure 29a). On the other hand, when network density increases, transmission power must be reduce to reduce interference.

— Transmission Rate Control (TRC), which specifically applies to periodical traffic patterns, consists on tweaking the transmission rate based on the perceived channel load.

5. The case wherein less than w_{CSmin} slots are available within the candidate set is very unlikely, thus neglected in this work.



(a) Low network density: high transmission power and long range

(b) High network density: lower transmission power and shorter range

Figure 29 – Transmission Power Control: maximum transmission power vs. reduced transmission power

— Transmit datarate control, which allows terminals to vary the Modulation and Coding Scheme (MCS) of their transmission based on the channel state. Higher MCS directly translate to lower packet transmission times, which result in lower channel occupancy. This scheme, however, does not apply to our proposed system, where the MCS must be fixed and predetermined. The packet-slots structure is in fact computed based on it, and it cannot be independently modified by the SBS-UEs. As thoroughly described in section 3.2.6, the partitioning function creates packet slots as sets of RBPs, whose number is sufficient to carry one CAM/BSM. For all of the SBS-UEs to partition the channel in the same way, it is necessary that each RBP contains a fixed amount of bits, which is dependent on the MCS. If SBS-UEs were allowed to modify it, the partitioning function would provide different results for each SBS-UE, which is not acceptable.

— DCC sensitivity control, which is the ability of users to modify the CCA threshold used to determine whether the channel is busy or free. This also does not apply to our proposed system, since neither OOC nor STDMA perform channel sensing before transmitting.

In this work, we will consider congestion control when dealing with OOC, focusing on TPC and TRC. Transmission Power Control may be easily applied, with the result of increasing or reducing the transmission range, as illustrated if Figure 29

Transmission Rate Control can be applied by muting some SBS-periods, as illustrated in Figure 31. This concept has then also being considered by the 3GPP in [56, §5.1.1.2], wherein lower transmission rate are presented as achievable by muting certain transmissions, which equates to perform them with zero power. In our case of interest, the maximum transmission rate is achieved

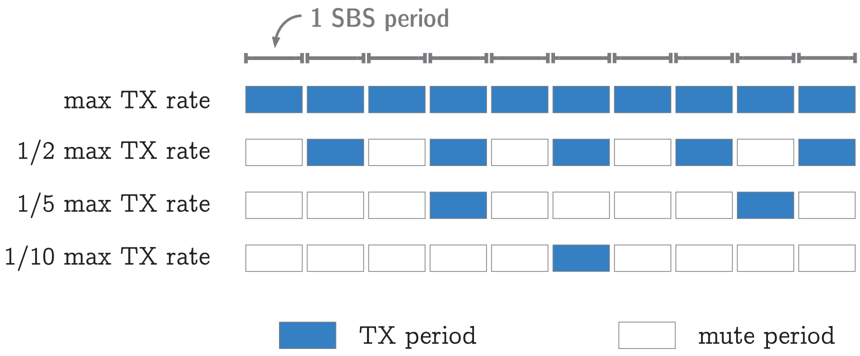


Figure 30 – Transmission Rate Control in OOC

by selecting one OOC codeword and transmitting in the w slots marked in it. Lower transmission rates can be achieved, as illustrated in the figure, by not transmitting any packet in some of the SBS-periods.

STDMA, on the other hand, handles the high congestion scenario by protocol design. As opposed to CSMA/CA, its reservation-based mechanism is in fact very efficient in exploiting the free available channel slots. Power and rate control may have detrimental effects on the behavior of the protocol. Reducing the transmission power will in fact prevent transmission to reach users at medium range distance, which might interpret those slots as free, and schedule transmissions in them, causing merging collisions. A procedure to modify the transmission range is defined in the STDMA protocol in [131], but, in order to comply with the structure of the protocol, it requires several seconds to be accomplished, a time scale much longer than the one needed, for instance, in 802.11p. Transmission muting is also non beneficial in STDMA, since packets contain important scheduling information, without receiving which other terminals might take inappropriate scheduling decisions, leading to collisions.

It is important to observe that congestion control in distributed systems is a *cooperative* endeavor: the positive effect caused by each terminal when it modifies its transmission parameters is in fact perceived by the remaining users. For the system to work fairly, it is thus essential that all of the terminals act according to and aware of the same principle. This means that some terminals shall not take advantage of transitory states of the channel load. The situation to avoid is the following: let us assume that a part of the users reduces their transmission rate, causing a reduction of the channel load. By sensing it, some other users could decide to increase their transmission rate, given they feel like having some headroom to do so.

Congestion control is implemented according to the control loop illustrated in Figure 31. The Unsupervised Device-to-Device (U-D2D) DCC control unit is fed with the desired with pre-configured system parameters (such as transmission power, transmission rate), and with a real time measurement of the channel load in the last SBS-period (set to 100ms in Figure 31) Based on this information, the U-D2D congestion control loop produces the set of optimal transmission parameters which are passed to the resource allocation (local scheduler) system. This parameters will eventually be utilized by the control loop for the determination of the TX parameters for the next SBS-period.

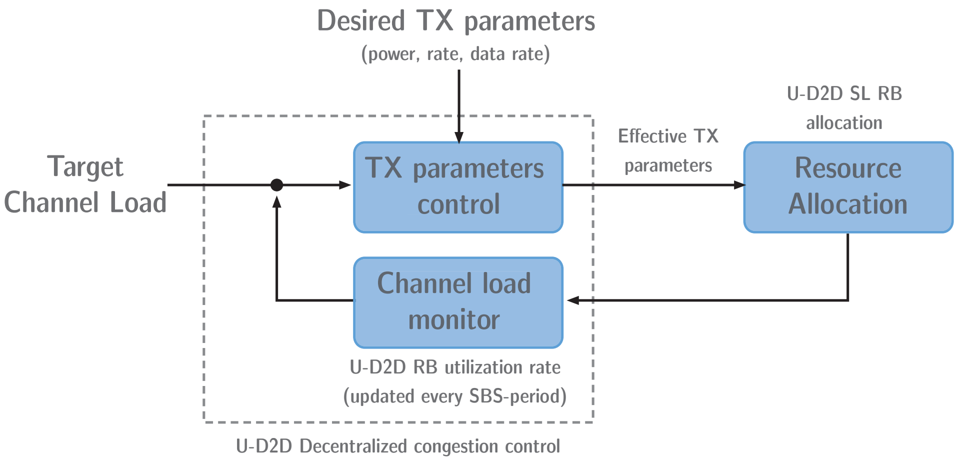


Figure 31 – Concept: congestion Control for for LTE-V2X

Channel Load Monitor function

SBS-UEs constantly monitor the channel state, which provides them with the information necessary to estimate the SL channel load. In the slotted system presented in this work, the channel load CL^{SL} is defined as the ratio between the number of busy slots and the totally available number of slots L available in a SBS period of duration T_{SBS}.

The channel load in one interval Δt equal to one SBS period is computed in equation (7),

$$CL^{SL}(\Delta t = T_{SBS}) = \frac{1}{L} \sum_{i=0}^{L-1} \mathbb{1}\{\sigma_i \in \mathcal{B}\} \tag{7}$$

where σ_i is the i^{th} slot of the SBS period, and $\mathcal{B}$ is the set of the busy slots.

4

MODELING

In this chapter, the details and the derivation to perform the quantitative evaluation of the protocols described in Chapter 3 are provided.

4.1 STATIC EVALUATION

The purpose of static analysis is understanding the influence that fundamental design aspects of each protocol have on their behavior, and as a consequence on their performance. The remainder of this section is organized as follows:

Topic	Section
OOC over LTE Sidelink: analytical performance evaluation	4.1.1
OOC vs 802.11p: analytical performance comparison	4.1.2
Self-Organizing TDMA: analytical performance evaluation	4.1.3
Simulator	4.1.4
Static evaluation by simulation	4.1.5

4.1.1 *OOC over LTE Sidelink: analytical performance evaluation*

Optical Orthogonal Codes were initially proposed in [129, 130, 135] as a medium access technique for vehicular communications, which provides reliability with multiple retransmissions. Retransmissions occur according to the pattern provided by OOC codewords, as described in section 3.4, which improve the probability of successful reception thanks to their cross-correlation properties. However, this also sets a limit to the number of available OOC codewords, as described in the following paragraph. For a thorough description of all the mathematical entities defined in this section, we invite the reader to refer to Table 9.

Cardinality of the OOC codeset

OOC codewords, considered singularly, are plain and simple binary codeword of L bits, with Hamming weight equal to w, meaning that w out of the L bits are "1s", and the remaining $L - w$ are "0s". What makes them attractive for medium access purposes are their cross correlation properties when considered as a codeset. In this case, the "orthogonality" property is such that the cross correlation between every couple of codewords in the set is at most equal

Table 9 – Mathematical notation (Unsupervised LTE D2D)

Symbol	Description
BW_{SBS}	bandwidth assigned to the SBS pool [RBs]
CL^{SL}	Measured Channel Load in the SL
λ	maximum cross-correlation between OOC codewords
L	length of an OOC codeword (i.e. number of slots per SBS-period)
l_{PKT}	length of the (fixed-size) safety packets [bytes]
l_{RBP}	number of RBPs per packet-slot
μ	spectral efficiency [bits per symbol]
μ_p	probability for an SBS-UE to transmit in the current SBS-period
N	number of SBS-UEs within respective TX/RX range
$N_{sf,SBS}$	number of subframes into the SBS pool per SBS-period
n_{RE}	number of REs per RBP
n_s	number of slots located within one subframe
P_{cf}	probability for one SBS-UE to have at least one of its TX slots unaffected by collisions (collision free)
p_j	probability of an interference pattern of size j between a pair of OOC codewords
P_s	probability for a given SBS-UE to successfully receive at least one of the packets of another transmitting SBS-UE within the current SBS-period
SF_i	subframe number i
T_{SBS}	duration of an SBS-period [s]
w	Hamming weight of the OOC codewords (i.e. number of transmissions per SBS-period per SBS-UE)

to λ, where λ is a design parameter that should be set so that $\lambda < w$. From a physical point of view, this means that taking each couple of SBS-UEs within respective TX/RX range, and assuming they chose or were assigned different OOC codewords, at most λ of their 1 bits superimpose, which means that they experience at most λ collisions due to the other SBS-UE. While on one side improving the probability of successful reception, this also sets a limit to the number of available OOC codewords for any given choice of L, w, and λ.

There is closed expression to compute the cardinality of a OOC codeset, i.e. the number of available codewords in it. However, a few upper bounds are available, as detailed in [127, §IV]. The most relevant is the Johnson bound, which in that paper is stated for the most general case. Our case of interest, however, allows a very important simplification: we can in fact easily assume that the SBS-periods are synchronized for all of the SBS-UEs (thanks to GNSS and to the cellular network). In such case, the cardinality of the OOC codeset, thus the maximum number of users within respective transmission range that can be served is upper bounded by [129]:

$$N \leq \frac{L(L-1)\cdots(L-\lambda)}{w(w-1)\cdots(w-\lambda)}. \tag{8}$$

The upper bound in (8) also implies the assumption that all of the codewords have the same weight w. In [135] the use of codewords with different weights is envisioned to support Quality of Service, but this scenario is outside the scope of this work, where we focus on CAM/BSM messages.

Fortunately, the high spectral efficiency of LTE allows the allocation of high number L of slots per SBS period. This fact, united to the low number of transmissions (generally w=2) that are reasonably sustainable in dense networks, make code starvation an improbable event to occur in LTE V2X.

Probability of successful reception in TDMA configuration

We want to compute the probability for a message transmitted by one terminal (SBS-UE$_A$) to be received by another terminal (SBS-UE$_B$) within a SBS period, in the assumption that all of the w transmissions performed in it by SBS-UE$_A$ are identical replicas of the same message. With this premise, the problem becomes equivalent to finding out the probability for SBS-UE$_B$ to correctly receive at least one out of the w transmissions from SBS-UE$_A$. In order to simplify the mathematical tractability, we make the following assumptions:

- we consider an isolated network with N terminals, all located within respective TX/RX range. This represents either a static configuration, or a simple homogeneous mobility scenario, wherein the number N of neighboring terminals remains constant. The probability of successful reception P_s will thus be a function of N, which directly relates to the network density;
- since the scope of this work is to extrapolate and evaluate the MAC-layer performance, PHY layer will therefore be considered perfect, and no capture effect will be taken into account;
- as for the computation of the codeset cardinality, we maintain the assumption that SBS periods are synchronous for all the SBS-UEs.

In [129], the packet reception probability of OOC is computed for a similar scenario, where however a simple TDMA case is assumed: in this case, collisions are the only phenomenon that limits performance. We thus label this probability P_cf, as in probability of having (at least) one **c**ollision-**f**ree TX slot in the SBS period. This means that at least one of SBS-UE$_A$'s TX slots must not be chosen by any of the other $N-1$ SBS-UEs. P_cf is then computed as in (9):

$$P_{cf} = \sum_{k=1}^{w} (-1)^{k+1} \binom{w}{k} \left[1 - \sum_{j=1}^{w} p_j \sum_{i=1}^{\min(j,k)} \binom{k}{i} \binom{w-k}{j-i} \right]^{N-1} \tag{9}$$

where p_j is the probability for a pair of SBS-UEs to have an interference pattern involving a set of j transmission slots:

$$p_j = \mu_p \frac{\binom{L-w}{w-j}}{\sum_{l=0}^{\lambda} \binom{w}{l}\binom{L-w}{w-l}}, \quad 0 \le j \le \lambda. \tag{10}$$

Given that the maximum cross-correlation between OOC codewords is limited to λ, and given the SBS periods synchronization hypothesis, it results that $p_j = 0$ for $j > \lambda$. For each pair of SBS-UEs, $\binom{w}{j}$ interference patterns of size j exist: p_j hence represents the probability for each of them to happen.

The variable μ_p, with $0 \le \mu_p \le 1$ deserves particular attention. It is in fact used to model the transmission rate, hence used to evaluate the TRC method for congestion control. When it is set $\mu_p = 1$, UEs transmit at their maximum transmission rate, i.e. they transmit packets in every SBS-periods. Lower rates are modeled with lower values of μ_p: for instance, $\mu_p = 0.5$ means a TX rate equal to 50% of the maximum value, and $\mu_p = 0.2$ means a TX rate equal to 20% of the maximum value. This means that in the remaining $1 - \mu_p$ fraction of SBS-periods the SBS-UE will not transmit.

Probability of successful reception in LTE V2X

The LTE-V2X channel configuration presented in this work introduces one further complication, since slots are distributed both in time and in frequency. Reception performances are hence limited by two factors: collisions and Half Duplex impairment.

— *Collisions* happen when multiple SBS-UEs select the same slot for their transmissions. The effect is the missed reception of the packets in the affected slot for all the SBS-UEs within the range of multiple colliding transmitters.

— *Half duplex impairment* is due to the nature of the channel structure, wherein slots are distributed in both time and frequency, resulting in some of them being temporally co-located. Since SBS-UEs can exclusively be in TX mode or in RX mode at any given time, a transmitting SBS-UEs cannot receive packets transmitted within slots that are located within the same subframes as its own TX slots, as illustrated in Figure 32.

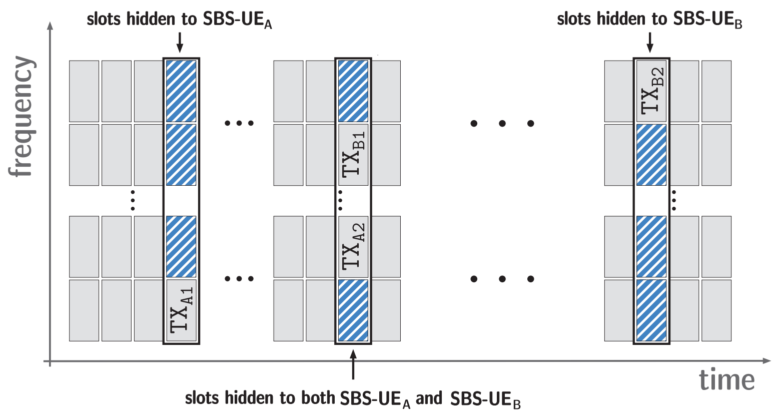


Figure 32 – Half duplex impairment: relative position of TX slots of two SBS-UEs

In Figure 32 a basic scenario is considered, wherein SBS-UE_A and SBS-UE_B each transmit into $w = 2$ slots, thereafter respectively labeled TX_{A1}, TX_{A2}, TX_{B1}, and TX_{B2}. In this work, we refer as "hidden" to the slots that one SBS-UE cannot receive due to HD impairment. As opposed to collisions, which affect all SBS-UEs in radio range, HD losses are local to each SBS-UE, as they are only due to the relative position of A and B's TX slots and to the internal transceiver state.

In the remainder of this section, we present the probability of having at least one of the TX slots free from collisions within a SBS-period for any choice of w and λ. Next, we evaluate the effects of HD impairment by computing the probability of successful reception for a configuration with $w = 2$ and $\lambda = 1$, a choice of parameters very important for real applications. The reasons are manifold: it represents a good compromise between improving reception probability, not saturating the channel with excessive retransmissions, reducing the energy cost of the protocol, while also simplifying the tractability of the problem, and allowing for the generation of larger codesets. Since OOC channel access does not perform channel sensing before transmitting, there is no hidden terminal effect: for the purpose of this evaluation, an isolated group of N SBS-UEs is thus considered, all within respective TX/RX range.

Probability of successful reception for $w = 2$ and $\lambda = 1$

We now evaluate the probability P_s for a message to be successfully received by an SBS-UE, considering both the effects of collisions and half duplex, for $w = 2$ and $\lambda = 1$.

Let us consider once again a pair of SBS-UEs as in Figure 32, respectively labeled "A" and "B", one of which plays the role of transmitter (SBS-UE_A), while the other (SBS-UE_B) is the receiver . Since every SBS-UE periodically assumes both roles, the evaluation also holds when these are switched. The successful reception of a packet by SBS-UE_B depends on:

— how many among TX_{A1} and TX_{A2} are collision-free;
— whether TX_{A1} and/or TX_{A2} are hidden to SBS-UE_B because of half duplex.

Focusing on collisions first, three events are worth considering, each requiring a separate analysis:

E_1: both TX_{A1} and TX_{A2} are collision-free;

E_2: only one among TX_{A1} and TX_{A2} is affected by collisions, with SBS-UE_B not involved in the collision(s);

E_3: only one among TX_{A1} and TX_{A2} is affected by collisions, with SBS-UE_B being one of the colliding SBS-UEs.

Event E_1 takes place when none the '1' bits in SBS-UE_A's OOC codeword overlap with any of the '1' bits in the codewords of the remaining $N-1$ SBS-UEs in the network. E_1 thus has probability:

$$Pr\{E_1\} = (1 - 2p_1)^{N-1} \tag{11}$$

Event E_2 occurs when SBS-UE_B does not collide with SBS-UE_A(with probability $(1 - 2p_1)$), while any number between 1 and $N - 2$ of the other SBS-UEs all collide with either TX_{A1} or TX_{A2}. Assuming that each SBS-UE chooses its codeword randomly, this happens with probability:

$$Pr\{E_2\} = 2(1-2p_1) \cdot \sum_{n=1}^{N-2} \binom{N-2}{n} {p_1}^n (1-2p_1)^{N-n-2} \tag{12}$$

Finally, E_3 occurs when SBS-UE_B and any other number of the remaining $N-2$ SBS-UEs collide with either TX_{A1} or TX_{A2}:

$$Pr\{E_3\} = 2p_1 \cdot \sum_{n=0}^{N-2} \binom{N-2}{n} {p_1}^n (1-2p_1)^{N-n-2} \tag{13}$$

It is worth noting that $Pr\{E_1\} + Pr\{E_2\} + Pr\{E_3\}$ is equal to P_{cf} in (9) evaluated for $w = 2$ and $\lambda = 1$.

Let us focus on half duplex impairment now: since it depends on the relative position between the transmission slots of the current transmitter (SBS-UE_A) and any given receiver SBS-UE_B), it is important to distinguish between the following two scenarios:

E^*: both TX_{A1} and TX_{A2} are within the same subframe (temporally co-located);

E^{**}: TX_{A1} and TX_{A2} are in different subframes.

To compute the probabilities of these two events, let us denote with n_s the number of slots that fit into a subframe:

$$n_s = \lfloor BW_{SBS}/l_{RBP} \rfloor. \tag{14}$$

Event E^*: occurs with probability [1]:

$$\begin{aligned} Pr\{E^*\} &= Pr\{\text{TX}_{\text{A1}} \in \text{SF}_i, \text{TX}_{\text{A2}} \in \text{SF}_i\} \\ &= N_{sf,SBS} \cdot \binom{n_s}{2} / \binom{L}{w}, \end{aligned} \tag{15}$$

and, being E^{**} its complementary event, we have:

$$\begin{aligned} Pr\{E^{**}\} &= Pr\{\text{TX}_{\text{A1}} \in \text{SF}_i, \text{TX}_{\text{A2}} \in \text{SF}_j, i \neq j\} \\ &= 1 - Pr\{\text{TX}_{\text{A1}} \in \text{SF}_i, \text{TX}_{\text{A2}} \in \text{SF}_i\}. \end{aligned} \tag{16}$$

In (15) and (16) SF_i indicates the i^{th} subframe belonging to the SBS subframe pool, relative to the start of the current SBS-period.

Every combination of events $\{E_1, E_2, E_3\}$ and $\{E^*, E^{**}\}$ needs to be separately considered when studying the probability of reception. Considering that E^* and E^{**} are related to the positioning of TX_{A1} and TX_{A2} within SBS-UE_A's codeword, whereas E_1, E_2 and E_3 are related to the relative position of the TX slots of all the SBS-UEs, we have, under the assumption of random codeword choices, that the two sets of events are independent of each other. We thus define, for $k = 1, 2, 3$, the following compound events with the associated probabilities:

$$E_k^* = E_k \cap E^*, \qquad Pr\{E_k^*\} = Pr\{E_k\} \cdot Pr\{E^*\}; \tag{17}$$

$$E_k^{**} = E_k \cap E^{**}, \qquad Pr\{E_k^{**}\} = Pr\{E_k\} \cdot Pr\{E^{**}\}. \tag{18}$$

1. in this work we consider $\binom{a}{b} = 0$ when $a < b$

The desired probability of successful reception P_s can finally be obtained from (17) and (18) as follows:

$$P_s = \sum_{k=1}^{3} [(1 - Pr\{loss_{hd} \mid E_k^*\})Pr\{E_k^*\} \quad + \\ (1 - Pr\{loss_{hd} \mid E_k^{**}\})Pr\{E_k^{**}\}] \quad (19)$$

where the terms $Pr\{loss_{hd} \mid E_k^*\}$ and $Pr\{loss_{hd} \mid E_k^{**}\}$ are computed in (20)-(25) in the following paragraphs, and which represent the probability of losing both retransmissions in a frame given the occurrence of the events E_k^* and E_k^{**} respectively.

E_1: both TX$_{A1}$ and TX$_{A2}$ are free from collision.
In this scenario, for both retransmissions to be lost, they both must be hidden due to half duplex. In case both TX$_{A1}$ and TX$_{A2}$ are within the same subframe, it is sufficient that at least one between TX$_{B1}$ and TX$_{B2}$ are within the same subframe, with probability:

$$Pr\{loss_{hd} \mid E_1^*\} = \frac{(n_s - 2)(L - n_s) + \binom{n_s - 2}{2}}{\binom{L-2}{2}} \quad (20)$$

On the other hand, if TX$_{A1}$ and TX$_{A2}$ are in different subframes, for both of them to be lost, TX$_{B1}$ and TX$_{B2}$ must respectively be within the same subframes. This happens with probability:

$$Pr\{loss_{hd} \mid E_1^{**}\} = (n_s - 1)^2 / \binom{L-2}{2}. \quad (21)$$

E_2: one among TX$_{A1}$ and TX$_{A2}$ is affected by a collision, with SBS-UE$_B$ not involved.
In this scenario, only one among TX$_{A1}$ and TX$_{A2}$ is collision-free: for both retransmissions of the current frame to be lost, it is sufficient to have that one hidden because of half duplex. In case both TX$_{A1}$ and TX$_{A2}$ are within the same subframe, that happens with probability:

$$Pr\{loss_{hd} \mid E_2^*\} = \frac{(n_s - 2)(L - n_s) + \binom{n_s - 2}{2}}{\binom{L-2}{2}} \quad (22)$$

whereas in the case in which TX$_{A1}$ and TX$_{A2}$ belong to different subframes, we have:

$$Pr\{loss_{hd} \mid E_2^{**}\} = \frac{(n_s - 1)(L - n_s - 1) + \binom{n_s - 1}{2}}{\binom{L-2}{2}} \quad (23)$$

E_3: One among TX$_{A1}$ and TX$_{A2}$ is affected by a collision, with SBS-UE$_B$ being one of the colliding users.
In this last scenario, both SBS-UE$_A$ and SBS-UE$_B$ only have one slot left free from collision. In the case in which both TX$_{A1}$ and TX$_{A2}$ are on the same subframe, the colliding transmission slot of SBS-UE$_B$ hides them both, causing:

$$Pr\{loss_{hd} \mid E_3^*\} = 1 \quad (24)$$

On the other hand, if TX_{A1} and TX_{A2} are on different subframes, the transmissions from $SBS\text{-}UE_A$ for the current frame are all lost if the collision free among TX_{B1} and TX_{B2} does fall within the same subframe of the non colliding one among TX_{A1} and TX_{A2}. Thus:

$$Pr\{loss_{hd} \mid E_3^{**}\} = (n_s - 1)/(L - 1). \tag{25}$$

Application-level performance: Inter Reception Time

The application-layer performances evaluate the effect perceived by the application, as a result of packet losses on the radio channel. One such metric of our interest is the inter reception time, which is a receiver-side metric that represents the mean time between consecutive successful packet receptions from one given transmitter. This is directly linked to the quality of the awareness, as it relates to how old the information that $SBS\text{-}UE_A$ has about $SBS\text{-}UE_B$'s state at any given time.

For the evaluation of the mean IRT, we maintain the assumption made previously in this paper that the w transmissions made by each SBS-UE within a SBS-period contain the same information. The inter reception time is thus evaluated only between packets containing different information, i.e. generated in different SBS-period. We further assume that consecutive packet losses are uncorrelated, which allows us to model it as a function of the probability of successful packet reception in (19) according to a geometric law:

$$IRT = T_{SBS} \cdot \left(1 + \sum_{n=0}^{\infty} n \cdot P_s (1 - P_s)^n\right) = T_{SBS}/P_s \tag{26}$$

where T_{SBS} is the duration of the SBS-period, i.e the inverse of the maximum TX rate. The model in eq. (26) considers a reception successful if at least one of the $w = 2$ transmissions within a SBS period is correctly received.

4.1.2 *OOC vs 802.11p: analytical performance comparison*

In this section, we compare the performance of the unsupervised LTE-V2X scheme presented in this work against those of IEEE 802.11p. For this purpose, we consider the IEEE 802.11p analytic model introduced by Yin et al. in [136], in which the authors model the IEEE 802.11p CSMA/CA-based channel access according to the Semi Markov Process, whose state diagram is depicted in Figure 33.

The states $\{0 \ldots W - 1\}$ represent the value of the backoff counter, with W being the maximum width of the contention window. States $D_i, i \in \{0, \ldots, W - 2\}$ represent the transmission deferral states, in which the protocol enters when the channel is sensed busy while the backoff counter has value $i + 1$. The protocol is in *idle* state when the transmit buffer is empty: when a new packet enters the transmission queue of an idle transmitter, the protocol enters the CS_1 state. From CS_1, the current state could either move to TX, in which the packet is transmitted, or to state D_{CS}, in which the protocol stays until the channel is sensed free for one DIFS. State CS_2 represents the channel sensing state in which the protocol enters when a packet has just been transmitted and in the transmitter's buffer there are other packets waiting. The Semi Markov Process evolution is dominated by four probabilities:

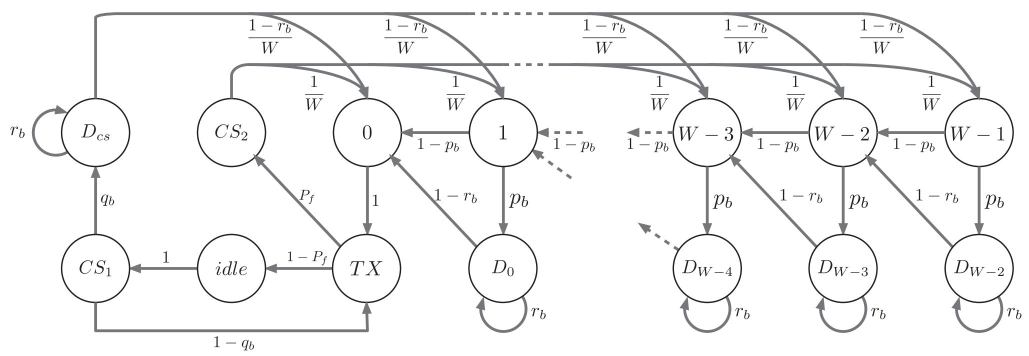


Figure 33 – Semi Markov Process state diagram of DSRC, adapted from [136]

— p_b: the probability for the channel to be sensed busy during one CSMA/CA slot;
— q_b: the probability for the channel to be sensed busy during one DIFS interval;
— r_b: the probability that the channel is sensed busy during one DIFS because of a concurrent transmission that has terminated in the meantime;
— P_f: the probability for a packet to be discarded while still in the queue because its lifespan expired.

We invite the interested reader to refer to [136] for more details and for the entire derivation. In the rest of this section, we will only recall the important aspects for its comparison with unsupervised LTE-V2X, and for the analytic derivation of the IRT for IEEE 802.11p.

Probability of successful reception in IEEE 802.11p

For reasons of analytic tractability, vehicles in [136] are distributed along a single lane according to a Poisson point process, whose parameter β is the mean vehicular density. A "tagged user" is defined as the user currently transmitting a packet. The receiver-centric probability of packet reception for IEEE 802.11p is then obtained, for a terminal at distance x from the tagged user, as in (27): the meaning of all the variables therein is defined in Table 10.

$$P_{s,11p}(x) = \exp\left(-2\pi_{TX}\beta x - 2\frac{\pi_1}{\pi_{TX}}\left[1 - e^{-\beta\pi_{TX}(R-x)}\right] - \beta x\pi_1\right) \tag{27}$$

$P_{s,11p}$ is a function of the x, and of the carrier sense range R because of the presence of hidden terminals. Since we make no hypothesis on the relative position between the tagged user and any other terminal, we consider the mean value of $P_{s,11p}(x)$ over all the possible $x \in [0, R]$:

$$\overline{P}_{s,11p} = \frac{1}{R}\int_0^R P_{s,11p}(x)dx. \tag{28}$$

No closed form exists for the integral in (28), hence it must be approximated with numerical methods.

Table 10 – Mathematical notation (IEEE 802.11p model in [136])

Symbol	Description
β	mean vehicular density [vehicles/m]
IRT_{11p}	Inter Reception Time for IEEE 802.11p
N_{cs}	expected number of vehicles within carrier sense range
N_{ph}	expected number of vehicles in the hidden terminal area
p_b	probability for the channel to be sensed busy during one CSMA/CA slot duration
P_f	probability that a packet is discarded while still in queue for lifespan expiration
$\overline{P}_{s,11p}$	mean probability of reception for IEEE 802.11p over the transmission range
$P_{s,11p}(x)$	Probability of successful reception for IEEE 802.11p as function of the distance x from the transmitter
π_Y	steady-state probability for the Semi Markov Process to be in state Y
q_b	probability for the channel to be sensed busy during one DIFS interval
R	transmission range
r_b	probability that the channel is sensed busy during one DIFS because of a concurrent transmission that has terminated in the meantime
T	inter transmission time
W	width of the contention window

Inter Reception Time in 802.11p

To compute the Inter Reception Time for IEEE 802.11p, we apply a similar methodology that for the unsupervised LTE-V2X described in section 4.1.1, thus having:

$$IRT_{11p} = T + T \cdot \sum_{n=0}^{\infty} n \cdot \overline{P}_{s,11p} \cdot (1 - \overline{P}_{s,11p})^n = \frac{T}{\overline{P}_{s,11p}} \tag{29}$$

where T is the inverse of the transmission rate.

4.1.3 *Self-Organizing TDMA: analytical performance evaluation*

General model description

The purpose of this work is to compute the asymptotic Slot Occupation Distribution (SOD) of STDMA as defined in [101], i.e the probability distribution for one slot to be reused by i users. The Packet Level Incoordination (PLI) [100], i.e. the probability for a transmitting user to have one reserved slot being reused by other terminals, can then be derived directly from the SOD. In order to achieve analytical tractability, we make the following abstractions:

— as we focus on evaluating the steady state behavior of the reservation process, we assume a network of users already aware of each other's presence. Hence, only the *continuous operations* phase is modeled;
— the CS is compiled without knowing the reservation pattern of concurrent users: instead, slots are added based on their probability of being sensed free;
— when necessary, the externally allocated slot to include in the CS will be chosen randomly, instead of based on the relative distance between the contending terminals;
— being our focus on MAC layer performance, we assume a perfect PHY layer. Path loss and fading would indeed impair the probability of reception, but also reduce the number of terminals competing for the same channel resources;
— terminals are either static or in homogeneous mobility.

To describe the behavior of STDMA we need to model two processes:

A. the *timeout mechanism* terminals associate to each NTS;

B. the *slot re-reservation* mechanism.

We model both these mechanisms using Markov Chains, following a methodology inspired by the seminal work in [72], wherein Prof. Bianchi modeled the DCF mechanism, which is the base of CSMA/CA. Despite the protocol being structured deterministically, aspects such as the distribution of the allocated slots and the choice of the NTSs are inherently random, making the state of the system at any point in time and space a random process. Both A) and B) will thus be described with stochastic models.

Timeout process (π_t)

The timeout mechanism determines for how many consecutive frames one user reserves each of its NTSs. When the counter reaches its minimum value, a re-reservation event is triggered and a new timeout is chosen. Assuming that users always have r packets per frame to transmit and 0 being the minimum value of the counter, we can model the timeout process as a discrete-time Markov Chain, whose state diagram is represented in Figure 34. The time unit is 1 frame, since this is the counter update interval. Denoting with $\pi_{t,i}$

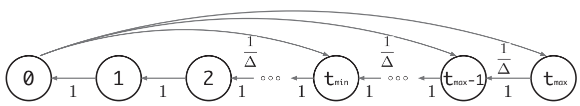


Figure 34 – Markov Chain associated to the timeout mechanism

the steady state probability for the counter to be in state i, we can compute the stationary distribution as follows:

$$\begin{aligned} \pi_{t,t_{max}} &= \pi_{t,0}/\Delta \\ \pi_{t,i} &= \pi_{t,0}/\Delta + \pi_{t,i+1} && t_{min} \leq i < t_{max} \\ \pi_{t,i} &= \pi_{t,t_{min}} && 0 \leq i < t_{min} \end{aligned}$$

with $\Delta = t_{max} - t_{min} + 1$. Imposing the normalization condition:

$$\sum_{i=0}^{t_{max}} \pi_{t,i} = 1$$

we can obtain $\pi_{t,0}$, the probability for a slot re-reservation event to take place, as in (30).

$$\pi_{t,0} = 2/(t_{max} + t_{min} + 2) \quad (30)$$

Slot re-reservation process

Let us consider an isolated network of N_t terminals (users) within each other's transmission range. Let us then consider a chunk χ of NI consecutive time slots: on average, we can assume that all of the N_t users will need to transmit in exactly one of these NI slots. Among these NI, we identify one generic slot σ_t, we will refer to as the *tagged slot*. The re-reservation process, from the perspective of the tagged slot, can be modeled with the discrete-time Markov chain depicted in Figure 35. Again, the time unit is 1 frame, being 1 frame the time interval between timeout counter value updates. The state

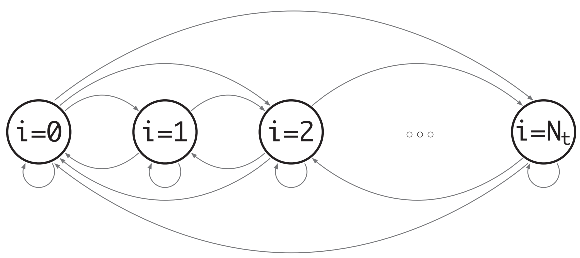


Figure 35 – Markov Chain of the reservation process as seen by the tagged slot. The state variable i is the number of terminals reusing the tagged slot.

variable i represents the number of terminals currently reusing the tagged slot. The tagged slot will thus be free for $i = 0$, allocated by a single user for $i = 1$ and reused by multiple users when $i > 1$. The extreme theoretical case is represented by the tagged slot being simultaneously allocated by all of the N_t users, while all of the other NI -1 slots in χ are free. Denoting with π_i the steady state probability for the tagged slot to be in state i, the stationary distribution $\boldsymbol{\pi} = \{\pi_0, \ldots, \pi_{N_t}\}$ represents the SOD we are interested in.

Denoting with $p_{i,i+j}$ the probability for the process to transition from state i to state $i + j$, the SOD can be computed solving the following equation:

$$\boldsymbol{\pi} = \boldsymbol{\pi}\mathbf{P} \quad (31)$$

where $\mathbf{P}$ is the transition probability matrix:

$$\mathbf{P} = \begin{pmatrix} p_{0,0} & p_{0,1} & \cdots & p_{0,N_t} \\ p_{1,0} & p_{1,1} & \cdots & p_{1,N_t} \\ \vdots & \vdots & \ddots & \vdots \\ p_{N_t,0} & p_{N_t,1} & \cdots & p_{N_t,N_t} \end{pmatrix}.$$

In order to compute a general expression for $p_{i,i+j}$ with $0 \leq i \leq N_t$, $0 \leq i+j \leq N_t$, we define the following events:

— an *arrival* in the tagged slot happens when a user in the process of re-reserving its transmission slot within χ choses the tagged slot as its NTS;

— a *departure* from a generic slot in χ happens when the timeout of one of the users that were previously allocating it expires, thus forcing that user to reserve a new NTS.

Since the timeout processes of the N_t users are independent from each other, so are the departure events that involve them. Denoting with D the number of departures that occur in χ and with $\overline{D}$ the number of departures that occur in the tagged slot, we have that the probability of having a total of d departures in χ of which $\overline{d}$ are from the tagged slot while it is in state i can be computed as:

$$p_i\{\overline{D} = \overline{d} | D = d\} = \binom{i}{\overline{d}} \binom{N_t - i}{d - \overline{d}} {\pi_{t,0}}^d (1 - \pi_{t,0})^{N_t - d} \tag{32}$$

with $0 \leq \overline{d} \leq i$, as the number of departures from the tagged slot cannot exceed the number of users currently reserving it.

Let us now consider the arrival events in the tagged slot. For an arrival to occur, the following conditions must verify:

1. somewhere in χ one or more departures must occur;
2. one of the departing users' SI includes the tagged slot;
3. the tagged slot is included into the CS;
4. the tagged slot is chosen as the NTS.

The probability of having $A = a$ arrivals in the tagged slot must then be conditioned on having $d \geq a$ departures in χ. The probability for the tagged user to belong to the SI of one generic re-reserving user is given by [2]:

$$p_{SI} = p\{\sigma_t \in SI\} = \min\left\{\frac{|SI|}{NI}, 1\right\} \tag{33}$$

where $|SI|$ represents the cardinality of SI, i.e. the number of slots in SI. The probability to have $A = a$ arrivals in the tagged slot given that d departures occur in χ can then be expressed as:

$$p\{A = a \mid D = d\} = \sum_{k=a}^{d} \binom{d}{k} {p_{SI}}^j (1 - p_{SI})^{d-k} \binom{k}{a} p^a (1-p)^{k-a} \tag{34}$$

where p represents the probability for the tagged slot to be chosen by a re-reserving user as its next NTS, given that σ_t belongs to that user's SI.

2. *min* operation is necessary as it can be $|SI| > NI$ when $s = 1$ in (3).

By combining (32) and (34) we can finally obtain the probability $p_i\{\overline{d}, a \mid d\}$ of having a arrivals in the tagged slot and $\overline{d}$ departures from it, given that d total departures happen in χ and σ_t is in state i as in equation (35).

$$p_i\{\overline{d}, a \mid d\} = p_i\{\overline{D} = \overline{d} \mid D = d\} \cdot p\{A = a \mid D = d\} =$$
$$\binom{i}{\overline{d}}\binom{N_t - i}{d - \overline{d}}{\pi_{t,0}}^d(1-\pi_{t,0})^{N_t - d} \cdot \sum_{k=a}^{d}\binom{d}{k}{p_{SI}}^k(1-p_{SI})^{d-k} \cdot \binom{k}{a}p^a(1-p)^{k-a} \tag{35}$$

Finally, the probability $p_{i,i+j}$ can be obtained as the sum of all the probabilities of the combinations of events such that the balance between the arrivals in the tagged slot and the departures from it is equal to j. Mathematically, this translates to:

$$p_{i,i+j} = \sum_{C_{i,i+j}} p_i\{\overline{d}, a|d\} \tag{36}$$

where the set of conditions $C_{i,i+j}$ is defined as follows:

$$\begin{aligned} &C_{i,i+j}: \\ &0 \leq d \leq N_t \\ &0 \leq \overline{d} \leq min\{i, d\} \\ &0 \leq a \leq d \\ &j = a - \overline{d} \end{aligned}$$

To be able to compute (36) we still need to determine p, that appears in (34) and (35). According to the STDMA protocol, the probability for a slot to be chosen as NTS by one re-reserving user (given that it belongs to its SI) depends on the state the tagged slot is sensed to be in.

The tagged slot is sensed free

If the tagged slot is sensed free, it is automatically included into the candidate set of the re-reserving user, from which the NTS is chosen with uniform probability. We then have that the probability for the tagged slot to be chosen while sensed free p_f is:

$$p_f = \frac{1}{\max\{\mathbb{E}[n_f], w_{CSmin}\}} \tag{37}$$

where $\mathbb{E}[n_f]$ is the expected number of free slots within the SI and can be computed as:

$$\mathbb{E}[n_f] = \sum_{k=1}^{|SI|} k \cdot \binom{|SI|}{k}\hat{p}^k(1-\hat{p})^{|SI|-k}$$

with $\hat{p}$ being the probability for one slot to be sensed free.

The tagged slot is sensed allocated

If the tagged slot is sensed allocated, it only has a chance to be part of the candidate set of a re-reserving user if there are less than w_{CSmin} free slots within its SI. Specifically, if $\overline{n_f}$ slots are free within the SI, with $\overline{n_f} < w_{CSmin}$, we have that:

$$p\{\sigma_t \in SI \mid \text{allocated} \wedge \overline{n_f}\} = \frac{w_{CSmin} - \overline{n_f}}{|SI| - \overline{n_f}}.$$

The probability for the tagged slot to be part of the CS while allocated is then:

$$p\{\sigma_t \in SI \mid \text{allocated}\} =$$
$$= \sum_{k=0}^{w_{CSmin}-1} \frac{w_{CSmin}-k}{|SI|-k} \cdot \binom{|SI|}{k} \hat{p}^k (1-\hat{p})^{|SI|-k}$$

Since the NTS is again chosen with uniform probability from the CS, the resulting probability p_a for the tagged slot to be chosen while allocated is:

$$p_a = \frac{1}{w_{CSmin}} \cdot \sum_{k=0}^{w_{CSmin}-1} \frac{w_{CSmin}-k}{|SI|-k} \cdot \binom{|SI|}{k} \hat{p}^k (1-\hat{p})^{|SI|-k} \tag{38}$$

The probability p in equations (34) and (35) must then be chosen between p_f and p_a according to the state the tagged slot is sensed being in. Since a slot is sensed free when, during the previous frame:

— it was free and no other user reserved it;

— it was allocated by i users and all of them have to perform a re-reservation in the current frame;

in (34) and (35) we must set:

$$\begin{cases} p = p_f & \text{if } i = 0 \vee \bar{d} = i; \\ p = p_a & \text{otherwise.} \end{cases}$$

Following the same principle we can finally determine $\hat{p}$, the probability for a slot to be sensed free, as follows:

$$\hat{p} = \textstyle\sum_{k=0}^{N_t} \pi_k^{(ff)} \cdot \pi_{t,0}{}^k \tag{39}$$

where $\pi_k^{(ff)}, 0 \leq k \leq N_t$ is the resulting SOD after that all the N_t users have finished their first frame phase, entering the network. By computing (31), we can evaluate the asymptotic performance of the STDMA protocol configuration evolving from an initial state distribution $\boldsymbol{\pi}^{(ff)} = \{\pi_0^{(ff)}, \ldots, \pi_{N_t}^{(ff)}\}$.

Finally, we can compute the Packet Level Incoordination experienced by a user allocating the tagged slot as the probability for the tagged slot to be reused by more than 1 terminal:

$$PLI = \textstyle\sum_{k=2}^{N_t} \pi_k. \tag{40}$$

Initial state

As just mentioned, the initial state distribution $\boldsymbol{\pi}^{(ff)} = \{\pi_0^{(ff)}, \ldots, \pi_{N_t}^{(ff)}\}$ is computed based on the state of the system after all the terminals have finished the first frame phase. This depends on the Offered Channel Load (OCL), which is the ratio between the number of slots required by the N_t users, each transmitting r packets per frame, and the number N of available slots: $OCL = N_t \cdot r/N$. $\boldsymbol{\pi}^{(ff)}$ after the first frame phase can be computed as in equation (41).

$$\begin{cases} k = \lfloor N_t \cdot r/N \rfloor \\ \pi_{k+1}^{(ff)} = N_t \cdot r/N - \lfloor N_t \cdot r/N \rfloor \\ \pi_k^{(ff)} = 1 - \pi_{k+1}^{(ff)} \\ \pi_j^{(ff)} = 0 \qquad \forall j \neq k \vee j \neq k+1 \end{cases} \tag{41}$$

It is worth noting that an endless reservation scenario can be obtained by setting $t_{min} = t_{max} \rightarrow \infty$. In this scenario, we obtain $\pi_{t,0} = 0$, which substituted in (35), then in (36) and in (31), provides a transition probability matrix $\mathbf{P}$ equal to the identity matrix. In such a scenario, re-reservation is not observed, and slots that are in a given state at the end of the first frame phase keep remaining in the same state.

4.1.4 *Simulator*

The next part of our work is constituted by the evaluation of the protocol performance by means of simulation. To do so, we decided to implemented a custom, agent-based simulator written in Python [137]. The choice of creating our own custom tool provides several advantages over choosing an already available simulation software. Firstly, it allows us to control the level of abstraction: with the same platform it is in fact possible to simulate both ideal static scenario and more realistic setups, which include mobility, path loss and fading. Secondly, it allowed us to develop a MAC-focused simulator for vehicular environments, able to efficiently simulate high-densities scenarios with possibly hundreds of contemporary vehicles, without the need to implement the physical layer of the LTE V2X in any specific platform. Finally, only relying on free software, it did not require the licensing of any commercial software product.

The block diagram of the simulator is illustrated in Figure 36. Vehicles are represented by agents, each equipped with an instance of the protocol under test. Vehicles move according to a customizable mobility model, and information about their position can be exploited by the protocol they are equipped with. The protocol blocks, embedded in each agent, interact with each other via a customizable channel module.

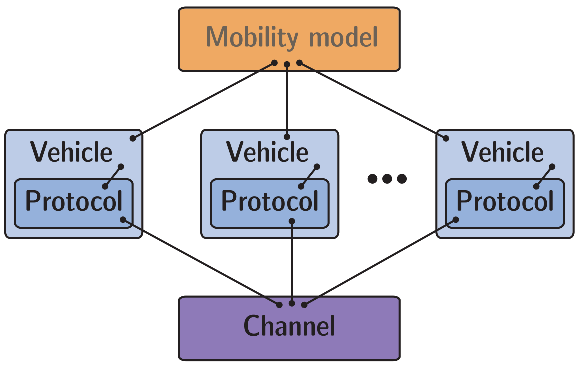


Figure 36 – Static evaluation: simulator block scheme

The mobility model dictates the physical interaction between vehicles. In our work, two cases are of particular interest. For the static evaluation (section 4.1.5), we modeled a drop-down scenario, wherein users are generated in random positions all within respective radio range, and never leave such position. On the other hand, for the dynamic evaluation treated in the last part of this chapter (section 4.2), we implemented a multi-lane highway scenario as described in section 4.2.1.

The channel model accounts for two important aspects for the simulation: the resource management of the SBS-pool, and the propagation aspects. Its first responsibility is to read a configuration file provided in input by the user, which contains information about the time and frequency allocation of the resource pool, and convert it into a SBS allocation pattern. Once the SBS-pool is defined, the channel module takes care of modeling all of the propagation-related phenomena. These can as well be tailored to the type of behavior one wants to isolate in a specific simulation run.

The Vehicle module manages the position and the transceiver operations. Instances of vehicle periodically update their position based on the initial position they were generated on, and on the speed they have been assigned to by the mobility model module. At the same time, all of the packet transmissions and receptions are handled by this module, in order to make them transparent to the MAC protocol. Furthermore, the vehicle module can provide position information to the protocol, which is to be included in transmitted packets, as it is exploited by protocols such as STDMA. At the same time, each vehicle can also maintain an internal map of the positions of the neighboring vehicles, which is updated based on the CAM/BSM messages it receives: this representation is for instance enabled when STDMA is modeled, since it is necessary during the slot re-reservation process.

The protocol module, eventually, contains the actual implementation of the protocol one wants to test in a specific simulation run. To maintain the model as realistic as possible, each vehicle is equipped with its own independent instance, which has independent state, and set of parameters. The protocol module communicates with the vehicle for position information, and TX/RX methods. The combination of one vehicle instance and one protocol instance constitutes a SBS-UE.

The time scale of the simulator is discrete, with the time unit equal to 1 ms: this is the TTI of LTE, and the minimum possible time duration of a packet-slot, hence it serves as the base time unit for the protocols. Within each subframe, packet-slot are handled individually, in order to properly model half duplex impairment, where needed. The mobility process might on the other hand update at a slower pace: 1 ms might in fact represent a granularity too fine for position updates, and increase the computational load, whereas updates every 100 ms would lighten this burden while still provide relevant and accurate results.

Transmissions are centrally managed: at the occurrence of every packet-slot, the simulator collects the packets from SBS-UEs which are meant to transmit in it, and computes the propagation between them and the neighboring users via the channel module, and delivers it to the receivers with the appropriate computed SINR. This is computed based on channel model, and occurrence of other concurrent transmissions, which might result in collisions. At the end of this round, each SBS-UE processes the reception, and acts according to the protocol, to the SINR, and to its internal state.

Protocols are implemented based on schedulers, which act on a packet-slot basis, which every SBS-UE uses to assign a state to a given future packet-slots. At each 1 ms time step, or subframe, the simulator handles the packet slots contained in it independently: each SBS-UE fetches the event (or events) scheduled for that packet slot and operates the appropriate decisions, which we illustrate for the protocols of our interest in the remainder of this subsection.

Simulator implementation of OOC

Even when modeling OOC, we adopted for notational convenience the names of the states according to terminology of STDMA. A slot is hence labeled as "internally allocated" when a transmission is scheduled for that specific slot.

Since OOC does access the channel blindly, packet slots can only assume two states: "internally allocated", and "hidden". At the beginning of each SBS-period, a SBS-UE is assigned (or independently choses) a OOC codeword, and it consequently schedules w internal allocated slots, each with the adequate offset, as indicated by the position of the "1" bits contained in it. If half duplex impairment is modeled, the SBS-UE also schedules an appropriate number of "hidden" slots: specifically, one of them for each of the slots belonging to the same subframe of an internally allocated slot, which is not internally allocated itself.

When the system time reaches one of the internally allocated slots, a packet is transmitted by the current SBS-UE. On the other hand, when a hidden slot is reached, the receiver is disabled, as the transceiver would not be able to receive any transmission is it, as it would be set in TX mode.

Simulator implementation of STDMA

In the STDMA implementation, slots can assume the following states:

— **internally allocated**: these corresponds to the NTSs, and are scheduled every time the protocol performs a reservation. Each time a NTS is reached and the timeout attached to it has not reached 0 yet, a new one is scheduled with offset equal to one SBS-period in the future, and the timeout reduced by one unit. When it reaches 0, the re-reservation procedure is performed, and a new one is scheduled with the the offset corresponding to the offset to the new position.

— **externally allocated** slots are scheduled when a SBS-UE receives a transmission from another SBS-UE. If the timeout indicated in the CAM/BSM packet is non-zero, it is scheduled on SBS-period in the future. On the other hand, if it is equal to zero, this time offset also accounts for the offset to the position of that SBS-UE's new NTS, which is attached to the packet.

— **unavailable** is the state associated to packet slots wherein a collision has occurred, or a power level above the CCA is detected. These packet-slots shall be excluded from any CS: to do so, when any of the mentioned phenomena is sensed, SBS-UEs schedule a "unavailable" slot one SBSs-period in the future.

— **hidden** are the slots that cannot be received, because the transceiver is in TX mode. They are scheduled, as for OOC, in all of the slots belonging to the same LTE subframe as the internally allocated ones.

Free slots, wherein no transmission is envisioned or expected, are not modeled for efficiency reason. The absence of any event scheduled for the coordinate of a given packet slot is interpreted as that slot being free.

4.1.5 *Static evaluation by simulation*

The static evaluation by simulation, serves the double purpose of validating the analytical results, and test the protocols' behaviors under ideal conditions, but with a more realistic setup than possible with mathematical models.

We are specifically interested in comparing the fundamental behavior of STDMA, OSTDMA, SH-STDMA, and OOC in terms of packet reception probability versus a new metric we defined as OCL. OCL, in a isolated network wherein all of the SBS-UEs are within respective TX/RX range, represents the ratio of the slots that are necessary to satisfy the communication needs of all the SBS-UEs, and the total number of available slots. For instance, if the SBS period contains 100 slots, and 5 SBS-UEs are in the network, each transmitting 10 packets per SBS period, they would need 50 packets slots per SBS period to satisfy their communication needs, which results in a OCL of 0.5. If on the other hand there were 10 SBS-UE in the same setting, the resulting OCL would be 1.0. OCL can indeed be larger than one, wherein more slots are needed than the ones that are available.

We are interested in the fundamental behavior of the different protocols to increasing OCL, i.e. to increasing densities of SBS-UEs, in a ideal LTE V2X channel configuration. We thus configured the simulator to not apply transmission degradation due to propagation: the system's performance are hence limited only by collisions (which happen every time any of the SBS-UEs in the system transmit within the same packet slot), and by HD impairment.

During the simulation, the number of SBS-UEs is progressively increased by dropping new ones in a random position within range of all of the previous ones. After being dropped, SBS-UEs remain static in that position. The reaction of the protocols to increasingly high offered channel loads is then logged, and averaged. The results, obtained by averaging multiple Montecarlo simulation instance, are displayed and discussed in section 5.1.4.

4.2 DYNAMIC EVALUATION

Dynamic evaluation aims at showing the behavior of the protocol in realistic scenario, where mobility and propagation aspects are taken into account. The remainder of this section is organized as follows:

Topic	Section
Highway configuration and mobility model	4.2.1
Channel model	4.2.2
Dynamic evaluation metrics	4.2.3

4.2.1 *Highway configuration and mobility model*

We consider a 2-dimensional highway, with a wrap around configuration as illustrated in Figure 37, and recommended for the freeway configuration [56, §A.1.2], with the system parameters as described in table 11. At simulation

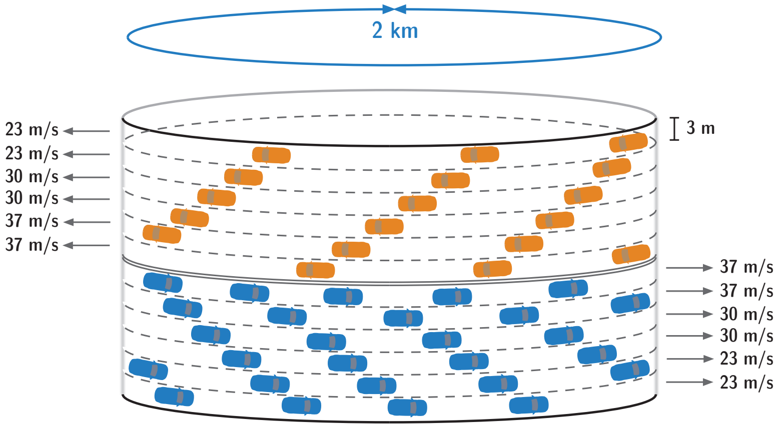


Figure 37 – Dynamic evaluation: highway simulation scenario

startup, vehicles are generated according to a Poisson point process per each lane, in order to achieve the target density. Vehicles are assigned a speed equal to the mean value for the lane they have been generated on, plus a random, normal distributed term with mean equal to 0 m/s and standard deviation equal to 1 m/s. Vehicles then proceed on a straight line until the end of the highway, after which a wrap around is applied, i.e. they re-appear maintaining the same speed on the other end. Lane changing is not simulated: if a vehicle reaches another vehicle driving in the same lane in front of it (because of the speed difference introduced by this random component), it "overtakes" it by passing through it. The concept of wrap-around is applied to the propagation of transmissions alike. This is done to improve the computational efficiency of

Table 11 – Simulation: highway configuration parameters

Parameter description	**value**
Highway length	2 km (wraparound)
Number of lanes per direction	6
Lane width	3 m
Average vehicular speed per lane (lower speed on external lanes, higher speed in central lanes)	23 m/s, 23 m/s, 30 m/s, 30 m/s, 37 m/s, 37 m/s

the simulator, since it eliminates the necessity of guard areas that compensate for the border effect, which means that at any time (except for the transient at the very beginning of the simulation) all of the vehicles being simulated are actively producing samples. As a further effect, the number of vehicles in the system remains constant during each simulation run.

4.2.2 *Channel model*

The channel model is a fundamental aspect of the simulation toolset, as it deeply influences the reception performance. This is particularly relevant for reservation-based protocols such as STDMA, as the reception of reservation information of other terminals is a fundamental principle on which medium access is based.

In this work we will consider the SBS resource pool to be allocated within the ETSI ITS-G5 CCH (5895-5905 MHz, with central frequency $f_0 = 5900$ MHz), which is also listed by the 3GPP in the bands for LTE V2X (band 47).

We apply the channel model configuration as in [90] which is based on a measurement campaign performed by the authors of [138] in Pittsburgh, PA, USA. Despite being taken within a urban area, the measurement in [138] are applicable in a highway scenario, since they concern large roads, in areas far away from tall buildings. The propagation model consists of a two slopes path loss and a Nakagami-m fading.

According to the dual slope path loss, of which an instance is represented by the solid magenta line in Figure 38, the power $P_{pl,dBm}(d)$ in dBs at distance d from the transmitter is computed as in equation (42)

$$P_{pl,dBm}(d) = P_{TX,dBm} + G - L + 20\log_{10}\left(\frac{\lambda_0}{4\pi d_0}\right) + \begin{cases} -10\gamma_1 \log_{10}\left(\frac{d}{d_0}\right) + X_{\sigma_1} & d_0 \leq d \leq d_c \\ -10\gamma_1 \log_{10}\left(\frac{d_c}{d_0}\right) - 10\gamma_2 \log_{10}\left(\frac{d}{d_c}\right) + X_{\sigma_2} & d > d_c \end{cases} \tag{42}$$

where:

— $P_{TX,dBm}$ is the transmitted power in dBms;
— G is the combined TX/RX antenna gains in dBs;
— L is the net loss in dBs due to cabling and TX/RX electronics;
— λ_0 is the wavelength;
— d_0 is the distance at which the first slope starts. We assume that any terminal closer to the transmitter than d_0 receives a power equal to $P_{TX,dBm}$;
— d_c is the (critical) distance at which the second slope starts.
— γ_1 and γ_2 are the path loss exponents for the first and second slope respectively;
— X_{σ_1} and X_{σ_2} are random Gaussian distributed variables with 0 mean and standard deviation equal to σ_1 and σ_2 respectively.

Those parameters are set according to the values in Table 12.

Fading is based on the Nakagami-m distribution [139], which has been widely recognized as an accurate channel model for vehicular highway scenarios. It is able to account for both small scale and large scale fading; according to the value assigned to the m parameter it can represent Rayleigh fading,

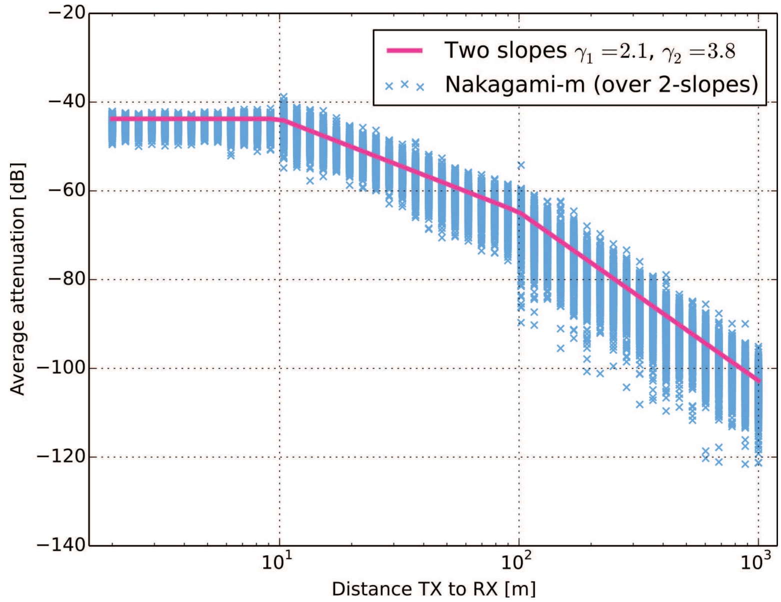


Figure 38 – Dual Slope Propagation with Nakagami-m fading

Table 12 – Propagation Model parameters

Parameter	Value	Description
d_0	10 m	start distance of slope 1
d_c	100 m	start distance of slope 2
γ_1	2.1	Path loss for slope 1
γ_2	3.8	Path loss for slope 2
G	4.5 dB	Global gain of the TX chain
L	3.4 dB	Global losses of the TX chain
λ_0	0.051 m	wavelength for $f_0 = 5.9$ GHz
σ_1	2.6 dB	standard deviation for slope 1
σ_2	4.4 dB	standard deviation for slope 2
$P_{TX,dBm}$	23 dBm	transmission power

where all received components are completely scattered, and the Rice fading, wherein both Line of Sight (LOS) and Non Line of Sight (NLOS) components are accounted for. The probability density function is given by equation (43).

$$f(x, m, \Omega) = \frac{2m^m}{\Gamma(m)\Omega^m} x^{2m-1} \exp(-\frac{m}{\Omega}x^2) \tag{43}$$

The Nakagami distribution has 2 parameters: a shape parameter m, and a spread parameter Ω. The shape parameter depends on the distance between the transmitter and the receiver, whereas the spread parameter is related to the mean received power.

The received power P_r (in linear units) at distance d from the transmitter is finally given by equation (44).

$$P_r(d) = \zeta \cdot P_{pl}(d) \quad (44)$$

where $P_{pl}(d)$ is the $P_{pl,dBm}(d)$ as computed in equation (42) converted into linear units, and ζ is a Nakagami-m distributed random variable, with the m parameter set as a function of the distance between the TX and the RX as in Table 13, and the spread parameter normalized to $\Omega = 1$, as indicated in [138, Table III]. From a practical standpoint, these Nakagami-m random variables can be generated according to the acceptance-rejection algorithm presented in [140]. A cloud of samples generated according to this technique is also represented in Figure 38.

The so-obtained channel model hence accounts for path loss, shadowing and fast fading: a sample representation of the power attenuation caused by the described setting is illustrated in Figure 38.

In order to maintain the focus on the MAC layer performance of the protocols under examination, in this work we will neglect the effects of inter-channel interference that might be caused by one transmission in one packet slot to the adjacent slots within the same subframe, which has been analyzed in detail by the authors in [141].

Table 13 – Nakagami fading m values

Distance TX-RX	m
$d \leq 6$m	4.07
6 m $< d \leq 14$ m	2.44
15 m $< d \leq 36$ m	3.08
36 m $< d \leq 91$ m	1.52
91 m $< d \leq 231$ m	0.74
231 m $< d \leq 588$ m	0.84
$d > 588$ m	0.84

4.2.3 *Dynamic evaluation metrics*

With the dynamic simulation setup, we aim at evaluating the behavior of OOC, STDMA, OSTDMA, and SH-STDMA in a realistic scenario with the channel and mobility models as previously described described in this section.

The main key performance indicator we are interested in are the Packet Reception Rate versus the distance between the transmitter and the receiver. Furthermore, we focus on the causes that lead to the loss of the transmissions that failed to be received correctly. Four possible causes were identified:

— **collision**: this case occurs when multiple packets are transmitted on the same packet slot, and a receiving SBS-UE fails to decode any of them because the resulting SINR does not allow it;

— **another stronger transmission**: this event occurs when, similarly to collisions, the same packet-slot is selected by multiple SBS-UEs for a trans-

mission. Differently from the collision case, the transmitter in this case manages to correctly decode one of these thanks to capture effect, because its SINR is sufficient to allow it. This cause is attributed to the packets that, on the other hand, were not successfully decoded;
— **half duplex impairment**: this cause is attribute to a transmission that takes place in a slot hidden to a receiving SBS-UE, that it would be successful had that slot not been hidden. This means that for instance, if a collision happen in a SBS-slot hidden to a certain receiver, that missed reception is labeled as due to collision, not to HD impairment;
— **path loss**: this case covers packet losses due to propagation effects, which include path loss, fading and shadowing. This happens for instance when the power of an incoming transmission falls below the sensitivity of a receiver of the SINR is too low to allow for correct decoding.

All of the aforementioned performance indicators are collected for three different setups:

— **globally**, i.e. by including all of the samples globally collected in the simulated area;
— by filtering TX/RX events between SBS-UEs traveling **in the same direction**;
— by filtering TX/RX events between SBS-UEs traveling **in opposite directions**.

This is meant to filter out the effects that mobility has on the protocols' behavior. By filtering only the reception events from transmitters moving on the same direction, we exclude the merging collisions from the performance computation. Their impact on the global performance is on the other hand highlighted when only the TX/RX pairs moving on different directions (i.e. located on opposite ways of the highway) are considered.

5 RESULTS

This chapter is dedicated to the illustration, comparison, and discussion of the numerical results presented in detail in Chapter 4. It will thus reflect its structure, with a first part dedicated to static results (section 5.1), and a next one dedicated to dynamic results (section 5.2).

5.1 STATIC EVALUATION: RESULTS

5.1.1 *OOC over LTE Sldelink: analytical performance results*

Basic system assumptions

For the static evaluation, we consider a LTE V2X system, wherein SBS-UEs are equipped with a single antenna, resulting in a broadcast Single Input Single Output (SISO) system, with general parameters as described in table 14.

Table 14 – General system parameters

Description	Symbol	Value
Antenna configuration		SISO
CAM packet size	l_{PKT}	300 bytes
Number of packet-slots per SBS-period	L	300
SBS-period duration	T_{SBS}	100 ms
Transmission rate		10 Hz

As according to the standard, each RB contains 12 subcarriers with 15 kHz inter carrier spacing (180 kHz/RB); normal cyclic prefix configuration is adopted, which results in each subcarrier carrying 14 REs per millisecond, i.e a total of 168 REs per RBP. QSPK modulation is used, with every RE thus carrying 2 bits. With this configuration, in order to be able to fit a 300 bytes CAM/BSM packet, slots need to be the union o $l_{RBP} = 8$ consecutive RBPs in frequency, which results in a total slot capacity of 336 bytes. At the time this work was developed, the standardization of LTE-V2X was still an ongoing process: the amount of overhead to be allocated for the transmission of pilot tones and/or time guard interval is thus not yet specified. For the evaluation in this work, we will hence abstract this, and for simplicity, we assume the aforementioned slot size is appropriate to host a CAM/BSM packet.

In the remainder of this section, we evaluate the performance of the proposed LTE-based V2X mechanism, and discuss on how the choice of system parameters affects its performance.

Probability of successful reception vs network density

In this section, we aim to highlight the effect of the number of retransmissions per SBS-frame on the packet-level performance. In order to maintain the analytical tractability, only relatively to this subsection we will temporarily ignore the effects of half duplex impairment. Figure 39 illustrates the packet delivery rate as a function of the network density, represented by the number of neighboring SBS-UEs: P_{cf} as in eq. (9) is plotted against the network density for $w = 2, 3, 4$ and 7 and $\lambda = 1$, in a scenario in which $L = 300$ slots per SBS-period are available. Higher number of retransmissions are shown providing

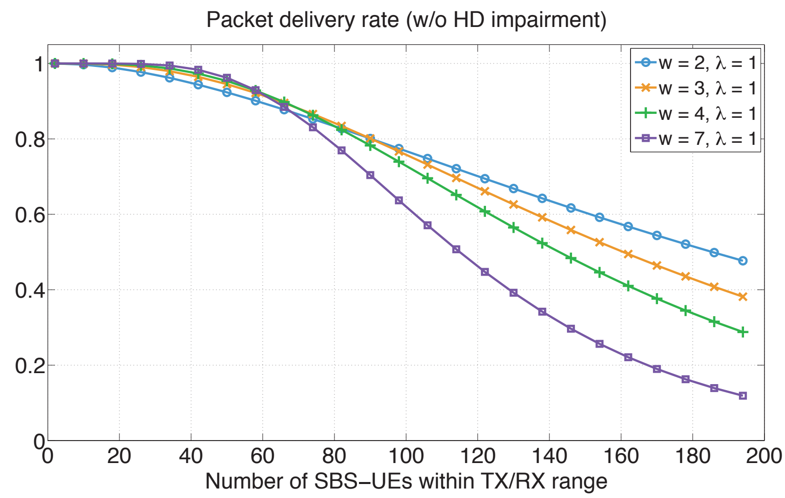


Figure 39 – Probability of collision-free slot within a SBS-period, vs w (SBS-period = 100 ms with $L = 300$ slots available)

slightly better performance for lower network densities, but quickly saturating the channel when the number of neighbors increases. The marginal benefit for low SBS-UE densities is thus overshadowed by the noticeable losses at higher densities. By increasing w, the crossover point between the curves moves leftward, towards lower number of neighboring SBS-UEs. It is worth noting, as remarked in sec. 3.4 and in [130], that the maximum size of the OOC codeset decreases with w and λ: higher values of w might thus also require tolerating higher cross-correlation λ, in order to be able to generate large enough codesets, fundamental for reducing the probability for multiple SBS-UEs to pick or be assigned the same codeword.

OOC: impact of Decentralized Channel Congestion Control

In this section, we illustrate how maintaining channel congestion affects the performance of OOC-based LTE V2X. In sections 3.1 and 3.7, it is described how SBS-UEs must locally find a trade-off between the TX rate and TX range (representative of the number of neighboring UEs) given a target maximum SL channel load. This trade-off is visually illustrated on Figure 40, wherein the optimal curve of transmission rate vs. number of neighboring SBS-UEs, for a reference SL channel load of 65%, in a configuration that has the SBS period carrying 6000 packet-slots.

The number of supported SBS-UEs on the vertical axis, can directly be related to the vehicular density once a transmit power is fixed. The curve in

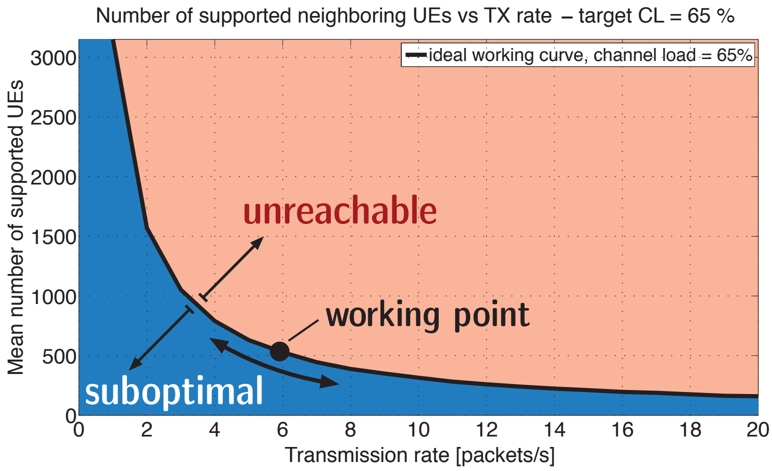


Figure 40 – Transmission rate vs Number of neighboring SBS-UEs for channel load 65%

Figure 40 was plotted by means of Monte Carlo simulations, generating a set of OOC codewords using the *greedy algorithm* in [127], and progressively adding SBS-UEs to the network up to the point in which the critical channel load is reached. Figure 40 depicts a curve separating two zones: (i) a first zone situated below the curve corresponds to a combination of (TX rate - number of SBS-UEs) leading to an under-utilization of the channel; (ii) a second zone situated above the curve corresponds to an unreachable combination of (TX rate - number of SBS-UEs), which leads to a channel load higher than the target. The curve is therefore the optimal operational point for unsupervised LTE V2X resource allocations, which may only select one parameter (TX rate or TX power), the second being automatically extracted from this curve.

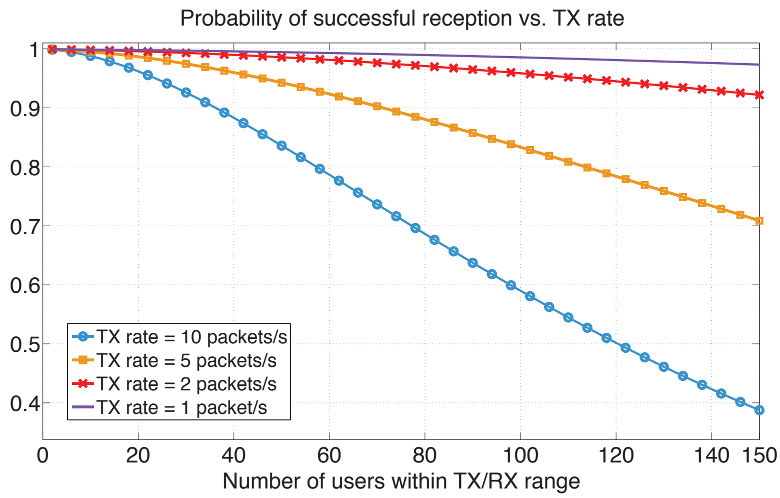


Figure 41 – TX Rate Adaptation in Unsupervised LTE-V2X

Figure 41 illustrates the impact of the Transmission Rate Control on the probability of successful reception P_s. The curves represent plots of Eq. (9) for different values of the parameter μ_p in (10), with values corresponding to the TX rate as in Table 15. When the perceived number of SBS-UEs within range is changing (due for instance to mobility, or channel fading), temporarily reducing the transmit rate allows more SBS-UEs to successfully transmit on the LTE

V2X SL. As it is shown on Figure 41, considered a target probability of successful reception equal to 0.9, TX rate of 10Hz may only allocate ≈40 SBS-UEs within respective TX range, whereas reducing it to 5Hz and 2Hz will enable up to ≈70 SBS-UEs and ≈160 SBS-UEs, respectively. These values should not be considered as a LTE D2D tight performance limit, as other parameters come into play, but as an illustration for the need to dynamically adjust the TX rate as function of the TX channel load in order to support the number of UEs in a given TX range required by a V2X critical safety application.

Table 15 – Correspondence between μ_p and TX rate in (10)

μ_p	TX rate
1	10 packets/s (max)
0.5	5 packets/s
0.2	2 packets/s
0.1	1 packet/s

OOC: probability of successful reception vs TX rate

We evaluate the impact of the transmission rate on the packet delivery rate, by plotting equation (19) for different values of μ_p in the equation (10). We consider the following values of μ_p: 1, 0.5, 0.2, and 0.1, which respectively correspond to statistical TX rates of 10 Hz, 5 Hz, 2 Hz, and 1 Hz. This is equivalent, for SBS-UEs, to only transmit packets in a subset of the SBS periods, effectively reducing their average transmission rate by a factor $(1 - \mu_p)$. In Figure 42 it

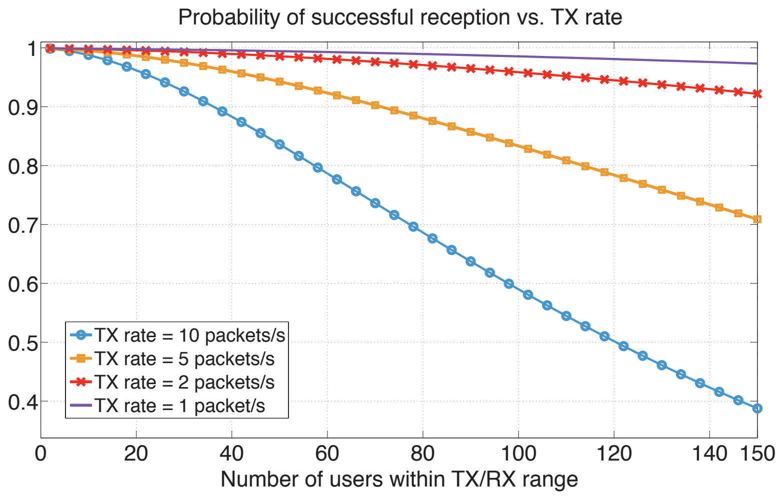


Figure 42 – Tx Rate Adaptation in Unsupervised LTE-D2D

can be observed that reducing the transmission rate can drastically improve the probability of successful reception. It is evident that the transmission rate reduction is an effective way to control the channel congestion when the network density increases. This is especially important for distributed channel access schemes such as the one we propose in this paper, since SBS-UEs need to autonomously apply congestion control mechanisms, based on the channel load they locally measure. These could act by modifying the transmission rate, with the effects as shown in Figure 42, or the transmission power, which affects the radio range, and consequently the number of SBS-UEs within range. It is for future study whether the existing congestion control mechanisms designed for 802.11p (based on CSMA/CA) will adapt to the LTE V2X channel access, or new one will need to be designed specifically for its slotted TDMA-like system.

Half-Duplex impairment evaluation

We compare the impairment effect due to half duplex on the probability of packet reception, for values of the SL bandwidth equal to $BW_{RB} = 16, 32, 48, 64$ and 96 RBs (corresponding to $n_s = 2, 4, 6, 8$ and 12 slots per subframe) against a case in which HD impairment is neglected. A reference scenario was chosen

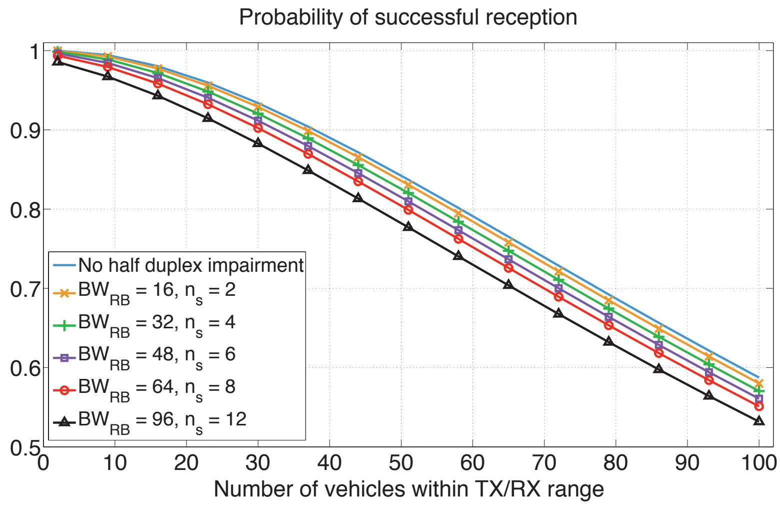


Figure 43 – Probability of collision-free slot within a SBS-period vs w and λ

with $w = 2$, $\lambda = 1$ and $L = 192$, which allows for a fair comparison, since 192 is a multiple of all the considered n_s values.

Table 16 – Time / Frequency occupation of SL configurations for a 100 ms SBS-period. BW in MHz does not include guard intervals.

n_s	BW_{SBS} [RBs]	BW [MHz]	Subframes needed	Coexistence efficiency
2	16	2.88	96	4%
4	32	5.76	48	52%
6	48	8.64	32	68%
8	64	11.52	24	76%
12	96	17.28	16	84%

Figure 43 and Table 16 illustrate the effect of different allocation policies for a target amount L (192, in this case) of slots per SBS-period. Excluding the upper bound case which neglects the HD impairment, the configuration that provides better reception performance is the one wherein the bandwidth of the SBS pool is only $BW_{SBS} = 16$ RBs, which corresponds to only having $n_s = 2$ slots co-located in time in each of the subframes, which minimizes the HD impairment. However, in this configuration, 96 subframes out of the 100 available in the SBS period must be assigned to the SBS pool. This means that SBS-UEs needs to be actively listening to the channel for 96% of the time. On the other side of the spectrum, when $BW_{SBS} = 96$ RBs, $n_s = 6$ slots are co-located in time in each of the SBS subframes; however, only 16 out of the available 100 subframes every 100ms need to be allocated to the SBS pool. SBS-UEs might thus enter an idle power saving mode during the remaining 84% of the time. This configuration, however, is the most affected by HD impairment, as shown in Figure 43. We refer to the ratio of subframe unoccupied by the SBS pool, hence exploitable by other coexisting technologies, as *"coexistence efficiency"*.

The choice of a optimal configuration is an open challenge for future work. On one hand, saving energy is particularly relevant for the implementation in battery-powered devices carried by pedestrians, cyclists and motorcyclists. On the other hand, the penalty in terms of probability of reception must be carefully weighted, as far as safety critical applications are concerned.

5.1.2 *OOC vs 802.11p: analytical performance comparison results*

In this section, we compare the performance of the scheme presented in this work against IEEE 802.11p. We evaluate 802.11p according to the system parameters in Table 17, and compare it against a collection of LTE V2X configurations, as in Table 17 and 18.

Table 17 – LTE V2X vs 802.11p: system parameters

802.11p		LTE V2X	
modulation	QPSK	modulation	QPSK
bandwidth	10 MHz	bandwidth	see Table 18
R_b	6 Mbps	R_b	see Table 18
TX rate	10 Hz	TX rate	10 Hz
R	500 m	w	2
slot duration	13 µs	λ	1
SIFS	16 µs	n_{RE}	168
DIFS	42 µs		
W	16		

The five scenarios we analyze for LTE V2X are labeled with letters from (a) to (e), and each presents a different time / frequency configuration, which results in different channel rates. In configurations (a), (b), and (c), for instance, all of the subframes ($N_{sf,SBS} = 100$ every 100 ms) carry the SBS resource pool, whereas in (d) and (e) only half of them do ($N_{sf,SBS} = 50$ every 100 ms). In this latter configurations, SBS-UEs can thus enter a power-saving state in the remaining 50% of the time, whereas in the former scenarios they need to be

Table 18 – LTE V2X configurations

config.	BW_{SBS} [MHz]	n_s	$N_{sf,SBS}$	L	R_b [Mbps]
(a)	16 (2.88)	2	100	200	5.37
(b)	32 (5.76)	4	100	400	10.75
(c)	48 (8.64)	6	100	600	16.13
(d)	32 (5.76)	4	50	200	5.37
(e)	48 (8.64)	6	50	300	8.06

tuned in to the SBS resource pool 100% of the time. Within these two group, different bandwidth are allocated to the SBS, resulting in different channel rates R_b and number of available slots L. The cost for the allocation of larger bands is a business matter in case of in-band deployment, and just a system parameter, to be weighted against HD impairment, in case of out-band development. The largest bandwidths are considered for scenarios (c) and (e), wherein the 8.64 MHz resulting from the allocation of 48 RBs to the SBS pool, plus guard intervals, is meant to fit the 10 MHz ITS control channel (CCH).

Probability of successful reception: LTE V2X vs IEEE 802.11p

Figure 44 compares the probability of successful packet reception, as a function of the network density, for the five configurations (a)-(e) of LTE V2X against IEEE 802.11p. One can observe that LTE V2X configurations (b) and

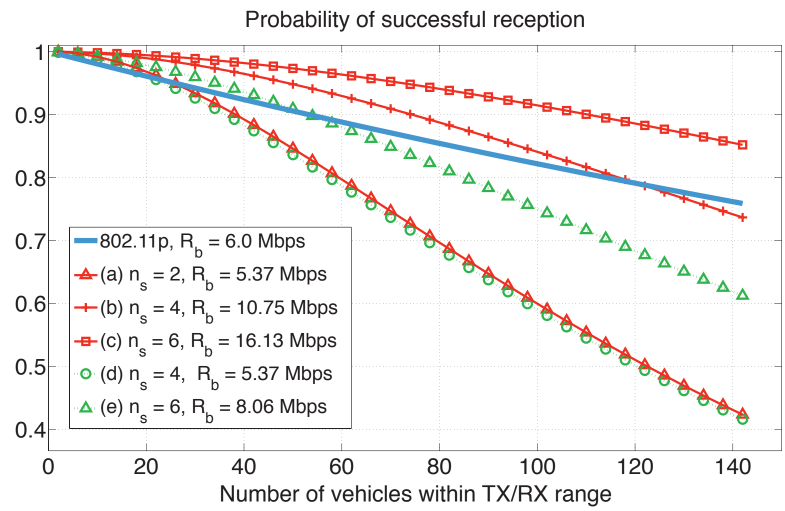


Figure 44 – Successful reception probability LTE D2D vs. IEEE 802.11p

(c), which enable the highest data rates, provide consistently better probability of successful reception than 802.11p. Specifically, (b) outperforms 802.11p up to about 120 SBS-UEs within range, after which the effect of the channel saturation due to the retransmissions causes a performance degradation. (c), on the other hand, provides better results beyond 140 SBS-UEs within range: specifically, at 120 SBS-UEs in range, it offers P_s 0.1 higher than both (b) and 802.11p. Scenarios (d) and (e), wherein only a fraction of the channel time is allocated to SBS pool, manage to provide performance comparable to or slightly better than 802.11p only for lower network densities. This, however, comes with the advantage of only requiring a subset of the available channel resources, which can be exploited for energy saving via discontinuous TX/RX, or used by 802.11p in the coexistence scheme illustrated in Figure 13b.

Inter reception time: LTE V2X vs 802.11p

Figure 45 similarly compares the mean Inter Reception Time for IEEE 802.11p, from equation (29) and for unsupervised LTE V2X, from equation (26), with the configurations and system parameters as in Table 17. Since the IRT is tightly

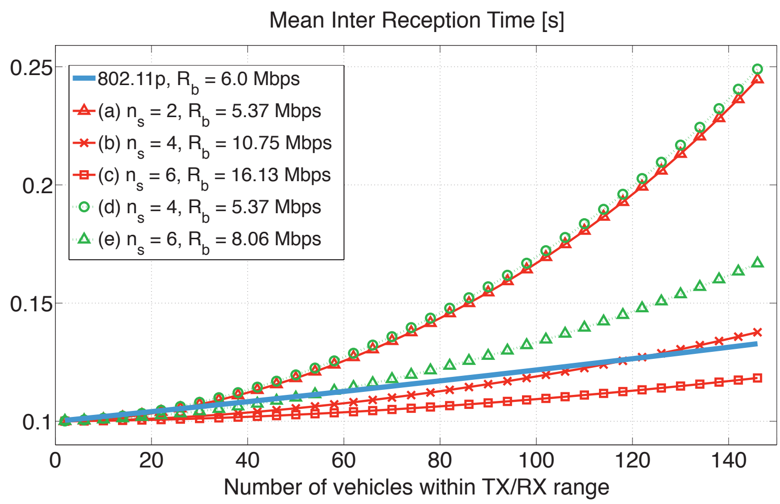


Figure 45 – Inter Reception Time: unsupervised LTE D2D vs IEEE 802.11p

related to the probability of successful reception, the curves reflects the results presented in Figure 44. It is worth remembering, however, that OOC-based LTE V2X performs multiple transmissions per SBS period. For our analysis, we considered the $w = 2$ packets transmitted every 100 ms to be identical replicas of each other; this results in the mean IRT being computed only between packets containing different information, i.e. transmitted in different SBS periods. By relaxing this hypothesis, and assuming that each packet contains fresh information, OOC-based LTE V2X can offer shorter (hence better) IRT.

5.1.3 *Self-Organizing TDMA: analytical performance results*

In this section the Slot Occupation Distribution (SOD) and Packet Level Incoordination (PLI) for STDMA are evaluated by computing the algorithm we proposed in section 4.1.3 in MATLAB for different parameters configurations. These metrics are specific to STDMA and well describe the behavior of the slot reservation process. Packet Delivery Ratio (PDR) can then be computed starting from them, once further hypotheses on transmission range and terminals disposition (out of the scope of this work) are made.

We evaluate the algorithm outputs for an *ideal* initialization (“Ideal S-TDMA"), a genie-aided system in which slots are exploited optimally up until enough free ones are available, and then the minimum number of slots is reused in case no free one is available.

For the timeout counter value, we consider two scenarios:

a. the extended values $t_{min} = 1$ and $t_{max} = 10^5$;

b. the standard [131] values $t_{min} = 3$ and $t_{max} = 7$.

Case a) is meant to reduce the spurious collisions due to simultaneous allocation of the same slot by multiple users. This phenomenon particularly affects our model due to the hypothesis of lack of knowledge of the concurrent reservation patterns. By comparing the values of a) with those obtained in scenario b) we can evaluate the impact of this phenomenon.

Slot Occupation Distribution

We compute the SOD for a system with $N = 860$ slots/frame, a value very close to the 859 slots/frame established in [91] for 800 bytes CAMs, that allows us to obtain exactly $OCL = 50\%$ with 43 users and a report rate of 10 packets/s, and $OCL = 100\%$ with the same 43 users transmitting 20 packets/s. In both cases $w_{CSmin} = 1$. In Figure 46 can observe that for low OCL, the algo-

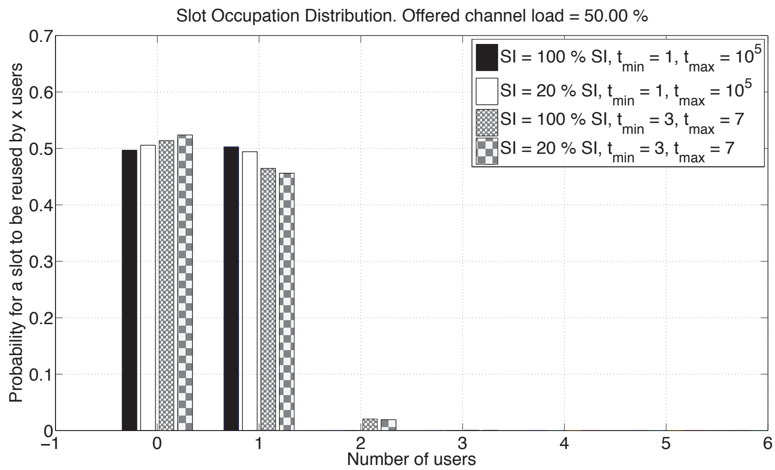


Figure 46 – SOD for OCL = 50%: $N = 860$, $N_t = 43$, $r = 10$

rithm describes quite well the expected behavior of the protocol. The size of the SI has little influence, since enough free slots are available in the CS for both configuration. When the standard timeout values are used, a small probability of slot reuse by 2 users is observed, due to the effect of simultaneous reservations of the same slot by multiple users. In Figure 47, the same scenario is evaluated for $OCL = 100\%$. In this case, we can observe that the output of the algorithm is less close to the ideal expected value of $\pi_1 = 1$, $\pi_i = 0, i \neq 1$. This behavior can be attributed to the stochastic algorithm modeling a deterministic phenomenon. In this specific scenario, we can observe how the SOD for standard timeout values provides the closest results to the expected behavior. This is due to the way the probability for a slot to be sensed free is computed in (39). A larger timeout counter range reduces the occurrences of simultaneous reservation by reducing the probability of a departure event $\pi_{t,1}$. As a side effect, the algorithm is less efficient in capturing the free slots left by the sporadic departures.

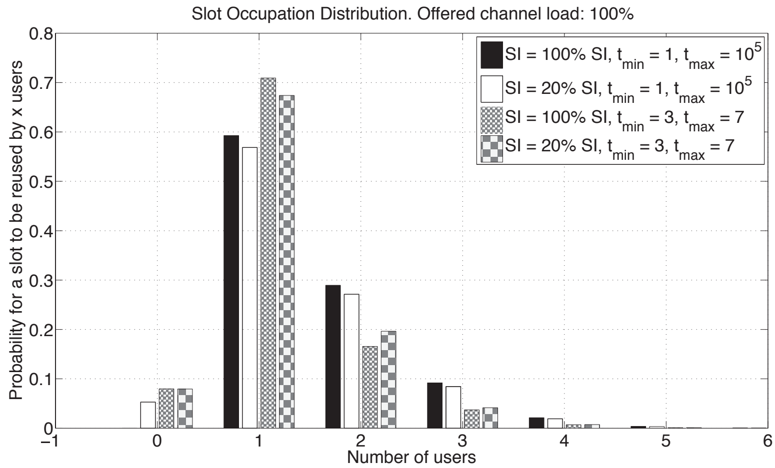


Figure 47 – SOD for OCL = 100%: $N = 860$, $N_t = 43$, $r = 20$

Packet Level Incoordination

In this section, we show the PLI in terms of its complementary, the Packet Level Coordination (PLC), or $(1 - PLI)$, the probability for one user not to have one transmission slot reused by other terminals. This metric is evaluated for timeout scenario a) in Figure 48 and for scenario b) in Figure 49. In both cases, we consider $N_t = 43$ users, with report rates spanning from $r = 1$ to $r = 40$ packets/s to obtain increasing values of OCL.

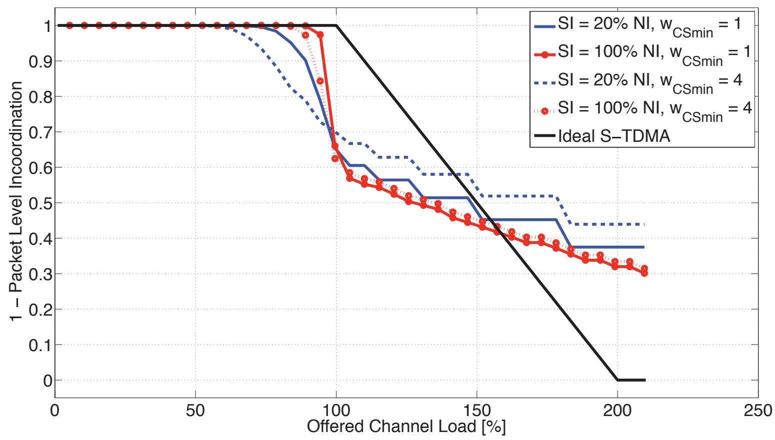


Figure 48 – Packet Level Coordination for $t_{min} = 1$ and $t_{max} = 10^5$

We can observe that the configuration with extended timeout counter range offers results closer to the ideal curve for $OCL \leq 100\%$, but then it tends to diverge from it for higher OCL values. On the other hand, the configuration with the standard values diverges from the expected curve earlier, but then, for higher OCL, the difference is lower. This behavior can again be attributed to the computation of the probability for a slot to be sensed free, which cannot efficiently capture the slots left free by re-reserving users in highly loaded scenarios.

The curves obtained for wider values of the minimum candidate set size w_{CSmin} introduce further impairment for higher OCL: this is originated by the

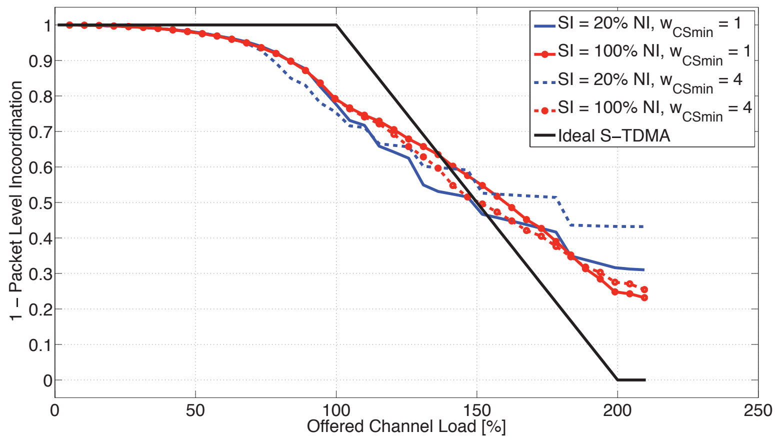


Figure 49 – Packet Level Coordination for $t_{min} = 3$ and $t_{max} = 7$

allocated slots that have to be included in the CS, which can be chosen with equal probability than the already scarce free slots.

5.1.4 *Static analysis by simulation: results*

In this section, we analyze the effect of the HD impairment on the STDMA reservation protocol by means of simulation, by using the simulator we described early on in this document in section 4.1.4. In order to isolated the effect of HD impairment on MAC layer, we consider a perfect PHY layer, and selected the parameters as in Table 19. We consider a scenario wherein all the UEs are within respective TX/RX range.

In Figure 50, the curves for STDMA are compared with and without considering the HD impairment, against the OCL. The OCL is a channel-side metric that accounts for the communication needs of all the UEs in a given area. In a slotted system, it represents the ratio between the number of slots needed to satisfy the communication needs of all the UEs in range of a given point and the number of slots available per second. Referring to the parameters in Table 19, with 900 slots available per second, and a report rate of 10 packets per second per UE, a OCL = 1.0 is obtained with 90 UEs within respective range.

STDMA without HD impairment

Three OCL regions might be identified, wherein the protocol shows different behaviors: the *low-to-mid*, the *mid-to-high*, and the *very high* OCL.

In the *low-to-mid* region ($OCL \leq 0.6$), the STDMA reservation mechanism shows a perfect MAC layer behavior. In this region, there is always more than w_{CSmin} free slots within the SI, which means that no slot reuse is needed.

In the *low-to-mid* region ($0.6 < OCL < 1.0$), the progressive reduction of free slots within the SI means that externally allocated slots are progressively added to the CS. Once they belong to it, they get the same probability of being chosen than free ones, which leads to increasing collisions. As mentioned in section 3.5.3, since slots are reserved for multiple consecutive frames, this causes recurrent collisions. The random nature of the selection is what causes

Table 19 – STDMA over LTE V2X: system parameters

Parameter	Value
Number of slots per frame (N)	900
Number of subframe per second assigned to the SL (N_{sf})	300
Number of packet-slots per subframe (n_s)	3
Packet type	CAM
Packet size (PHY) [bytes]	300
Channel Bandwidth [RBs]	50
Channel MHz [RBs]	10
Cyclic prefix configuration	normal
Number of REs per RBP	168 (12 subcarriers × 14 REs per subcarrier)
Modulation (spectral efficiency [bps/Hz])	QPSK (2)
STDMA parameters	**Value**
Report rate (r) [packets/s]	10
SI to NI ratio (s)	0.2
Minimum timeout value (t_{min})	3
Maximum timeout value (t_{max})	7
Minimum size of the CS in slots (w_{CSmin})	4

the 95% confidence interval to be wider in this interval, as raw performance is very much dependent on every instance.

In the *very high* region, the system is dominated by collisions, as free slots become very rare. In this extreme region, the behavior of the system becomes very predictable, as demonstrated by the very narrow 95% confidence region.

STDMA with HD impairment

The effect of HD impairment on STDMA can be observed by comparing the curve with the one not affected by it. Starting from the very beginning of the *low-to-mid* region, the performance moves away from the ideal benchmark, as the reservation information losses also happen at lower OCL. To this, we must add losses that each UE suffers of the packets transmitted in slots that are within the same subframe (time co-located) to its NTSs. The *mid-to-high* region shows the largest gap, as the effects of progressive addition of externally allocated slots to the CS and the HD impairment are combined. In the *very*

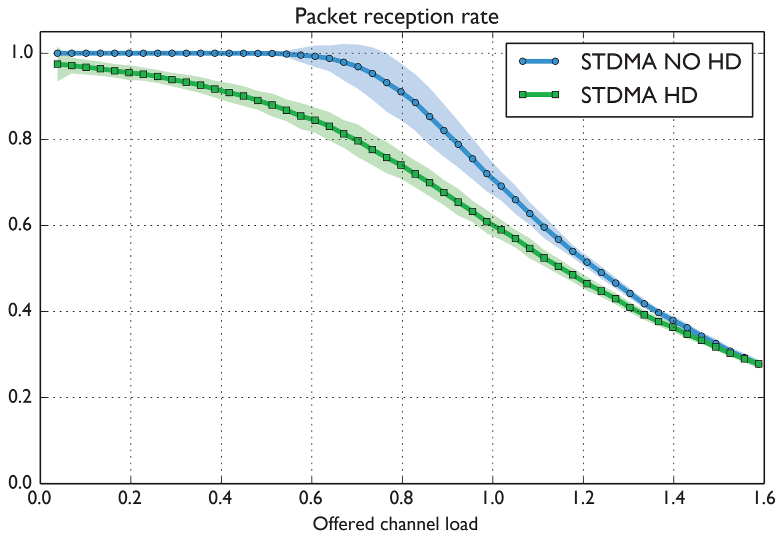


Figure 50 – STDMA comparison with and without HD impairment. The shaded area around the curves represents the 95% confidence interval

high OCL region, it is shown how the HD impairment becomes less and less relevant, as the system is dominated by collisions, by the fact that the curve superimposes with the ideal one.

Comparison with OOC

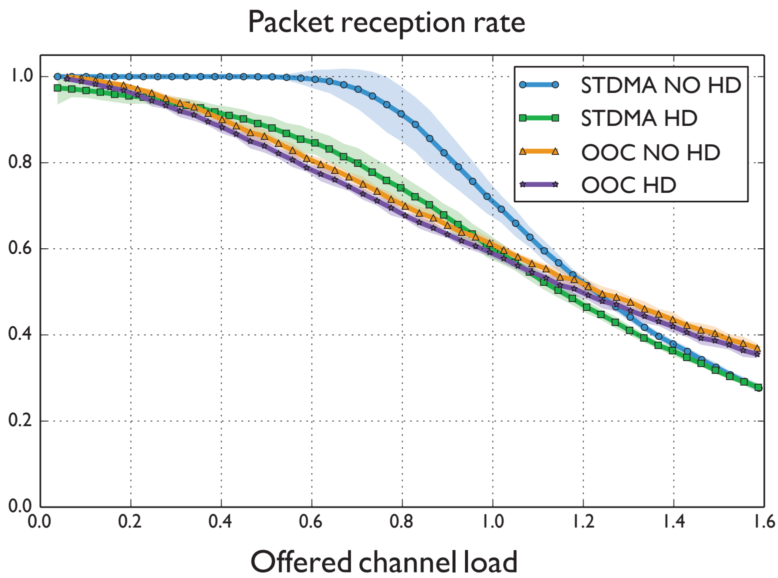


Figure 51 – STDMA and OOC comparison with and without HD impairment. The shaded area around the curves represents the 95% confidence interval

We proposed OOC as a distributed scheduling algorithm for LTE V2X in [16] and [20]. OOC are a blind channel access system that provides reliability by retransmitting multiple copies of each packet. Alike STDMA, OOC are based on a periodical structure, albeit with a shorter period of 100 ms, to support a maximum transmission rate of 10 packets/s. In the configuration of our choice, within each period, UEs re transmits $w = 2$ times each packet. The distinctive characteristic of OOC codesets makes it such that two separate UEs will collide at most $\lambda = 1$ times per period, thanks to their cross-correlation properties.

The results of the comparison of OOC and STDMA versus the OCL, both with and without taking into consideration the effects of HD, are shown in Figure 51. The OOC parameters are summarized in Table 20.

Table 20 – OOC over LTE V2X: system parameters

Parameter	Value
Period duration [ms]	100
Number of slots per period	90
Number of retransmissions per period (w)	2
OOC codewords maximum cross-correlation (λ)	1

From a pure MAC layer perspective, in the ideal case wherein HD is neglected, OOC offers generally worse performance than STDMA, because of its random nature. Furthermore, the retransmissions means that OOC generates a OCL w times higher than STDMA for the same amount of UEs.

On the other hand, the transmission redundancy and blind channel access show robustness against HD impairment throughout the whole OCL range. The only effect introduced by HD is in fact the loss of slots located within the same LTE subframe as each UE's transmission slots. The retransmission(s), however, compensate rather efficiently for this phenomenon.

Performance comparison

In Figure 52, the performance of STDMA, OSTDMA, and SH-STDMA are compared in a LTE V2X channel system as in Table 19, against the ideal case. The first thing we can observe, it that for lower OCL SH-STDMA provides optimal or near-optimal performance, thanks to its mechanism that avoids hiding users, allowing for a more efficient use of the channel's time dimension. When the OCL exceeds 25%, it becomes increasingly difficult to have subframes within the CS that are entirely made of free slots. It is worth noting that the 25% quote is dependent of the ratio between n_s and N. The considered scenario has the purpose of illustrating this phenomenon: realistic deployments might have much larger N (for instance, 3000 slots per second), and consequently larger SIs, which might move this point at higher OCL.

On the other hand, at lower OCLs, OSTDMA provides performance not too dissimilar from STDMA, since in this region performance are essentially affected by missed reception of hidden slots. The missed reception of reservation information is less relevant, due to the high availability of free slots in the CS, hence the lower probability of contemporary reservation of the same slot by multiple UEs.

In the *mid-to-high* region, one can observe a crossing between the SH-STDMA and the OSTDMA curves, with the latter starting to performing slightly better than the former. This phenomenon is very dependent on this specific simu-

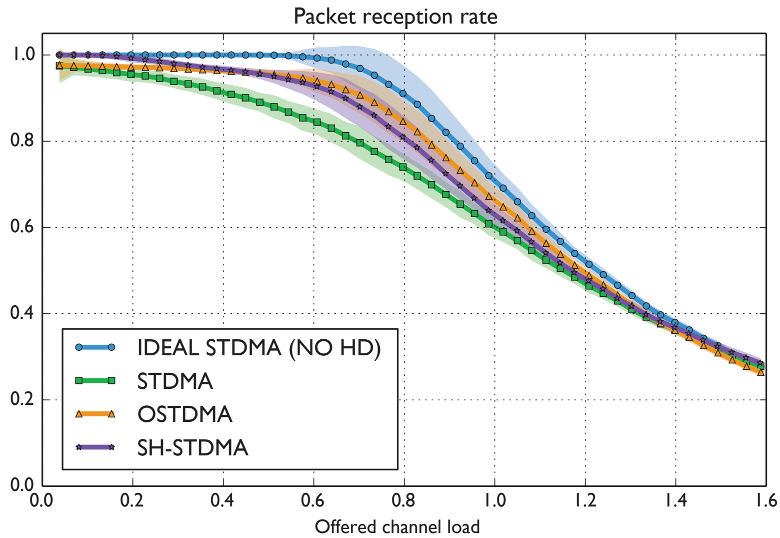


Figure 52 – Protocol extensions: OSTDMA and SH-STDMA vs STDMA. The shaded area around the curves represents the 95% confidence interval

lation scenario, and might be attributed to the choice of function $g(x)$ made for SH-STDMA, which does not assign a penalty to unavailable slots, those affected by collisions. The purpose of this perfect PHY configuration was to isolate the MAC layer performance; in a realistic implementation, however, those are also affected by the behavior of lower layers. Specifically, when fading is considered, in case of collision, the transmission coming from the closest UEs is likely to be received thanks to capture effect. In the scenario considered in this section, on the other hand, any kind of slot reuse makes a slot unavailable, hence considered by SH-STDMA as a viable slot to be hidden, by scheduling the NTS in a free slot located within the same subframe. The evaluation in a more realistic scenario will be done in a future work.

In the *very high* OCL region, the system is dominated by collisions, making all the scheduling systems perform equally, and equal to the ideal case.

5.2 DYNAMIC EVALUATION: RESULTS

In this final section, we present the simulation results comparing OOC, STDMA, OSTDMA, and SH-STDMA in a realistic scenario, wherein a mobility model and a channel propagation model is applied.

From the mobility standpoint, we consider a highway scenario, as described in section 4.2.1, with a 2 km long wrap-around highway, with 6 lanes per direction, wherein vehicles move according to the speeds listed in section 4.2.1.

From the channel and transceiver point of view, we consider the set of parameters listed in Table 21, whereas the parameters for OOC are listed in Table 22, and the parameters for STDMA, OSTDMA, and SH-STDMA are in Table 23.

We allocate a V2X sidelink resource pool in the ETSI Control Channel, wherein all of the available subframes are allocated to the pool. In such configuration, 3 slots can be allocated per subframe, which result is a 1 s long SBS period for STDMA containing 3000 slots; on the other hand, OOC have 100 ms SBS-period, within which each SBS-UE performs $w = 2$ transmissions.

Table 21 – Channel and transceiver parameters

Parameter	Value
Channel	10 MHz ETSI CCH
Packet type	CAM
Transmission power	23 dBm
Modulation and coding scheme	QPSK 2/3
Receiver sensitivity	-90.5 dBm
Minimum SINR for successful decoding (capture effect)	5 dB

Table 22 – OOC dynamic evaluation parameters

Parameter	Value
Hamming weight of OOC codewords (w)	2
Maximum cross-correlation between codewords (λ)	1

Table 23 – STDMA / OSTDMA / SH-STDMA dynamic evaluation parameters

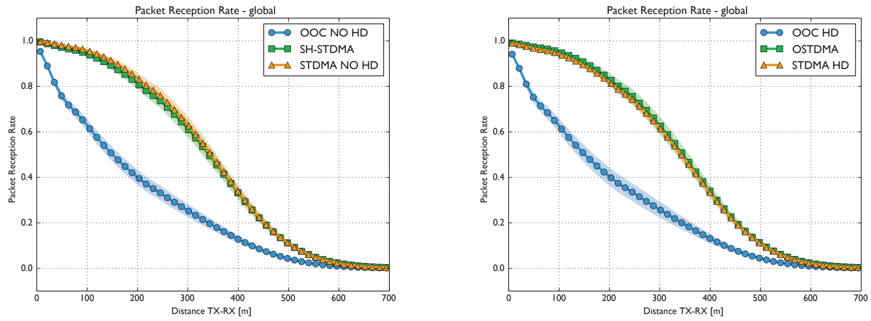
Parameter	Value
Report rate (r) [packets/s]	10
SI to NI ratio (s)	0.2
Minimum timeout value (t_{min})	3
Maximum timeout value (t_{max})	7
Minimum size of the CS in slots (w_{CSmin})	4

In the remainder of this section we will focus on a case which we find particularly interesting, with average vehicular density equal to 240 vehicles / km. In this configuration, the channel load approaches 100 %, thus challenging the protocols.

All of the figures presented in the remainder of this section have been obtained by averaging 15 Montecarlo runs, each simulating the system for 120 seconds. A 50 second transient is taken into account, during which SBS-UEs are started at random time instants, to allow the protocols to reach a steady state. During the transient, no sample were generated. The 95% confidence interval is displayed as a shaded area around each curve, wherever relevant.

5.2.1 *Dynamic evaluation: results for 240 veh/km*

In Figure 53, the Packet Reception Rate are compared for OOC, both considering and ignoring the effect of half duplex impairment, STDMA, both considering and ignoring the effect of half duplex impairment, and finally OSTDMA and SH-STDMA only in the half duplex scenario, which is the one they were specifically thought for. The curves have been split over two sub-figures to improve readability.



(a) (b)

Figure 53 – Packet reception rate versus TX-RX distance

We can observe that the OOC-based protocols are those most suffering the high vehicular densities, since their retransmission-based paradigm tends to saturate the channel well before other protocols. On the other hand, the STDMA-based protocols all tend to offer evenly remarkable performance. This also means that, despite suffering from HD impairment, the effect of these are less evident than the static analysis suggests, when propagation is factored in. Furthermore, in a realistic scenario, wherein the overhead of channel coding is to be considered, and low order modulations such as QPSK are to be used to ensure reliability, packet slots tend to span over large numbers of RBPs, which means that 3 slots can be stacked within the same subframe. This limits the number of reception losses due to HD, but should still make SBS-UEs miss precious reservation information. By missing such information, in fact, contending SBS-UEs might end up unknowingly reserving the same slot, which would lead to serial collisions, since these are reserved for several seconds, up until the timeout expires (a random amount of seconds in the range $[t_{min}, t_{max}]$). In reality, for high vehicular densities, and by considering the propagation effects, the HD effects are dominated by the collisions, due to the necessary slots reuse, to satisfy the communication needs of all the SBS-UEs.

Causes of missed RX for OOC

In Figures 54 and 55 are illustrated the causes that lead to a missed reception, respectively for OOC considering and neglecting the effect of HD. It is important to remind that for OOC, a transmission is considered received with success if at least one of the w retransmissions operated by the TX within one SBS period is correctly received by a given RX.

It is possible to observe the resilience of OOC to HD impairment: in fact, thanks to its retransmission mechanism, which minimizes the probability of losing both transmissions. Furthermore, due to the randomness of OOC it is possible to observe that no difference in performance can be observed when isolating vehicles proceeding in the same or in opposite directions.

In both cases, the contribution of propagation phenomena (here labeled generically as “path loss”) to missed reception is strictly a function of the

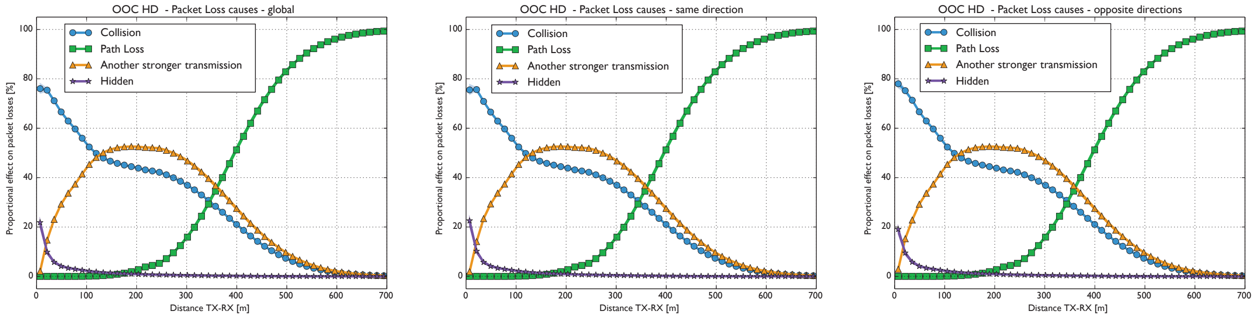


Figure 54 – Causes of packet loss for OOC with HD, 240 vehicles per km. **Left**: global performance; **center**: only couples of TX/RX proceeding in the same direction; **right**: only couples of TX/RX proceeding in opposite directions.

distance, and its behavior is unsurprisingly not affected by the protocol under test. This will also be the case for the remaining protocols in this section.

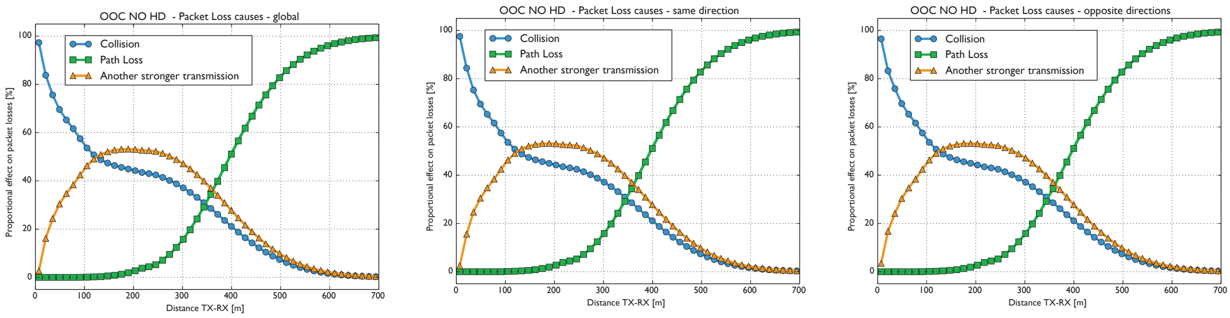


Figure 55 – Causes of packet loss for OOC without HD, 240 vehicles per km. **Left**: global performance; **center**: only couples of TX/RX proceeding in the same direction; **right**: only couples of TX/RX proceeding in opposite directions.

Causes of missed RX for STDMA

In Figures 56 and 57 are illustrated the causes that lead to a missed reception, respectively for STDMA considering and neglecting the effect of HD.

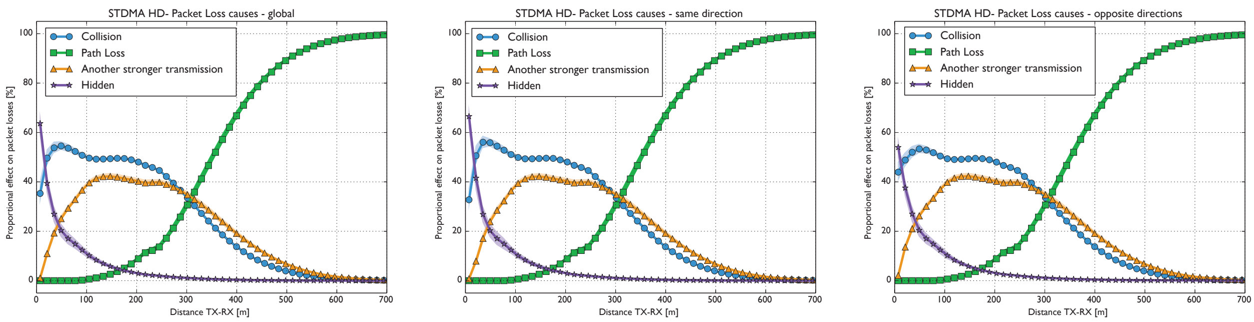


Figure 56 – Causes of packet loss for STDMA with HD, 240 vehicles per km. **Left**: global performance; **center**: only couples of TX/RX proceeding in the same direction; **right**: only couples of TX/RX proceeding in opposite directions.

With STDMA, it is possible to observe the impact of HD impact, which is the prime cause of missed reception at very short distances. Even though, as shown in Figure 53, few of the transmissions are lost, these are particularly dangerous in cases wherein the channel utilization is so high, as they deprive UEs from reservation information which might lead to serial collisions, which in fact are responsible for the most of the packet losses at distances between 25 and 300 meters.

At very short distance, we can observe that vehicles that proceed in the same direction suffer a 10 % higher influence of HD impairment with respect to vehicles proceeding in opposite direction. At the same time, however, they show being less subject to collisions. It is worth reminding that from a packet-level perspective, half duplex only cause a single SBS-UE to not be able to receive a packet because of its internal state, whereas collisions negatively affect the RX performance of the SBS-UEs in proximity of the colliding transmitters.

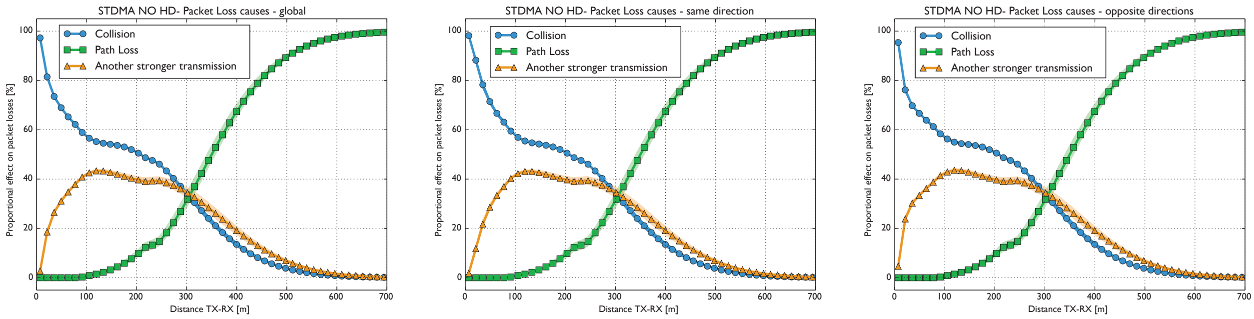


Figure 57 – Causes of packet loss for STDMA without HD, 240 vehicles per km. **Left**: global performance; **center**: only couples of TX/RX proceeding in the same direction; **right**: only couples of TX/RX proceeding in opposite directions.

Causes of missed RX for OSTDMA

Figure 58 illustrates the causes that lead to a missed reception for OSTDMA, when HD impairment is factored in. With respect to STDMA, at the time a packet-slot is to be reserved, OSTDMA excludes from the candidate set the slots that are hidden due to HD. It is shown providing a marginal yet consistent reception probability advantage over STDMA. With respect to STDMA, it shown a minor incidence on collisions at lower distances, which shows the re-reservation process is more efficient at avoiding them.

Causes of missed RX for SH-STDMA

Figure 58 illustrates the causes that lead to a missed reception for SH-STDMA, when HD impairment is factored in. The rationale behind SH-STDMA is to specific avoid collisions and packet losses due to HD impairment with SBS-UEs in close proximity. This is because they are those whose status is most important to keep updated, for multiple reasons. First of all, for collision avoidance reasons, as close-by vehicles and pedestrians are the ones to keep track of more accurately. Secondly, for positioning reasons, as these can be

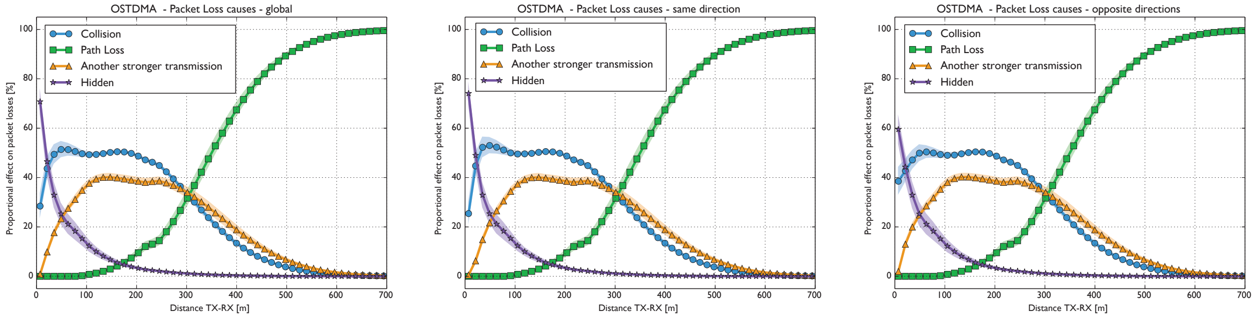


Figure 58 – Causes of packet loss for OSTDMA with HD, 240 vehicles per km. **Left**: global performance; **center**: only couples of TX/RX proceeding in the same direction; **right**: only couples of TX/RX proceeding in opposite directions.

used to improve the accuracy of the TX's position, as studied by the HIGHTS project. Thirdly, for automated drive applications, specifically related to the measurement of acceleration. There are in fact no affordable ways to measure the acceleration of another vehicle with onboard sensors, if not detecting a variation in the distance with it, at which point the acceleration / deceleration process has already started. This might cause instabilities in the control loops of applications meant to operate cruise control based on the position of other vehicles. On the other hand, by means of communications, it is possible to receive information about a vehicle's intention to reduce or increase speed, which allows for smooth and very compact platoons, which improve ride comfort and fuel consumption.

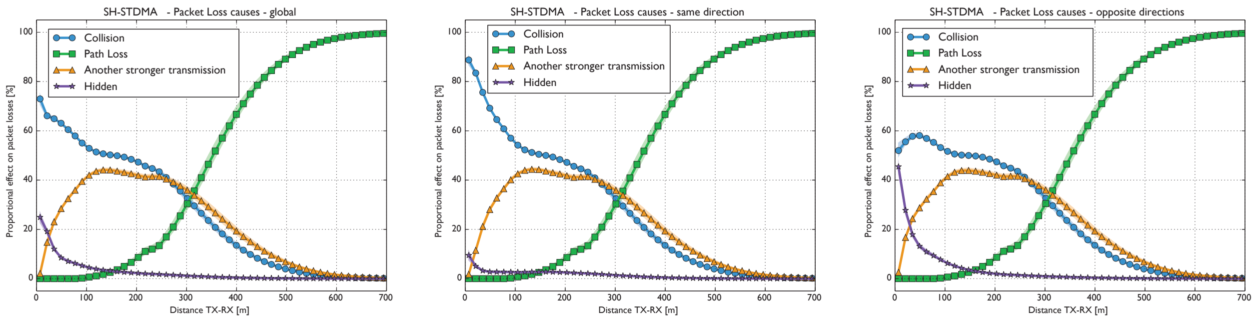


Figure 59 – Causes of packet loss for SH-STDMA with HD, 240 vehicles per km. **Left**: global performance; **center**: only couples of TX/RX proceeding in the same direction; **right**: only couples of TX/RX proceeding in opposite directions.

It is possible to observe that SH-STDMA significantly reduces the impact of losses due to HD at short ranges, thanks to the small size of the CS, which is always set equal to its minimum value, regardless of the amount of free slots in the selection interval, and to its penalty system. A penalty is assigned to each subframe based on the distance of the SBS-UEs whose transmissions would be hidden by transmitting in the same subframe as them.

It can be observed that the influence of HD related losses is globally reduced to 25 % at low distances, which is as low as 10 % if one considers only vehicles moving in the same direction, which show that SH-STDMA suffers more than the other protocols from merging collisions.

6 CONCLUSION AND PERSPECTIVES

6.1 CONCLUDING REMARKS

We live in a time wherein technological and scientific development proceed at a pace never seen before. The automotive domain, specifically, has seen in the last years one of the most breakthrough paradigm shifts it has ever experienced in its century-long history. In a world where automation is quickly becoming more relevant in cars, with the objective of one day being in full control of it, vehicular connectivity is becoming essential, thus opening technical challenges, as well as business and research opportunities. Vehicular connectivity is meant to serve a whole range of different purposes, ranging from safety-critical communications, to providing Internet connectivity for onboard infotainment, and cloud connectivity for a multitude of services, such as real time map updates, traffic efficiency and customer-tailored services offered by car manufacturers. Pushing the concept even further, cars are envisioned to become part of a much wider concept of the IoT and of the *Internet of Vehicles*, acting for instance as mobile array of sensors collecting data, or as mobile cache nodes, just to name a few. It is easy to figure out how many different paradigms of connectivity are necessary, just by quickly going through the list of the applications they will soon support.

The technological panorama, at the time the work on this thesis begun back in mid-2013, appeared fragmented and fractured. Specifically, concerning safety-critical communications, the research community had already been active for well over a decade in the domain of V2V communications. Standardization bodies were alike very active, which resulted in the specification, respectively in the EU and the US, of ITS-G5 and DSRC, both based on 802.11.

In parallel, however, LTE was becoming increasingly popular with consumer, fueling the connectivity needs of smartphone applications. Car manufacturers had already then started to sell connected vehicles, equipped with LTE technology, to extend such connectivity to cars, and to offer cloud-based services.

It appeared clear that, while 802.11 was the leading technology for horizontal ultra low latency communications between vehicles, LTE was affirming itself as the leading technology for vertical connectivity to the network. These two technologies, however, were evolving along separate paths, being supported by different industries, different communities, and different standardization bodies, despite operating in the same domain.

In 2013, this thesis was started with the purpose of integrating vehicular safety communications support in LTE, with several objectives in mind. Among these, extending the safety services to new class of road users, such as vulnerable road users, motorcyclists, and public transportation vehicles, so to make safety applications, previously limited to the cars, more inclusive.

Such an integration, however, was hiding technical and non technical challenges alike. At that time, in fact, no official V2V support was available from 3GPP; at the same time, the vehicular networking community was reluctant to consider LTE, a technology that differs from 802.11p in that it was meant to operate in licensed bands by a PLMN for a charge.

The first part of this work hence needed to be dedicated to making a case for technical work on LTE extensions to support V2X. A detailed study and analysis of the scenarios, the technological background, and both the standards on vehicular networking and LTE was performed. This first step was indeed important to convince member of both communities on the possibility offered by such integration. As a result of this, the decision was taken to tackle the problem by staying as close as possible to standards: the objective was thus to explore the ways LTE could be exploited to provide horizontal connectivity, in order to shed light on the directions to be taken for its future evolution.

Exploiting the time advantage on other related works, we were the first to propose innovative new concepts for LTE, such as envisioning a resource reservation based on resource pools, and taking away the scheduling duty from the eNodeB, in order to distribute it to the UEs. We proposed two paradigms to achieve this: a first one, based on eMBMS, relies on a novel interpretation, and different exploitation of an already available part of the standard. Despite not being adopted by the 3GPP, this paradigm was functional to illustrate the extensions needed to the standard to support V2X communications. The following year, when 3GPP introduced the SL for ProSe communication, we were able to extend our concept to it very rapidly, and propose it as a viable, standard supported resource reservation mechanism for LTE V2X. The 3GPP only officially announced working on LTE-based V2X much later, in 2016.

We finally examined two classes of distributed channel access algorithms, that tackle the problem of unsupervised channel access from two different perspectives: Optimal Orthogonal Codes, which blindly access the channel and provide reliability based on multiple transmissions and by protocol design, and STDMA, which is based on a reservation-based system, that efficiently exploits the channel and controls collisions. Both protocols were modeled analytically: in OOC, we extended an existing model for the packet reception probability to account for the impairment caused by HD. Furthermore, we showed the importance of a congestion control mechanism, and evaluated its impact on OOC performance. The performance of OOC were then compared against an analytical model of 802.11p, the only technology now available to support V2X, showing improved performance in low and medium densities networks. These are relevant scenarios, in that congestion control continuously acts to maintain the perceived channel load under control, which equates to the terminal perceiving a lower network density.

For STDMA, we derived a novel analytical model for the slot occupation distribution, and probability of successful reception for STDMA, a protocol that up until then had only been evaluated by means of simulations. Our models is aimed at showing the impact that the protocol's parameter have on its reception performance. From that study, it emerged that the re-reservation process is critical to the performance, because serial collisions are generate if multiple users chose to re-reserve the same packet slots for their transmissions. This can however be problematic when STDMA is applied to the LTE V2X channel we proposed, as half duplex impairment represents a new source of packet loss which may reduce the efficiency of the re-reservation process. For this reason, we proposed two protocol extensions for STDMA, designed to cope with this issue: OSTDMA, which eliminates the slots hidden due to HD impairment from the candidate set, and SH-STDMA, whose purpose is to mitigate losses due to HD of transmissions coming from the most nearby SBS-UEs, those whose information is most valuable.

The second part of the thesis was dedicated to the evaluation of the performances of these protocols by means of simulation, with a twofold purpose: first, validating the analytical results, and second to test the protocol's behavior in a realistic scenario. To do so, we developed our own simulation tool, which enables us to focus on the MAC layer evaluation, and controlling the level of abstraction to apply to the implementation of the PHY layer, since no specified PHY layer for LTE D2D exists yet.

The simulation confirmed the properties of the protocol in a static, ideal scenario, wherein the performance are only limited by MAC layer phenomena. When mobility and propagation effects are taken into account, the STDMA-based protocols shows capable of providing noteworthy performance also for high density networks, which on the other hand are very challenging for the random resource selection of OOC.

6.2 perspectives

Since day one, this thesis went on the direction of proposing a completely novel paradigm for two different domain of telecommunications. From the LTE perspective, this is a mode of operation wherein non Public Safety UEs are assigned a pool of resources to autonomously access, without supervision from the network. From the vehicular networking perspective, it is the adoption of a technology that is normally meant to be operated by companies for a charge, which can be solved by using the ITS dedicated band with a technology different from 802.11p. At the beginning of the works on this thesis, both sides would see this paradigm as unacceptable, and even nowadays, after being acknowledged by the community, there are resistances coming from both parties. It is hence normal that this thesis opened more problems than it solved, and with them, it opened many opportunities for future works.

From an analytical perspective, the mathematical models presented in this thesis might be improved, in order to extending their applicability. Specifically, the STDMA model can be extended to also cover transient phenomena, and model all of the protocol phases instead of the steady state phase only. The OOC models might benefit from a more detailed evaluation of the HD impairment, which covers broader cases.

As commercial deployment of V2X technologies gets everyday closer to being reality, the community is giving more and more value to prototype studies, which examine their behavior in real world deployments. Under this premise, realistic simulation and prototype implementations become more and more important. This is a more complicated issue than it is for ITS-G5, which can be freely tested and for which equipment and software development kits exist. In the case of LTE V2X, a difficulty is represented by the absence of a commercially available hardware able to support the waveforms for direct communications. On this respect, however, a very interesting future development is the implementation on the EURECOM-lead Open Air Interface (OAI) platform [142], which allows both a simulation and a emulation mode. The simulation mode will allow the testing of the system with full control of the environment, allowing and simplifying detailed studies on specific PHY-layer aspects like synchronization, adjacent carrier interference among slots, and co-existence with other technologies. Due to its complexity, however, simulation mode would not be able to support more than a few users at the same time.

Once the hardware for D2D communications will be made available, however, OAI will offer the support for a prototype deployment. For this specific case, however, the keyword is partnership: such a deployment would in fact require equipment, resources and a considerable manpower, which can only be achieved with the cooperation between academic members, vehicle manufacturers and operators, all of which have high interest in LTE V2X nowadays.

Regardless of the direction that commercially-deployed automotive solutions will take, either adopting the already available 802.11p-based solutions, or the rapidly emergent 3GPP-based cellular technologies, this thesis has provided some contributions useful for the future evolution of cellular networks. We are in fact in the transition phase between the fourth and the fifth generation of cellular network, and soon the defining aspects of the new generation, such as the architecture and the radio interface will need to be finalized and standardized. For this reason, more research then ever is needed to determine in which directions the technology needs to evolve and which are the modifications it needs and could afford to undergo to satisfy new needs.

This last point is particularly critical for 5G, which was entirely conceived starting from the new use cases and scenarios that will be supported in future by the network, which include industry 4.0, eHealth, energy and indeed automotive. By design, 5G will offer a much improved flexibility with respect to 4G, including a new modular architecture and new communication types such as device-to-device. With this thesis, we explored a novel communication type that opens for a new communication scheme, the periodical broadcast, that is paramount to support automotive safety communications. We proposed a mechanism to set it up, and evaluated its performance. These results will be useful to shape the evolution of the transmission techniques for cellular network. Comparing them with the research results coming from groups working on different techniques, such connection-based ones, will help the community and the standardization bodies establish what is the best way to offer V2X safety communications.

Appendices

A PROSE CHANNEL ACCESS

In this appendix, details about the ProSe standard are provided, specifically concerning the frequency allocation, discovery procedure, and resource allocation mechanisms for scheduled and unscheduled modes foreseen for D2D unicast transmissions.

A.1 SIDELINK FREQUENCY ALLOCATION

The Sidelink is defined as a subset of the UL channel resources in which ProSe transmissions can take place, and is limited to the bands indicated in Table 24 [49, Table 5.5D-1: E-UTRA ProSe operating bands].

Table 24 – ProSe operating bands

E-UTRA ProSe band	E-UTRA operating band	ProSe UE transmit F_{UL_low} - F_{UL_high}	ProSe UE receive F_{DL_low} - F_{DL_high}	ProSe duplex mode	ProSe direct Disc.	ProSe direct Comm.
2	2	1850 MHz – 1910 MHz	1850 MHz – 1910 MHz	HD	Yes	
3	3	1710 MHz – 1785 MHz	1710 MHz – 1785 MHz	HD	Yes	Yes
4	4	1710 MHz – 1755 MHz	1710 MHz – 1755 MHz	HD	Yes	
7	7	2500 MHz – 2570 MHz	2500 MHz – 2570 MHz	HD	Yes	Yes
14	14	788 MHz – 798 MHz	788 MHz – 798 MHz	HD	Yes	Yes
20	20	832 MHz – 862 MHz	832 MHz – 862 MHz	HD	Yes	Yes
26	26	814 MHz – 849 MHz	814 MHz – 849 MHz	HD	Yes	Yes
28	28	703 MHz – 748 MHz	703 MHz – 748 MHz	HD	Yes	Yes
31	31	452.5 MHz – 457.5 MHz	452.5 MHz – 457.5 MHz	HD	Yes	Yes
41	41	2496 MHz – 2690 MHz	2496 MHz – 2690 MHz	HD	Yes	
68	68	698 MHz – 728 MHz	698 MHz – 728 MHz	HD	Yes	Yes

One can observe that, being the Sidelink identical both in TX and in RX by ProSe UEs, within each band the bounds for transmit and receive frequencies are also identical. Within the bands in Table 24, the eligible channel widths for the sidelink are equal to:

— 5, 10, 15 or 20 MHz for discovery (PSDCH) ;
— 5 or 10 MHz for broadcast, control and shared channels (PSBCH, PSCCH, PSSCH);

cfr. [49, §A6.2 to A6.5].

A.2 DIRECT DISCOVERY

Discovery is the service that allow ProSe-enabled UEs to detect each other's presence in proximity. In ProSe, discovery and communications are defined as standalone services, which can either be functional to each other or be performed independently. The standard defines two modes of discovery [44, §5.3.1.2]:

— Model A: "I am here"

— Model B: "Who is there? / are you there"

In Model A, Announcing UEs advertise their presence by transmitting a discovery message on the PSDCH; at the same time UEs willing to discover other UEs in proximity (Monitoring UEs), monitor the PSDCH. In Model B, Discoverer UEs transmit a request on the PSDCH to verify whether there is an UE in proximity which is subscribed to the same ProSe application. If this is the case, the Discoveree UE (which monitor the PSDCH) replies with a direct message on the PSDCH with details about the discoverer's request.

A.2.1 *Resource Allocation for Direct Discovery [46, §14.3.3]*

The resource pool(s) for the PSDCH channel is (are) allocated based on the information contained on the System Information Block 19. SIB19 contains a list of up to 4 discovery resource pools for transmission and up to 16 discovery resource pools for reception. Discovery resource pools are periodically allocated every PSDCH period (determined by the `discPeriod` in SIB19, which can assume values between 32 and 1024 radio frames, 1 radio frame being equal to 10 ms). The subframe pool, however, does not necessarily span over the whole period: instead, it follows a generally shorter bitmap (between 4 and 42 bits), which gets repeated `numRepetition` consecutive times, where `numRepetition` is an integer in the range from 1 to 50, specified in the SIB19. There are two resource allocation modes for direct discovery [52, §5.15.1.1]:

— Mode 1: autonomous resource selection;
— Mode 2B: scheduled resource allocation

In mode 1, UEs choose the resources for the transmission of the discovery messages randomly within the PSDCH. Mode 1 is thus available in both `RRC_CONNECTED` and `RRC_IDLE`. The reception of mode 1 discovery messages can be impaired by collision.

In mode 2B, the UE requests a resource allocation to the eNodeB. Differently from other type of transmission, the allocation is not made via a DCI, but via dedicated RRC signaling instead. For this reason, mode 2B requires announcing or discoverer UEs to be in state `RRC_CONNECTED`.

A.3 DIRECT COMMUNICATIONS

ProSe supports both One-to-one and one-to-many communication paradigms, although the latter is reserved to Public Safety UEs [44]. ProSe supports two communications modes, which differ on the allocation scheme adopted for the transmission of the SCI on the Sidelink control channel PSCCH:

— Mode 1: scheduled resource allocation;
— Mode 2: autonomous resource selection.

In mode 1, transmissions on the Sidelink are authorized by the installed network, which provides the transmitting UE with PSCCH resources to transmit the SCI in, and PSSCH resources to transmit data in.

In mode 2, transmissions are unsupervised: transmitting UEs randomly choose the resources, within the PSCCH resource pool, in which to transmit the SCI.

A.4 PROCEDURES FOR SIDELINK TRANSMISSIONS

A.4.1 *Transmission mode 1 (Scheduled Resource Allocation)*

Prerequisites:

— The transmitting UE (UE_{TX}) is in state `RRC_CONNECTED`, and is being assigned a Sidelink Radio Network Temporary Identifier (SL-RNTI) by the eNodeB;

— The receiving UE (UE_{RX}) has already discovered UE_{TX}, and they are interested in the same ProSe application, characterized by a Group Destination Identifier

The procedure for UE_{TX} to transmit data to UE_{RX} on the Sidelink is the following:

1. When UE_{TX} has data to transmit on the Sidelink, it transmits to the eNodeB:
   a) Uplink Control Information (UCI) containing a Scheduling Request (SR) on the Physical Uplink Control Channel (PUCCH) (format 1) [46, §10.1] followed by a
   b) Sidelink Buffer Status Report (SL-BSR), detailing the amount of data that needs to be transmitted on the SL [52, §6.1.3.1a].
2. The eNodeB replies with a UL scheduling grant in the form of a DCI format 5, which is transmitted on the Physical Downlink Control Channel (PSCCH), with the Cyclic Redundancy Check (CRC) being scrambled with the SL-RNTI associated to UE_{TX} [46, §14.2]. The DCI format 5 contains [48, §5.3.3.1.9]:
   a) The PSCCH coordinates in which UE_{TX} will need to transmit the SCI format 0;
   b) The information to be included in the SCI itself;
3. UE_{TX} then transmits the SCI on the PSCCH coordinates specified by the DCI format 5. The SCI format 0 contains:
   — The Group destination Identifier of the ProSe application
   — The resource block assignment for the PSCCH
   — A frequency hopping flag for the PSSCH
   — A Time Resource allocation Pattern (T-RPT), a bitmap determining the subset of the UL subframes that will carry the PSSCH
4. UE_{RX}, which is interested in receiving ProSe communications, periodically monitors the PSCCH; when it finds a SCI whose Group Destination Identifiers matches a ProSe application it is interested in, it decodes it.
5. Based on the information contained on the SCI:
   a) UE_{TX} computes the coordinates of the PSSCH in which to transmit its data ([52, §5.14.1], and [46, §14.2.1]), while at the same time
   b) UE_{RX} computes the coordinates of the PSSCH in which to receive the data ([52, §5.14.2], and [46, §14.2.2]).
6. UE_{TX} transmits the data, UE_{RX} receives the data

A.4.2 *Transmission Mode 2 (Autonomous resource selection)*

Prerequisite: since no resource allocation is performed by the eNodeB , the following need to be preconfigured:

— A PSCCH resource pool, as allocated for transmission Mode 1;

— A PSSCH resource pool, similarly allocated, shared by all the Sidelink transmissions.

The procedure for a transmitting UE (UE_{TX}) to transmit data to a receiving UE (UE_{RX}) on the Sidelink is the following:

1. When UE_{TX} has data to transmit on the Sidelink:
   a) It randomly selects the time and frequency resources for the SL-SCH (the transport layer channel that maps onto the PSSCH at physical layer);
   b) It generates an SCI format 0 based on the set of resources selected at the previous step;
   c) It randomly selects resources within the PSCCH resource pool where
   d) It transmits the SCI generated at the previous step (which might be affected by collisions)
2. UE_{RX}, which is interested in receiving ProSe communications, periodically monitors the PSCCH; when it finds a SCI whose Group Destination Identifiers matches a ProSe application it is interested in, it decodes it.
3. Based on the information contained on the SCI:
   a) UE_{TX} computes the coordinates of the PSSCH in which to transmit its data ([52, §5.14.1], and [50, §14.2.1]), while at the same time
   b) UE_{RX} computes the coordinates of the PSSCH in which to receive the data ([52, §5.14.2], and [50, §14.2.2]).
4. UE_{TX} transmits the data, UE_{RX} receives the data.

B

VERSION FRANÇAISE

B.1 RÉSUMÉ

Les communications Véhicule-à-Véhicule (V2V) représentent une composante fondamentale pour les applications de sûreté telles que la conduite automatisée. Elles doivent donc respecter des strictes contraintes de fiabilité. Le standard de-facto pour V2V est actuellement 802.11p, qui a été formalisé en Europe par le European Telecommunications Standard Institute (ETSI) et aux États-Unis par le Federal Communication Commission (FCC). Au même temps, communication cellulaires comme le Long Term Evolution (LTE) sont aussi en train d'évoluer, pour pouvoir supporter le V2V. LTE, différemment de 802.11p, gère les communications de façon centralisée, ce que c'est une limitation pour le type de trafic, la topologie du réseau, et les contraintes de sûreté imposée par les communications véhiculaires. Toutefois, les dernières évolutions du standard LTE rendent possibles les communications Device-to-Device (D2D), qui ouvrent à l'utilisation de LTE en coexistence avec 802.11p. De cette façon, on fournis une redondance technologique qui est particulièrement importante pour les systèmes de sûreté. LTE D2D, notamment nommé Proximity Services (ProSe), retient une structure centralisée ; le mode opérationnel non supervisé par le réseau est maintenant réservé aux utilisateur de sûreté publique. Finalement, aucune des technologies couramment disponibles a été projetée pour supporter des applications véhiculaires. Le support de V2V à travers de LTE D2D, en particulier, nécessite d'une analyse attentive, car plusieurs questions se posent : comment peut-on transférer le contrôle des transmission de la station de base aux terminaux (véhicules) ? Comment est-ce qu'on peut exploiter la structure du canal radio LTE pour des communications broadcast, inter-cellules, et pan-opérateur ?

Dans cette thèse, nous montrons que les opérations non-supervisées, maintenant faiblement spécifiées en ProSe, sont essentielles pour V2V. Nous proposons un nouveau mécanisme pour V2V, qui partage le contrôle d'accès en deux phases : la phase de réservation des ressources, et l'ordonnancement distribué, dont seulement la première dépends du réseau. Nous proposons un mécanisme de réservation de ressources semi-statique, périodique, basé sur un groupement de ressources partagé. Ce système permets de organiser le canal en slots, qui permettent de traiter le problème de l'accès au ressources comme un système quasi-TDMA, dans lequel les slots sont arrangés en temps et en fréquence.

Nous présentons deux différents approches pour l'accès distribué au canal. Le premier, basé sur les Optical Orthogonal Codes (OOC), accède au canal de façon aléatoire ; le deuxième nommé Self-Organizing TDMA (STDMA), est basé sur la réservation de slots de transmissions, et exploite la connaissance des positions et des slots réservés par les autres véhicules. Leurs performances sont évaluées analytiquement, et comparées avec 802.11p. L'impact de la configura-

tion de canal LTE Vehicle to Everything (V2X) proposée sur les performances de ce deux protocole est évaluée mathématiquement et par simulation.

Le mécanisme cellulaire V2X que nous proposons permets communications broadcast, entre cellules différentes et opérateurs différents. La structure flexible du canal permet la coexistence avec 802.11p, ce que c'est problématique, à cause de la diversité entre les deux systèmes d'accès au canal. Nous montrons que OOC atteint une probabilité de réception meilleure de 802.11p, et au même ne subi que marginalement les pertes dues au fait que les slots sont disposés en temps et fréquence, et les terminaux opèrent en modalité half duplex. Toutefois, les performances de OOC dégradent rapidement quand la charge canal croit. STDMA, au contraire, atteint une performance meilleure de 802.11p et plus stable de OOC, mais son mécanisme de réservation des slots est plus sensible aux pertes de paquets due au half duplex, ce qui rend nécessaires des modifications pour l'adapter à la configuration LTE V2X proposée.

B.2 INTRODUCTION

B.2.1 *Le véhicule connecté*

Le temps futur ne sera bientôt plus nécessaire pour parler des véhicules connectés. Depuis plus d'un décennie en fait, l'industrie, l'université et la standardisation sont en train de travailler pour créer une plate-forme commune pour permettre aux véhicules de communiquer et d'interagir entre eux. Tout au début, des applications coopératives de sûreté et d'optimisation du trafic étaient envisagées. Ces applications sont nommées Intelligent Transportation System (ITS) par le département des transports américain [1], et Cooperative Intelligent Transportation System (C-ITS) [2] par l'Union Européenne et le ETSI [3], ces deux derniers étant particulièrement focalisés sur les aspects coopératifs. La connectivité requise par ce type d'application est "horizontale", soit permettant la communication directe entre terminaux.

Plus récemment, les nouvelles évolutions techniques dans les domaines de l'automobile et des télécommunications ont stimulé le développement de nouvelles classes d'applications liées à la connectivité véhiculaire. Les véhicules ne sont plus considérés que comme des moyen de transport : au contraire, ils deviennent des entités dans le paradigme du Internet of Things (IoT). De cette façon, la connectivité est étendue à plusieurs catégories d'utilisateurs, comme les piétons et les cyclistes, aussi nommés Vulnerable Road Users (VRUs), et des objets, comme par exemple des capteurs intelligents. Ce nouveau paradigme rends la connectivité plus complexe : une nouvelle dimension "verticale", qui connecte les utilisateurs au réseau, donc à Internet et au cloud.

Nous présentons trois approches différents aux communications véhiculaires :

— l'approche du Car-2-Car Communications Consortium (C2C-CC) ;
— l'approche de la 3rd Generation Partnership Project (3GPP) ;
— le approche du IoT.

Le C2C-CC est un consortium établi en 2002 entre constructeurs d'automobiles, centres de recherche et constructeurs d'appareils électroniques. La vision du C2C-CC est résumée dans son manifeste [4], qui identifie trois types d'applications véhiculaires :

— les applications de sécurité routière (**traffic safety**), qui incluent la signalisation coopérative de collision, sont basées sur l'échange périodique de l'état des véhicules. Celui inclus la position, la vitesse, l'accélération et la direction courantes. De cette façon, les véhicules sont conscients de la situation du trafic dans les alentours, et peuvent prendre des décisions qui bénéficient l'entière communauté des utilisateurs de la route ;
— les applications d'efficience routière (**traffic efficiency**) ont l'objectif d'améliorer la circulation en exploitant la connaissance de l'état courant du trafic. Un exemple est le service qui conseille la vitesse idéale pour traverser les feux de circulation avec le vert (Green Light Optima Speed Advisory (GLOSA)) ;
— les applications de infodivertissement (**infotainment**), connectent le véhicule avec internet et le cloud pour des application de cartographie et distribution de contenu multimédia.

L'architecture de communication conçue par le C2C-CC est essentiellement plate, basée sur des communications directes de proximité. L'idée à la base du paradigme de communication envisagé par le C2C-CC est que les applications de sûreté doivent être supportées par une technologie libre, qui opère dans une bande dédiée.

Le deuxième approche que nous considérons est celui de la 3GPP. La 3GPP est l'institution qui s'occupe de développer et maintenir les standards basés sur le Global System for Mobile communications (GSM), et aussi responsable des technologies LTE (4G) et 5G. Chaque nouvelle génération amènes des améliorations de performances, mais aussi le support de nouveaux scénarios et cas d'usage. La 5G Private Public Partnership (5G-PPP) est un partenariat privé-publique, spécifiquement actif dans la définition de ces nouvelles directions qui doivent être ciblés par les évolutions du standard. Les communications véhiculaires représentent un des scénarios qui ont été identifiés comme critiques pour la 5G [5]. D'un point de vue technologique, LTE part de l'avantage stratégique d'avoir déjà un réseau déployé, qui permet l'accès vertical, presque ubiquitaire, à internet. D'autre part, en 2013 (quand cette thèse a commencé), il n'offrait aucune possibilité de communication directe horizontale véhicule-à-véhicule.

Le troisième approche que nous considérons est IoT, qui envisage la connexion d'une multitude d'objets aux réseau, et entre eux. Dans cette vision, les véhicules mêmes, les capteurs, et les dispositifs à bord deviennent des entités faisant partie de ce vaste paradigme.

B.2.2 *Méthodologie*

L'objectif de cette thèse est d'introduire des extensions de la standardisation courante 3GPP LTE capables de supporter la connectivité horizontale pour applications véhiculaires. L'évolution du standard a joué un rôle très important dans le déroulement de ce travail : pour cette raison nous avons étudié les standards, à la fois du côte 3GPP et du côté ETSI c-its, à fur et à mesure que de nouveautés se rendaient disponibles. Tout au début de ce travail, en fait, la standardisation du D2D était dans une phase préliminaire, et aucun travail publique concernant le support du V2X par la 3GPP était disponible.

Dans la première partie de ce travail, une analyse qualitative des défis posés par V2X basé sur LTE est fournie. Celle-ce est nécessaire pour pouvoir proposer des protocoles adéquat aux nécessités. L'objectif est en fait de proposer des protocoles et les évaluer de façon analytique, avec particulière attention a l'effet que chaque paramètre a sur les performances.

Dans la phase suivante, les protocoles son modélisés par simulation. Un simulateur a été développé pour nous permettre l'évaluation soit dans des conditions idéales, pour valider les résultats obtenus analytiquement, soit en considérant des scénarios réalistes, qui considèrent les effets dus à la mobilité et à la propagation des signaux.

B.2.3 *Applicabilité*

Les concepts présentés dans cette thèse s'appliquent à plusieurs domaines des communications véhiculaires, concernant plusieurs catégories d'utilisateur de la route, comme illustré dans la Figure 60.

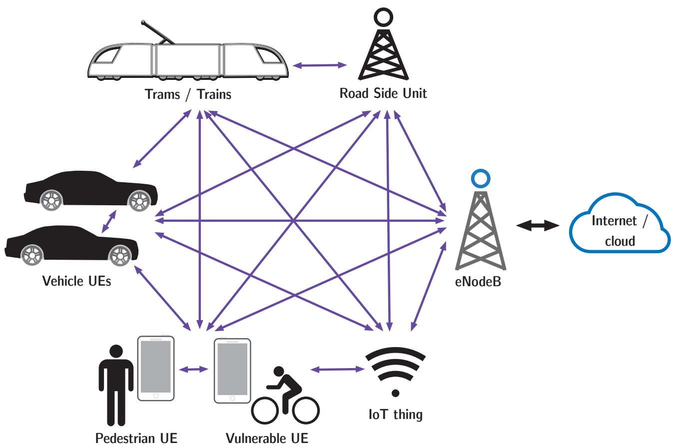


FIGURE 60 – Connectivité offerte par LTE plus LTE-V2X

La première partie de ce travail de thèse s'est déroulée dans le domaine du projet de l'Agence Nationale de la Recherche Système Télécom pour les Transports Urbains du Futur (SYSTUF) [143]. L'objectif de SYSTUF était de *"démontrer la faisabilité de l'utilisation d'une technologie de télécommunications unique telle que le LTE afin de répondre simultanément aux exigences et aux performances des applications vitales (contrôle-commande – Communication-Based Train Control (CBTC)) et non vitales (surveillance vidéo embarquée, télédiagnostic, maintenance - Closed Circuit Television (CCTV)) pour l'exploitant de transport collectif"*. Dans SYSTUF, la fonction du LTE V2X est fournir la connectivité directe entre trams, trains et tous les autres utilisateurs de la route, comme les piétons, les VRUs, et le réseau cellulaire.

Une application ultérieure de ce travail est la localisation à haute précision. Dans une deuxième phase, cette thèse a contribué au projet européen High precision Positioning for Cooperative-ITS (HIGHTS) [9]. L'objectif du projet est d'améliorer la qualité des mesures de position en exploitant les communications V2V. C'est particulièrement important achever des communications fiables, à faible latence, entre groupes sélectionnés de utilisateurs qui servent comme "ancres de mobilité".

B.2.4 *Panorama technologique*

Types de paquets

Le travail présenté dans cette thèse se focalise sur des communication à un saut, ayant la fonction de supporter des message périodiques, contenant informations critiques pour la sûreté véhiculaire. Soit en Europe que aux États Unis, les organismes de standardisation ont défini des spécifications pour ces paquets, qui portent information sur la position, vitesse et direction courante du véhicule transmetteur. En Europe, ce message sont nommés Cooperative Awereness Messages [123], définis par le ETSI. Les CAMs supportent deux possibles tailles, 300 octets et 800 octets, et nécessitent d'un taux de transmission entre un minimum de 1 paquet/seconde et un maximum de 10 paquets/seconde. Aux États Unis, un type de paquet analogue a été défini par la Society of Automotive Engineers (SAE), nommé Basic Safety Message (BSM) [144]. Dans le reste de cette thèse, les messages CAM seront considérés ; cette hypothèse ne cause aucune perte de généralité des résultats, qui seront donc également valides pour les BSMs.

Bandes de fréquence

Bien que avec des structures différentes, les gouvernements en Europe et aux États Unis ont réservé une partie du spectre électromagnétique aux transmissions véhiculaires, comme illustre en Figure 61. Dans tous les deux cas, cette bande est autour des 5.9 GHz : en Europe, 50 MHz sont alloués entre 5855 MHz et 5925 MHz [13], tandis que aux États Unis la FCC a réservé 75 MHz entre 5850 MHz et 5925 MHz [14]. Dans les deux cas, ces ressources sont partagés en canaux de 10 MHz, avec la possibilité de former des canaux de 20 MHz en couplant deux.

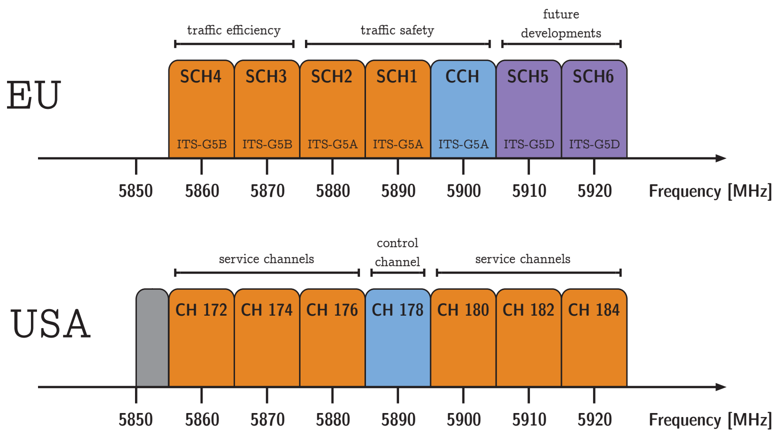


FIGURE 61 – Allocation des bandes de fréquence pour ITS-G5 en Union Européenne (EU, suivant l'acronyme anglais) et pour Dedicated Short Range Communications (DSRC) aux États Unis (USA, suivant l'acronyme anglais)

Deux typologies de canaux sont définies : le Control Channel (CCH), et les Service Channels (SCHs). Le CCH est le canal de référence, réservé pour communication de sûreté routière, sur lequel tous les véhicules doivent se syntoniser par défaut. Les SCHs, au contraire, peuvent supporter soit des communications de sûreté que d'autre type.

Technologie de transmission : 802.11p

Le type de trafic particulier imposé par les CAMs/BSMs a requis la définition d'une technologie de transmission dédiée. Le département des transports américain que l'ETSI ont convenu d'utiliser 802.11 à ce propos, comme fondation des technologies DSRC et ITS-G5 respectivement. 802.11p et un amendement du WiFi, conçu pour fonctionner hors du contexte du Basic Service Set. 802.11p ne nécessite pas de points d'accès, et est à même de supporter trafic de type Internet Protocol (IP) et non IP. En 2012 il a finalement été intégré dans le standard WiFi [15].

La couche physique (PHY) du 802.11p sur la configuration Orthogonal Frequency Division Multiplexing (OFDM) héritée de 802.11a. Quand configuré pour opérer dans un canal de 10 MHz (comme le CCH), celui-ci porte 64 sous-porteuses, desquelles 48 portent des données, 4 les pilotes, et les restantes 10 servent de intervalle de garde. La distance en fréquence entre deux sous-porteuses est la moitié de 802.11a (156.25 kHz en lieu de 312.5 kHz), ce qui porte une durée de chaque symbole double par rapport à 802.11a. Les modulations supportées sont Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), 16-Quadrature Amplitude Modulation (QAM), et 64-QAM. Selon la taille de la bande, et le type de modulation et codage de canal, différent débits sont supportés, comme indiqué en table 25.

TABLE 25 – Débits supportés par 802.11p [Mbps]

3	4.5	6	9	12	18	24	27
Configuration pour CCH : bande de 10 MHz, mod. QPSK							

Pour ce qui concerne le contrôle d'accès (couche MAC), 802.11p est basé sur Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), un type d'accès qui prévoit que les utilisateur écoutent le canal avant de transmettre (approche Listen Before Talk (LBT)).

B.2.5 *Objectifs et contributions*

L'objectif de ce travail de thèse est d'explorer mécanismes et stratégies pour supporter la connectivité entre utilisateur de la route, pour supporter les communications de sûreté routière. Les contributions de cette thèse sont résumés dans le reste de ce paragraphe.

Une description compréhensive de l'état de l'art est fournie, couvrant l'état de la standardisation, des activité et des projets de recherche.

La définition d'un nouveau mécanisme de réservation des ressources et un paradigme d'allocation des ressources pour LTE V2X. Ce mécanisme prévoit que le canal soit organisé en groupements semi-statiques de ressources, et le contrôle de l'accès à dites ressources est assigné aux terminaux (UEs) au lieu que à la station de base (evolved Node B (eNodeB)). Nous appelons ce paradigme "non-supervisé" et "centralisé", qui s'oppose a l'ordonnancement supervisé centralement par le eNodeB en LTE Rel. 8 et Rel. 10.

Deux différentes techniques sont proposés pour réserver le groupements de ressources de canal : la première, basée sur evolved Multimedia Broadcast Multicast Service (eMBMS), est basé sur une nouvelle interprétation d'un standard existant. La deuxième est basé sur le Sidelink (SL), une nouvelle interface directe UE-à-UE définie par la 3GPP, qui nous proposons d'adapter pour supporter V2X. De plus, les nouveaux défis liés au canal LTE V2X sont mis en évidence, comme par exemple l'effet de perte de paquets du à la configuration Half Duplex (HD) des terminaux.

Deux techniques d'ordonnancement distribué sont aussi examinées, la première étant basée sur les OOC, un type d'accès au canal aléatoire avancé, qui fournis fiabilité merci à plusieurs retransmissions et au propriété mathématiques du protocole. La deuxième est nommée STDMA, qui est un mécanisme basé sur une réservation intelligente qui exploite la connaissance de la position des terminaux.

Performances analytiques de OOC : la probabilité de bonne réception pour OOC est calculée, considérant son application à un système LTE V2X, donc influencé par les effets du half duplex. Ces performances sont comparés avec un modèle analytique de 802.11p disponible en littérature.

Performances analytiques de STDMA : nous présentons le premier modèle analytiques des performances de STDMA, qui permets de calculer la distribution de l'occupation des slots, et la probabilité de bonne réception.

Extensions protocolaires de STDMA : deux extensions sont proposées pour améliorer le comportement du protocole quand appliqués au canal LTE V2X, où les slots sont distribués en temps et en fréquence.

Développement d'un simulateur de la couche MAC de LTE V2X, pour la validation des résultats analytiques, et pour l'évaluation des performances dans scénarios réalistes (qui incluent la propagation des signaux et la mobilité des terminaux).

Évaluation des performances par simulation : les performances en termes de réception de OOC, STDMA et de ses extensions protocolaires son évaluées par simulation.

NOTE : dans ce court résumé en français, seulement un sous-ensemble de ces points est traité. Pour une discussion extensive, le lecteur est prié de faire référence à la version complète (en anglais) de cette thèse.

B.2.6 *Publications*

La liste des publications internationales résultantes des travaux présentés dans cette thèse est présentée dans la Table 26.

Table 26 – Liste des publications internationales

Papiers conférence	**Ref.**
Laurent Gallo and Jérôme Härri - *"Short Paper : A LTE-Direct Broadcast Mechanism for Periodic Vehicular Safety Communications"*, VNC 2013, IEEE Vehicular Networking Conference, 16-18 décembre, 2013, Boston, États-Unis	[16]
Laurent Gallo and Jérôme Härri - *"Analytical Study of Self Organizing TDMA for V2X Communications"*, DVC 2015, 1st IEEE ICC Workshop on Dependable Vehicular Communications, 12 juin 2015, Londres, Royaume Uni	[17]

Journaux	**Ref.**
Laurent Gallo and Jérôme Härri - *"Unsupervised LTE D2D - Case study for safety - Critical V2X communications"*, IEEE Vehicular Technology Magazine, Special Issue on Emerging Technologies, Applications, and Standardizations for Connecting Vehicles, 2017	[18]
Laurent Gallo and Jérôme Härri - (under submission) *"Distributed Radio Resource Management (RRM) for Ad-Hoc LTE-V2X Automotive Safety Broadcast"*, soumis au Elsevier Journal on Vehicular Communications	[-]

Rapports de recherche	**Ref.**
Laurent Gallo and Jérôme Härri - *"Resource Allocation for LTE-Direct Broadcast of Periodic Vehicular Safety Messages"*, Rapport de recherche RR 13-290, octobre 2013	[19]
Laurent Gallo and Jérôme Härri - *"Analytic performance comparison of unsupervised LTE D2D and DSRC in a V2X safety context"*, Rapport de recherche RR-14-298, December 2014	[20]
Laurent Gallo and Jérôme Härri - *"Vehicular safety critical communications : a case study for unsupervised LTE D2D "*, Rapport de recherche RR 16-327, novembre 2016	[21]
Laurent Gallo and Jérôme Härri - *"Self organizing TDMA over LTE sidelink"* Rapport de recherche RR-17-329, janvier 2017	[22]

Posters	**Ref.**

Laurent Gallo and Jérôme Härri - *"Dedicated LTE communications for public transportations"* BMW-EURECOM-TUM Summer School on Smart Mobility 2020, 21-27 juillet 2013, Île Chiemsee, Allemagne	[23]
Laurent Gallo and Jérôme Härri - *"LTE-direct broadcast of periodic safety messages"*, BMW-EURECOM-TUM Summer School on Autonomous Driving in the Internet of Cars, 27 juillet - 1 août 2014, Lac Tegernsee, Allemagne	[24]

White papers	**Ref.**
Jérôme Härri, Laurent Gallo and Friedbert Berens - *"Enhanced 11p Investigations and Proposal "* CAR 2 CAR Communication Consortium, 17 février 2017	[-]

B.3 ÉTAT DE L'ART

Dans cette section, une version condensée de l'état de l'art est fournie. Pour raisons d'espace, nous nous focalisons sur *l'état du standard* et sur les perspectives business. Pour plus de détails sur l'état de la recherche, le lecteur est gentiment invité a consulter la version complète en anglais de la thèse.

B.3.1 *État du standard*

Introduction à LTE

LTE est un système de communication cellulaire centralisé, qui par conception prévoit que toutes les transmissions passent à travers des eNodeBs et du réseau cœur, nommé Evolved Packet Core (EPC). Chaque transmission est ordonnancé par le réseau à travers de la station de base. L'interface radio est profondément asymétrique. Dans la version initiale du standard (Release 8), deux canaux sont définis : le Downlink (DL), qui relie le eNodeB avec le UE, et le Uplink (UL), qui relie le UE avec le eNodeB. En DL, le eNodeB est le seul transmetteur et les UEs sont les récepteurs, tandis que en UL, les UEs transmettent vers le eNodeB, qui est le seul récepteur. Ces deux canaux adoptent formes d'onde différente pour les transmissions, du à différente contraintes. En fait, Orthogonal Frequency Division Multiple Access (OFDMA) est utilisé pour le DL, de façon à maximiser l'efficience spectrale et par conséquence le débit. En UL, au contraire, la priorité est la gestion de la puissance de transmission et la réduction du coût matériel du terminal. Pour ces raisons, le UL est basé sur Single Carrier Frequency division Multiple Access (SC-FDMA), qui fournis un meilleur Peak to Average Power Ratio (PAPR) par rapport à OFDMA, ce qui permet de simplifier l'amplificateur de transmission. En plus, SC-FDMA peut être obtenue en utilisant la même chaîne de transmission de OFDMA, en ajoutant à la fin un "Discrete time Fourier Transform (DFT) spreading block". Donc, bien que les ondes transmises sur le canal radio soient différentes, les signaux peuvent être générés et représenté d'un point de vue logique de même façon pour le DL et pour le UL.

Une illustration de dite représentation logique du canal LTE est fournie en Figure 62. Pour maximiser l'efficience avec laquelle le canal radio est exploité,

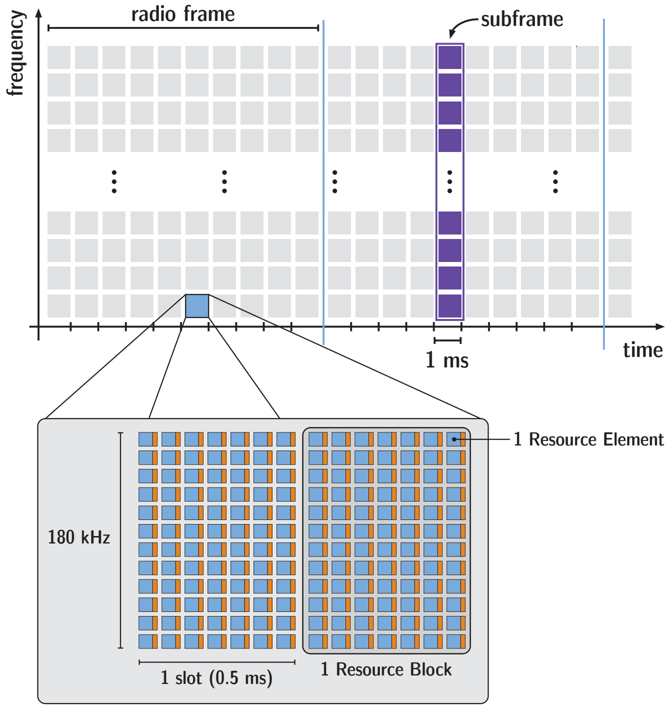


FIGURE 62 – Nomenclature du canal radio DL de LTE

LTE utilise un approche synchrone, où la référence temporelle est fournie par l'eNodeB. Comme illustré en Figure 62, les ressource de canal en temps et fréquence sont partagés dans une grille de Resource Block Pair (RBP), chacune occupant 180 kHz en fréquence, et 1 ms en temps. Cette dernière quantité est la durée minimale d'une transmission, ou Transmission Time Interval (TTI), en LTE. Internement, chaque RBP est composé par une couple de RBs, chacun partagé à sa fois en Resource Elements (REs). Un RE contient un symbole de modulation, plus un préfixe cyclique, qui sert à protéger contre les interférences causées par la propagation par trajets multiples.

Les RBs/RBPs sont les blocs fondamentaux de l'interface radio de LTE, et ils sont donc utilisés aussi pour mesurer les bandes de fréquence. Les largeurs de bande (Bandwidth (BW)) disponibles en LTE, exprimées soit en MHz que en RBs sont mentionnées en Table 27.C'est important de mentionner que les valeurs en RBs ne incluent pas les intervalles de garde.

TABLE 27 – Largeurs de bande (BW) supportées en LTE en MHz et valeurs correspondentes en RBs

BW [MHz]	1.4	3	5	10	15	20
BW [RBs]	6	15	25	50	75	100

Dans le domaine du temps, l'ensemble des RBPs contenu dans l'entière bande du canal et dans le même TTI de 1 ms est nommé *"sous-trame"* (*"sub-frame"* en anglais), tandis que un groupe de 10 sous-trame consécutives est dit *"trame"* (*"frame"* ou *"radio frame"* en anglais).

Services de proximité (ProSe)

Les communications D2D sont nécessaires pour supporter les services V2X sur LTE. Les travaux de standardisation de D2D ont commencé dès les premières phases de la Release 12 sous le nom de ProSe dans [42] et [43], respectivement en 2012 et en 2013. Le premier est un étude des cas d'usages et des scénarios, tandis que le deuxième explores les architecture et les protocoles pour les supporter.

ProSe offre aux UEs des services de découverte (discovery) et communication : la découverte peut soit être fonctionnelle à la communication, soit représenter un service indépendant elle même [44, §5.3.1.1]. Deux types de découverte sont disponibles : géré par le réseau cœur (EPC-level discovery, [44, §5.5]), ou directement faite par les UEs (direct discovery, [44, §5.3]). Cette dernière est la configuration à laquelle nous sommes intéressés dans ce travail. D'un point de vue de la gestion des ressources radio (RRM), deux stratégies sont prévues par le standard : la sélection autonome de ressources (Type 1), et l'allocation des ressources faite par le réseau (Type 2B). La sélection autonome de ressources (Type 1) nécessite la définition d'une nouvelle structure de canal, basé sur des groupements de ressources (resource pools) semi-statiques, desquelles la couche PHY est décrite en [46, §14.3.3].

De façon similaire, deux mécanismes existent pour supporter les communications [45, §9.1.2] : avec les ressources assignée par le réseau (Mode 1), et avec la sélection autonome des ressources, faite par les UEs (Mode 2).

Sidelink

À côté de l'interface User to UTRAN (Uu), qui relie les utilisateurs à la station de base, une nouvelle interface à été définie qui relie UE-à-UE. Cette interface, connue comme "PC5", supporte le sidelink, un nouveau lien directe entre UEs qui s'ajoute au uplink et au downlink.

Le sidelink est un sous-ensemble des ressources uplink qui est assigné aux transmissions D2D. La forme d'onde utilisée est donc le SC-FDMA. La spécification prévoit que le sidelink peut être alloué dans les bandes en [49, Table 5.5D-1].

Comme illustré en Figure 63, l'allocation des ressources est basé sur des groupements de ressources (resource pools), qui est composé par :

— un groupement de sous-trames (subframe pool) dans le domaine du temps, qui inclus toutes les sous-trames qui contiennent le slidelink
— un groupement de resource blocks (resource blocks pool), dans le domaine de la fréquence, qui contient le sous-ensemble des resource blocks appartenant au groupement de sous-trames qui font effectivement partie du groupement de ressources.

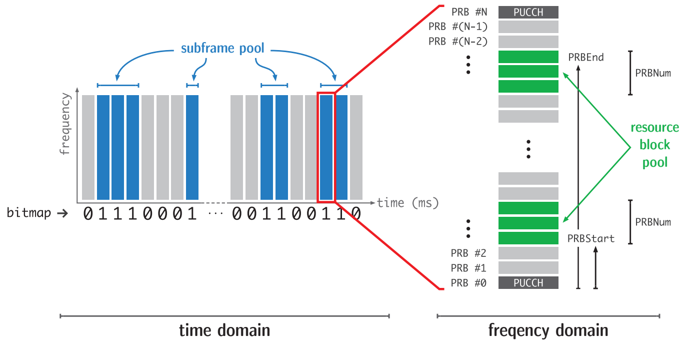


FIGURE 63 – LTE sidelink : disposition des ressources en temps/fréquence - groupement (pool) de sous-trames (subframes) et de resource blocks

LTE-based V2X

Très récemment, la 3GPP a commencé a publier des spécifications pour supporter des applications V2X basées sur LTE. Une nouvelle extension d'architecture, illustrée en Figure 64, contenante des nouvelles entités et des nouveaux liens a été définie.

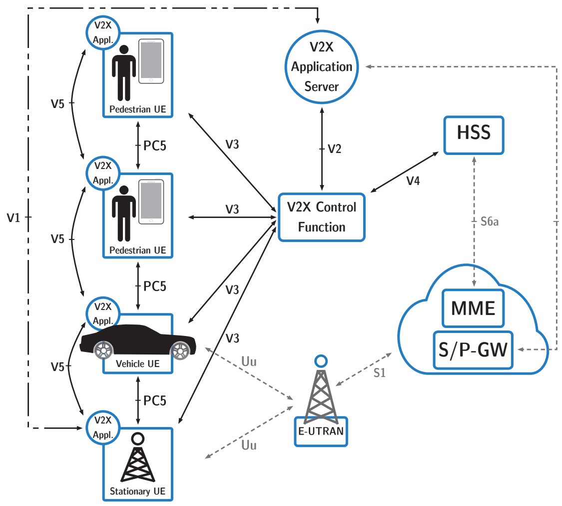


FIGURE 64 – LTE-based V2X : extension d'architecture pour scénarios non-roaming. Adaptée à partir de Figure 4.2.1.1-1 en [54]. Le lecteur est invité à consulter [54] et ses références pour une description détaillée des interfaces et des liens. Les lignes noires représentent les nouvelles interfaces LTE-V2X, les lignes grises pointillées représentent les interfaces déjà existantes. Le l'interface V1 est définie, mais pas encore spécifiée

Les communications directes V2V, Vehicle to Pedestrian (V2P), et Vehicle to Infrastructure (V2I) sont supportées par l'interface PC5 déjà définie pour ProSe, mais des extensions sont nécessaires pour supporter les contraintes imposées par les communications V2X [53]. Dites modifications incluent le support pour messages de type non IP (comme les CAMs/BSMs) [54, §4.4.2], le support des communications de type "one-to-many" [55, §6.2.2] nécessaires car ces message nécessitent du mode broadcast, et la sélection autonome des ressources [56, §5.1.1.2] faite par les UEs. De façon similaire à ProSe, deux nouveaux mode de transmissions sont introduits : le "Mode 3", qui prévoit que les ressources soient alloués centralement par le eNodeB, et le “Mode 4”, dans lequel la gestion des ressources radios (RRM) est distribué aux UEs.

B.3.2 *Perspective business*

La connectivité est critique pour rendre possibles des nouvelles classes d'applications et fonctions véhiculaires, qui représentent des nouvelles opportunités d'affaires. Cependant, la première tranche d'application qui a été développée (applications “day one”), ne concerne que les industries et les entreprises historiquement liées au monde de l'automobile ou des transports publics. Les messages de sûreté CAMs/BSMs, en fait, son transmis gratuitement via WiFi sur une bande sans license. Les applications de efficience routière et de infodivertissement sont censés être supportées par un réseau de Road Side Units (RSUs) ; toutefois, aucun déploiement commercial de RSUs est couramment disponible, faite exception pour quelque projet de recherche.

LTE, au contraire, est une technologie déjà bien établie, basée sur une infrastructure de réseau déjà amplement disponible et en constante expansion (voire les données sur la couverture en [37]). Le réseau cellulaire a permis le développement de nombreux services, comme par exemple la publicité personnalisée, l'infodivertissement, la récolte de données, et les réseaux sociaux. Les constructeurs d'automobiles sont déjà en train de vendre des véhicules fournis de connectivité LTE pour fournir des nouveaux services comme la navigation, la mise à jour de la cartographie, et au même temps recueillant des données pour améliorer leurs systèmes de conduite assistée (Advanced Driving Assistance Systems (ADAS)). Pour que ça soit possible, la connectivité au cloud du constructeur est nécessaire, ce qui n'est pas faisable avec les plans courant de développement de 802.11p. De plus, LTE est une technologie intéressante car il permets d'étendre la connectivité à des nouvelles classes de utilisateurs de la route comme les piétons et les cycliste, à travers de leurs dispositifs mobiles.

Au delà des efforts et des résultats de la communauté de recherche, un rôle fondamental pour déterminer le succès d'une technologie et joué par l'industrie. Une des entreprises plus engagées dans le développement de 802.11p, en fait, est NXP, qui a été récemment acquise par Qualcomm, un des leaders dans la production de chipsets LTE. Cet événement aura sans doute un effet sur les développements futur. En tout cas, les communications véhiculaires basées sur LTE, qui parait non nécessaire il y a quelque années, seront inévitable en futur.

B.4 ANALYSE ET PROBLÉMATIQUE

Dans cette section, nous examinons les exigences des communications V2X (sec. B.4.1), sur la base desquelles nous proposons un concept partagé en deux phases : la première, la réservation des ressources (en section B.4.2), et l'ordonnancement distribué (en sections B.4.3, B.4.4, et B.4.5).

B.4.1 *Exigences de service et défis*

Le support des communications véhiculaire avec communications LTE D2D se démontre être particulièrement difficile, car les transmissions de sûreté nécessitent d'un paradigme de transmission pour lequel LTE n'avait pas initialement été conçu. Nous présentons donc une liste des exigences qui doivent être satisfaite pour rendre V2X sous LTE possible :

broadcast local - le but des messages CAMs/BSM est de permettre aux véhicule de découvrir la présence et l'état des autres véhicules en proximité, et d'être découvert par les autres véhicules. Ces messages doivent donc atteindre tous les autres véhicule en proximité, sans avoir connaissance préalable des destinataires. Pour que ce soit possible, le broadcast local doit être rendu possible.

faible latence - les CAMs/BSMs portent information sur la position, vitesse et direction du véhicule, soit des quantités qui changent très rapidement. C'est donc très important de réduire au minimum la latence entre la génération d'un de ces paquets et sa réception.

opérations distribuées - l'ordonnancement centralisé ne convient pas aux applications véhiculaires, car ils assument que le transmetteur connaisse préalablement la liste des destinataires, ce que n'est pas le cas dans les applications de sûreté routière. De plus, l'infrastructure et le réseau deviennent des points de défaillance : c'est donc important que les UEs puissent ordonnancer leurs transmissions par eux mêmes.

communications machine-à-machine périodiques - l'information portée par les CAMs/BSMs doit être mise à jour très souvent. Pour cette raison, ces paquets doivent être transmis périodiquement, plusieurs fois par seconde. Selon le standard, le taux de transmission peut varier entre 1 Hz et 10 Hz [123].

B.4.2 *Réservation des ressources*

La phase de réservation des ressources est réalisée par le réseau, avec l'objectif de dédier un sous-ensemble des ressources de canal pour les transmissions V2V, V2P, et V2I. De façon de maximiser la fiabilité du système, c'est important de minimiser l'intervention du réseau dans la procédure. Nous proposons donc de baser le système sur un groupement de ressources (resource pool) qui soit semi-statique et périodique. De cette façon, la signalisation requise pour instruire les UEs sur les coordonnées du groupement est réduite au minimum. De plus, en cas de perte de couverture temporelle, les UEs peuvent continuer à utiliser ce même ensemble de ressources, ce qui bénéficie la fiabilité. C'est aussi très important que le réseau ne soit pas responsable de la gestion de la mobilité. Les utilisateur véhiculaires sont en fait très mobiles : le grand nombre de handovers simultanés introduiraient donc des délais qui ne sont pas tolérables dans les applications de sûreté. Nous proposons donc que le groupement de ressources soit maintenu uniformément sur une large surface, qui contient plusieurs cellules adjacentes. La configuration résultante est illustrée en Figure 65, où est montré comme un utilisateur dans une cellule peut choisir un sous ensemble d'un groupement de ressources partagé et commune aux cellules adjacentes, là où se trouvent des véhicules qui doivent recevoir ses CAMs/BSMs.

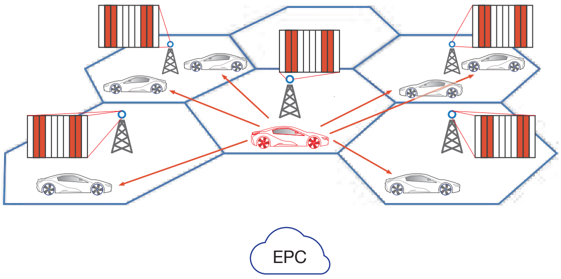


FIGURE 65 – Réservation des ressource semi-statique inter-cellule

Nous définissions la surface couverte par les cellules qui allouent le groupement de ressources "Safety Broadcast Area (SBA)", comme illustré en Figure 66. De façon similaire, nous appelons le service de transmissions véhiculaires broadcast Safety Broadcast Service (SBS) : les UEs qui transmettent ces messages sont donc nommées SBS User Equipments (SBS-UEs).

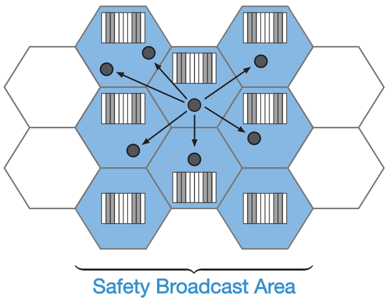


FIGURE 66 – SBA : safety broadcast area

Une fois que un groupement de ressources commun pour les transmetteurs V2X à été défini, nous proposons un mécanisme qui permets aux SBS-UEs de choisir un sous-ensemble des ressources pour transmettre un paquet. Le but est d'obtenir une structure comme celle illustré en Figure 67.

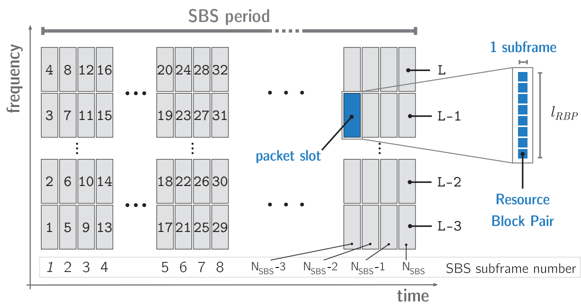


FIGURE 67 – Partage du groupement de ressources en slots pour paquets (packet-slots)

Le temps est partagé en périodes nommés "SBS periods", laquelle durée dépends du taux de transmission et du mécanisme d'ordonnancement choisi. À l'intérieur de chaque SBS period, les sous-trames qui appartiennent au groupement de ressources pour le SBS sont partagés en packet-slots, soit des slots durant 1 ms, ayant une bande contenant suffisamment de RBPs pour transporter un paquet CAM/BSM. De cette façon, L packet-slots sont réservés pour chaque SBS-period. La haute efficience spectrale de LTE permet d'allouer plusieurs packet-slots dans chaque sous-trame dans une bande de 10 MHz, ce qui permet de réserver un nombre de potentielles transmissions plus haute par rapport à 802.11p, qui permet la transmission d'un paquet seulement à chaque instant sur le canal. Cependant, une nouvelle limitation apparaît, due à la configuration half-duplex des SBS-UEs : vu qu'un transmetteur ne peut pas transmettre et recevoir au même temps, les SBS-UEs qui transmettent un paquet dans un slot ne peuvent pas recevoir les autres paquets qui sont transmis dans les autres slots qui se trouvent dans la même sous-trame.

Dans cette thèse, nous avons proposés

B.4.3 *Ordonnancement distribué*

La deuxième phase de notre proposition est l'ordonnancement distribué, soit un mécanisme qui permets au SBS-UEs de choisir de façon autonome quels packet-slots utiliser pour leurs transmissions. Dans ce travail nous présentons deux différent protocoles, l'une basée sur les OOC (en section B.4.4) et l'autre sur STDMA (en section B.4.5).

B.4.4 *Codes Optiques Orthogonaux*

Les OOC sont des séquence binaires de "0s" et "1s" avec des propriété de corrélation favorable pour leur utilisation comme contrôle d'accès. L'utilisation de OOC pour supporter applications véhiculaires à été proposée en [129], et reprise en [16].

Comme illustré en Figure 68, chaque SBS-UE est censée générer (ou être assignée) un mot de code OOC long L bits pour chaque SBS-period. Pour OOC, la durée du SBS-period est égale au taux de transmission maximum que doit être supporté : dans le cas des applications véhiculaires, où ce taux de transmission est de 10 Hz, la durée du SBS-period est fixée à 100 ms.

Chaque mot de code OOC contient w "1s" et $L - w$ "0s" : chaque bit est associé, dans l'ordre au packet-slot correspondent dans le SBS-period. Le SBS-UE se configure donc en mode transmission dans chaque slot correspondent à un bit 1, et en mode réception dans les slots correspondants aux bits 0.

En Figure 68, le principe des OOC est illustré : un message est correctement reçu dans un packet-slot si seulement une SBS-UE transmet dans ce slot. Par contre, si plus d'une transmission est ordonnancée dans le même slot, la collision qui en résulte cause la perte de ce paquet par toutes les SBS-UEs entre portée de plus d'une de ces transmissions.

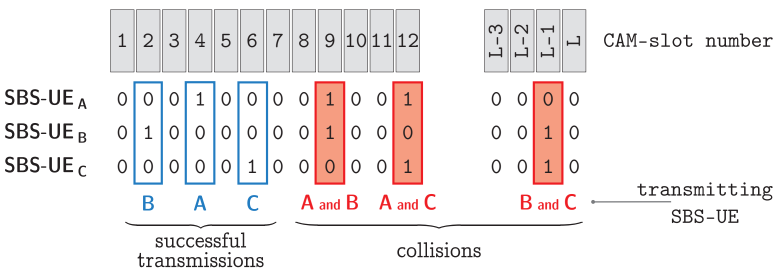


Figure 68 – Ordonnancement distribué : OOC

Les OOC fournissent fiabilité en 2 façons : en re-transmettant chaque paquet w fois, et merci à ses propriété de corrélation entre mot de code. Cette-ci prévoit que chaque couple de mot de code a une corrélation maximale égale à $\lambda < w$. Ça signifie que chaque couple de mot de code ont au maximum λ “1s” dans la même position. L'implication pratique est donc que au maximum λ collisions peuvent se passer entre couples de SBS-UEs, ce qui améliore la probabilité de réception.

B.4.5 *Self-Organizing TDMA*

STDMA est un protocole d'accès au canal slotté, basé sur un système de réservation des slots, où les terminaux choisissent leurs slots de transmissions, en exploitant la connaissance des slots réservés par les autres terminaux. STDMA est conçu pour supporter la transmission de messages périodiques, ce que c'est le cas d'intérêt de cette thèse. STDMA est en fait déjà couramment employé commercialement dans applications maritimes (Automatic Identification System (AIS)) [131], et aériennes [132].

L'objectif de STDMA est de permettre à chaque terminal la transmission de r paquets par seconde, où r est le “Report Rate (Rr)”, soit le taux de transmission, comme illustré en Figure 69.

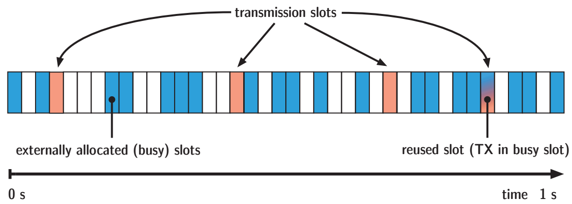


FIGURE 69 – STDMA : transmissions périodiques. Dans cet exemple, le transmetteur réserve $r = 4$ slots de transmission, colorés en rouge. Les slots colorés en bleu sont ‘externally allocated”, soit réservés par des autres terminaux.

En STDMA, le temps est partagé en trames (frames) périodiques de durée égale à 1 seconde. À l'intérieur de la trame, N slots sont alloués, chacun contenant suffisantes ressources de canal pour transporter un paquet de taille fixe, comme un CAM/BSM.

Pour achever ce but, le protocole STDMA prévoit 4 phases, que les terminaux doivent suivre dans l'ordre quand ils désirent commencer à transmettre. Ces phases sont :

1. la **phase de initialisation**, pendant laquelle le terminal écoute l'état du canal pendant la durée d'une trame entière (1 s). L'objectif est de acquérir information sur l'état de chaque slot, qui est sauvegardé dans la mémoire interne du terminal ;
2. la **phase de entrée dans le réseau**, une phase de courte durée (moins d'une trame), dans laquelle le terminal transmet un paquet ayant la fonction de communiquer aux terminaux en proximité son entrée dans le réseau. Rattachée à ce paquet, est aussi contenue information par rapport aux cordonnées du premier slot de transmission (Nominal Transmission Slot (NTS)) de ce terminal ;

3. la **phase de la première trame**, durant une trame, dans laquelle le terminal réserve tous les restant $r-1$ slots qui sont nécessaires pour supporter ses transmissions ;
4. la **phase des opérations continuelles**, qui est le régime permanent du protocole. Dans cette phase, le terminal fait ses transmissions, en utilisant les NTSs réservés en précédence. Ces slots, cependant, ne sont pas alloués indéfiniment : au contraire, après un certain nombre de trames, une nouvelle position doit être choisie pour chaque NTS. Ce procès, nommé ré-réservation est décrit plus tard dans cette section.

États des slots

En STDMA, chaque terminal maintient internement une représentation de l'état de tous les slots dans la trame. Les états qu'un slot peut assumer sont les suivants :

— **libre** : ce slot n'est utilisé par aucun terminal en proximité ;
— **alloué externe** : ce slot est réservé par un autre terminal en proximité ;
— **alloué interne** : ce slot est réservé par ce terminal ;
— **indisponible** : dans ce slot, une puissance supérieure à une valeur dite Clear Channel Assessment (CCA) est détectée, mais aucune information ne peut être décodée. Cette situation se passe quand le Signal to Interference and Noise Ratio (SINR) est trop faible, ce que peut être dû à une collision entre paquets.

Procès de ré-réservation

Les NTSs doivent périodiquement être changés de position, pour éviter les **"merging collisions"**. Celles-ci, sont des collisions qui se passent quand deux terminaux en proximité mais pas entre respective portée, et se déplaçant l'un vers l'autre, réservent le même slot. Pour cette raison, l'allocation des NTSs doit être périodiquement changée. Pour supporter ce mécanisme, STDMA prévoit que 2 champs soient ajoutés à chaque paquet :

1. **timeout**, indiquant pour combien de trames ce NTS sera encore utilisé par le terminal courant ;
2. **offset**, indiquant la position du NTS courant dans la prochaine trame, par rapport à la position courante.

B.4.6 *Extensions protocolaires pour STDMA en LTE-V2X*

STDMA présente des défis ultérieurs quand appliqué au canal LTE-V2X présenté dans cette section, dans lequel les slots sont disposés soit en temps que en fréquence. Á cause du half duplex, en fait, les terminaux ne peuvent pas transmettre et recevoir dans les mêmes sous-trames LTE, ce qui cause la perte des autre slots y présent, comme illustré en Figure 70. Nous appelons ces slots "cachés" (hidden) : la leur perte ne cause pas seulement la perte du CAM/BSM, ce qui est dommage pour les application véhiculaires, mais aussi des informations de réservation attaché au paquet. Cette information est particulièrement critique, car ces slots sont à l'intérieur de l'intervalle de sélection, à l'intérieur duquel les nouveau NTS est sélectionné. Cette perte réduit la connaissance des

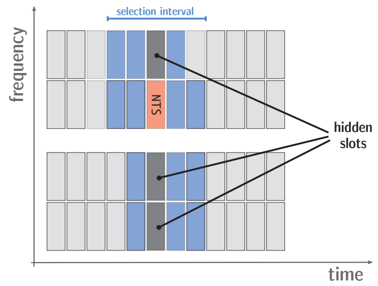


FIGURE 70 – STDMA : slots cachés due au half duplex

terminaux, ce qui peut porter à des mauvaises ré-réservations, qui causent des collisions.

Dans ce travail, nous proposons deux techniques pour contraster les effets du half duplex, nommées STDMA for OFDMA deployments (OSTDMA) et Selective Hiding STDMA (SH-STDMA). Dans ce résumé, nous focalisons notre attention sur SH-STDMA, qui est décrit dans le prochain paragraphe.

SH-STDMA

SH-STDMA est conçu pour éviter sélectivement de cacher les slots occupés par les terminaux plus proches au transmetteur. Ceux-ci sont en fait les véhicules desquels est plus important recevoir le CAMs/BSMs. Pour achever ce but, SH-STDMA modifie la politique de composition du Candidate Set (CS) de STDMA. En SH-STDMA, le candidate set est compose comme suit :

1. un Selection Interval (SI) est composé comme en STDMA ;
2. une valeur de pénalité est assigné à chaque sous-trame. Cette valeur est la somme de pénalité assignées à chaque slot y contenu, qui est calculé selon une fonction décroissante avec la distance, comme illustré en Figure 71 ;
3. les slots sont ajoutés au candidate set de façon suivante :
   — il doit contenir seulement le nombre minimum de slots w_{CSmin} ;
   — les slots libres sont ajoutés à partir des sous-trames ayant la plus faible pénalité ;
   — si moins de w_{CSmin} slots libres sont disponibles, les restants sont choisis parmi les slots alloués externes à partir des sous-trames ayant pénalité plus faible, partant de ceux alloués par les terminaux plus loin.

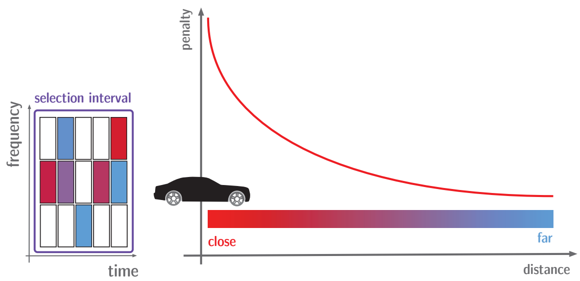


FIGURE 71 – SH-STDMA, fonction de pénalité.

B.5 MODÉLISATION

Dans cette section, nous présentons un résumé de l'évaluation des protocoles introduits dans la section précédente. Deux type d'évaluation ont été faits dans ce travail : l'évaluation statique (en section B.5.1), et l'évaluation dynamique (en section B.5.2)

B.5.1 *Évaluation statique*

L'objectif de l'évaluation statique est de comprendre l'influence que les aspects fondamentaux des protocoles ont sur les performances en réception. Dans cette version résumée, nous nous focalisons sur STDMA, duquel nous présentons le modèle analytique.

STDMA : modèle analytique

STDMA est un protocole déjà utilisé dans des déploiement réels et bien connu en littérature. Cependant, les travaux qui l'étudient desquels nous sommes à connaissance sont tous basé sur simulation, et ont tiré des conclusions parfois contrastantes. En [74], les auteurs soutiennent que STDMA as des performances de réception meilleures de 802.11p indépendamment de la présence de terminaux cachés ("hidden terminals"). En [100], toutefois, les auteurs concluent que STDMA a des performances meilleures seulement dans des scénarios idéals. Les mêmes auteurs en [101] découvrent finalement que des scénarios peuvent être fabriqués pour faire prévaloir un protocole sur l'autre.

Un étude que soit indépendant des scénarios de simulations s'est donc rendu nécessaire, et est l'objectif de cette section. L'approche analytique permet en fait d'éliminer la dépendance de la configuration, mais nécessite de faire des abstractions pour que soit faisable. Ces abstractions sont :

— l'intérêt est l'analyse du régime permanent du protocole : seulement la phase des opérations continuelles est donc modélisée ;
— le candidate set est composé sans exploiter la connaissance des réservation des terminaux en proximité (car difficile à modéliser de façon analytique). Au contraire les slots y sont ajoutés basé sur la probabilité qu'ils soient libres ;
— quand ce rend nécessaire ajouter des slots alloués externes au CS, c'est fait de façon aléatoire, au lieu que basé sur la distance entre les terminaux ;
— étant le travail focalisé sur les performances de couche MAC, nous considérons une couche PHY parfaite, négligeant donc les effets de path loss, fading, shadowing, et considérant une propagation instantanée (zéro délai) ;
— les terminaux sont statiques ou en mobilité homogène.

L'objectif est de calculer la Slot Occupation Distribution (SOD), comme définie en [100], soit la distribution de la probabilité pour un slot d'être occupé par i terminaux. Avec la SOD on peut calculer la Packet Level Incoordination (PLI), soit la probabilité pour une transmission de se passer dans un slot aussi réservé par autre(s) terminaux en proximité.

Nous devons modéliser deux processus, en suivant une méthodologie similaire à l'article fondateur de Bianchi [72] concernant la Distributed Coordination Function (DCF) de CSMA/CA. Ces processus sont :

A. le mécanisme du *timeout* associé à chaque NTS ;

B. le mécanisme de *ré-réservation* des slots.

Processus du timeout (πt)

Le timeout associé à chaque NTS détermine pour combien de trames (secondes) consécutives ce NTS va occuper ce slot, avant de nécessiter une ré-réservation. Ce processus est modélisée par la chaîne de Markov en Figure 72, où la variable d'état représente la valeur courante du compteur timeout.

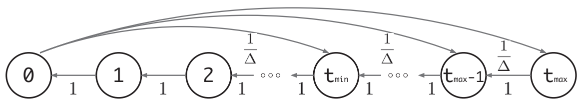


FIGURE 72 – Chaîne de Markov associé au processus de timeout pour un slot

Indiquant avec $\pi_{t,i}$ la probabilité pour le compteur d'avoir valeur i, nous pouvons calculer la distribution en régime permanent comme suit :

$$\begin{aligned} \pi_{t,t_{max}} &= \pi_{t,0}/\Delta & \\ \pi_{t,i} &= \pi_{t,0}/\Delta + \pi_{t,i+1} & t_{min} \leq i < t_{max} \\ \pi_{t,i} &= \pi_{t,t_{min}} & 0 \leq i < t_{min} \end{aligned}$$

avec $\Delta = t_{max} - t_{min} + 1$. Imposant la condition de normalisation :

$$\sum_{i=0}^{t_{max}} \pi_{t,i} = 1$$

nous pouvons obtenir $\pi_{t,0}$, la probabilité qu'une ré-réservation se passe, comme en (45).

$$\pi_{t,0} = 1/(\Delta + 1) \tag{45}$$

Processus de ré-réservation des slots

Nous considérons un réseau isolé composé par N_t terminaux, chacun entre respective portée TX/RX. Nous donc considérons un ensemble χ de NI slots consécutifs : nous pouvons donc partir de l'assomption que chacun des N_t terminaux a réservé un NTS en χ. Parmi ces slots, nous en choisissons un, nommé σ_t : vu de la perspective de σ_t, le processus de réservation est modélisé par la chaîne de Markov en Figure 73.

La variable d'état i représente le nombre de terminaux qui ré-utilisent σ_t : σ_t est donc libre pour $i = 0$, réservé par un terminal seulement pour $i = 1$, et ré-utilisé au même temps par i terminaux quand $i > 1$. Indiquée avec π_i la probabilité de régime permanent que le slot σ_t soit en état i, la State Occupation Distribution dont nous sommes intéressés est représentée par $\boldsymbol{\pi} = \{\pi_0, \ldots, \pi_{N_t}\}$.

Indiquée avec $p_{i,i+j}$ la probabilité d'une transition du processus de l'état i à l'état $i + j$, la SOD peut être calculé avec l'équation

$$\boldsymbol{\pi} = \boldsymbol{\pi}\mathbf{P}$$

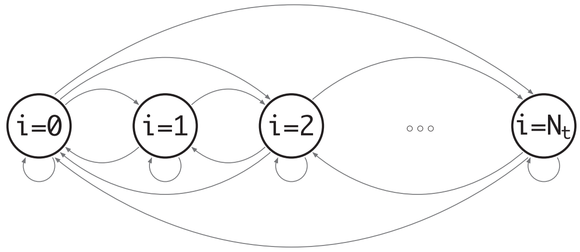


Figure 73 – Chaîne de Markov du processus de réservation des slots. La variable d'état i représente le nombre de terminaux qui ré-utilisent le slot σ_t.

dans laquelle $\mathbf{P}$ est la matrice des probabilités de transition :

$$\mathbf{P} = \begin{pmatrix} p_{0,0} & p_{0,1} & \cdots & p_{0,N_t} \\ p_{1,0} & p_{1,1} & \cdots & p_{1,N_t} \\ \vdots & \vdots & \ddots & \vdots \\ p_{N_t,0} & p_{N_t,1} & \cdots & p_{N_t,N_t} \end{pmatrix}.$$

Les détails du modèle, et la procédure pour calculer les $p_{i,i+j}$ sont fournis intégralement en [17].

Simulateur

Une partie importante du travail a été représenté par l'évaluation des performances des protocoles par simulation. Pour achever ce but, nous avons développé un simulateur dédié en langage Python [137]. Le choix de développer un outil personnalisé a été dictée par plusieurs raisons. Premièrement, nous avons le contrôle sur le niveau d'abstraction : avec une seule plate-forme est en fait possible simuler soit des scénarios idéaux et statiques, que des scénarios réalistes qui tiennent compte des effets de la propagation des signaux et de la mobilité des terminaux. Deuxièmement, de cette façon nous avons pu développer un simulateur focalisé sur la couche MAC pour les applications véhiculaires, capable de simuler scénarios à haute densité, sans l'effort et l'emploi de temps nécessaire pour implémenter la couche physique de LTE-V2X sur une plate-forme spécifique. Dernièrement, le projet est entièrement basé sur du logiciel libre, ce qui nous permets d'éviter les coûts des logiciels commerciaux.

Figure 74 représente le schéma logique du simulateur, dans lequel véhicule est une instance indépendante, portant une instance du protocole. Les blocs "protocole" interagissent à travers d'un modèle de canal adaptable selon exigence. De façon similaire, les véhicules se déplacent suivant un modèle de mobilité qui peut être sélectionné selon les objectifs de simulation.

Le "modèle de canal" est responsable de deux aspects fondamentaux de la simulation : la gestion du groupement de ressources pour le SBS, et la propagation des signaux.

Le bloc "véhicule" est responsable de la position du terminal et des aspects liés à la transmission et réception, de façon que les phénomènes de couche PHY soient transparents au protocole de couche MAC.

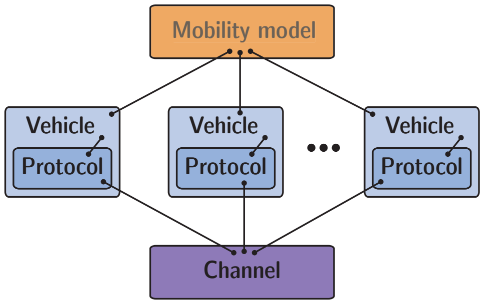


FIGURE 74 – Simulateur : diagramme logique

Le bloc "protocole" contient l'implémentation du protocole MAC couramment sous examen. Chaque véhicule contient une instance indépendante du protocole, avec ses paramètres et son état interne.

L'échelle temporelle du simulateur est discrète, basée sur une unité de temps égale à 1 ms, soit le TTI de LTE, et la durée minimale d'un slot pour un paquet.

Évaluation statique par simulation

L'évaluation statique par simulation a la double fonction de valider les résultats obtenu analytiquement, et de tester les performances des protocoles dans des scénarios idéaux, mais plus réaliste des modèles mathématiques. Dans cette version résumée, nous nous focalisons sur la modélisation de STDMA et de SH-STDMA en termes de probabilité de réception. Celle-ci est évaluée en fonction du Offered Channel Load (OCL), une métrique qui définit la fraction des slots disponibles qui sont nécessaires pour satisfaire les besoins de communications des terminaux, dans un réseau isolé. Par exemple, dans un scénario où 100 slots sont disponibles, et le réseau contient 5 terminaux qui doivent chacun transmettre 10 paquets par seconde, le OCL est égal à 0.5.

B.5.2 *Évaluation dynamique*

Pour pouvoir évaluer les performances des protocoles dans des scénarios réalistes, nous introduisons un modèle de mobilité et un modèle de propagation.

Le modèle de mobilité que nous considérons dans ce travail est une autoroute 2-dimensionnelle à 12 voies (6 par direction), représentée en Figure 75. Suivant les recommandations en [56, §A.1.2], la longueur du trait considéré est de 2 km, et les deux bouts sont connectés entre eux. Un véhicule qui joint un des but de l'autoroute, ré-apparaît donc à l'autre but, dans la même voie, maintenant la même vitesse. Au début de la simulation, les véhicules sont positionnés sur les voies en positions aléatoires. Le nombre de véhicules générés dépends de la densité. La vitesse assignée à chacun d'eux dépends de la voie (comme indiqué en Figure 75), plus un terme aléatoire gaussien avec moyenne 0 m/s et déviation standard 1 m/s.

Le modèle de propagation considéré, suivant les résultats des travaux en [138], est représenté en Figure 76, qui montre ses deux composantes : l'affaiblissement de propagation et le fading. L'affaiblissement de propagation suit

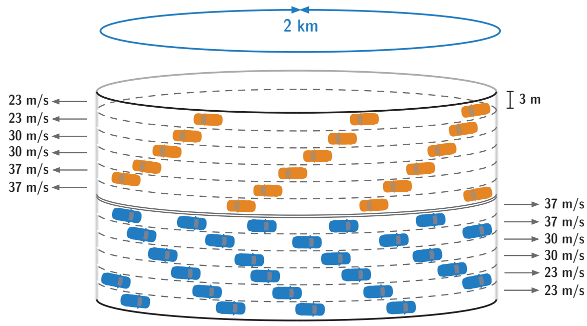


FIGURE 75 – Scénario d'évaluation dynamique : autoroute

un modèle a deux pentes, avec deux distances critiques de 10 m et 100 m. Le modèle de fading choisi est le Nakagami-m [139], avec les paramètres calculés pour le cas "freeway" en [138].

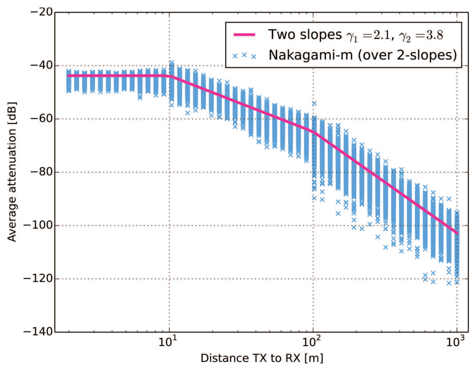


FIGURE 76 – Propagation à double pente avec fading Nakagami-m

La métrique de performance que nous considérons dans l'analyse dynamique est le Packet Reception Probability (PRR) mesuré en fonction de la distance entre transmetteur et récepteur. De plus, nous nous focalisons sur les messages que ne sont pas reçus, pour déterminer l'incidence les possible causes des pertes de paquets, qui sont :

— **collision** : quand plusieurs paquets sont transmis dans le même slot, et un récepteur mesure un SINR si faible de ne pas permettre le décodage d'aucun message ;
— **une autre transmission plus forte** ("another stronger transmission") : cet événement se passe quand plusieurs transmissions se passent dans le même slot. Différemment du cas collision, le récepteur décode un de ces messages, mais pas le courant ;
— **half duplex** : dans ce cas, un paquet qui autrement aurait été reçu correctement est perdu parce que le récepteur est en train de transmettre dans un autre packet-slot dans la même sous-trame ;
— **propagation** : quand un seul paquet est transmis dans un packet-slot, mais les effets de la propagation rendent la puissance reçue si faible que le message ne peut pas être décodé.

B.6 RÉSULTATS

Cette section est dédiée à l'illustration, la comparaison et la discussion des résultats obtenus en section B.5.

B.6.1 *Évaluation statique : résultats*

STDMA : résultats analytiques

Nous calculons la Slot Occupation Distribution pour une configuration de canal avec $N = 860$ slots / trame (seconde), qui permets d'obtenir un OCL égale à 50% si le taux de transmission est 10 paquets/s, et un OCL égale à 100% quand le taux de transmission est de 20 paquets/s. Ces deux scénarios sont représentés respectivement en Figure 77 et Figure 78 respectivement. Dans les deux cas, $w_{CSmin} = 1$. Différente configurations sont examinées, avec des différentes valeurs de timeout et de rapport entre le Selection Interval (SI) et le Nominal Increment (NI).

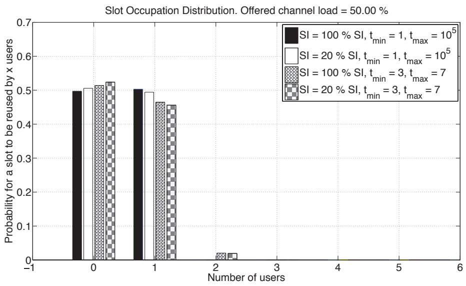


FIGURE 77 – SOD pour OCL = 50% : $N = 860$, $N_t = 43$, $r = 10$

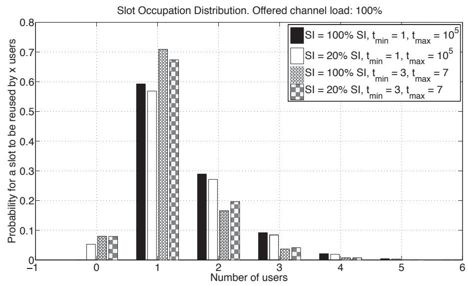


FIGURE 78 – SOD pour OCL = 100% : $N = 860$, $N_t = 43$, $r = 20$

On peut observer que pour le OCL = 50%, l'algorithme reproduits correctement le comportement du protocole, où chaque slot a une probabilité de environ 0.5 d'être libre, et de environ 0.5 d'être réservé par un seul terminal. Dans certaines configurations (avec les valeurs $t_{min} = 3$ et $t_{max} = 7$) ont peut observer que les slots ont petite mais non négligeable probabilité des slots d'être réservé simultanément par deux terminaux, bien qu'il y ait des slots libres : ce comportement est bien représentatif de STDMA et peut être vérifié se passer en simulation aussi. Dans le cas de Figure 78, avec OCL = 100 % (soit il y a exactement un slot à disposition pour chaque transmission), on peut observer que les la probabilité que un slot soit réservé par un terminal seulement est de environ 0.6 à 0.7 selon configuration, et que la probabilité qu'il soit utilisé par 2, 3, 4 ou même 5 terminaux est progressivement décroissante mais non négligeable. De nouveau, ce résultat bien représente le comportement réel de STDMA : la composante aléatoire dans le choix du NTS parmi les slots dans le CS, en fait, peut porter à des réservations multiples du même slot, qui sont observables aussi en simulation.

En partant de la OCL, on peut calculer la Packet Level Coordination, qui dans un réseau isolé est équivalent à la probabilité de réception. Elle est montré en fonction du OCL, respectivement pour $t_{min} = 3$ et $t_{max} = 7$ en Figure 79 et pour $t_{min} = 1$ et $t_{max} = 10^5$ en Figure 80. Ces deux cas représentent un les valeurs standard du timeout, et l'autre une configuration conçue pour réduire la probabilité de multiple ré-réservations simultanés, utile pour évaluer l'effet introduit par les abstractions faites dans l'algorithme analytique. Dans les deux cas, les performances sont comparés contre "ideal STDMA", soit un scénario où les terminaux occupent les slots libres, jusqu'à quand il y en a de libres, et réutilisent les slots une fois seulement lorsque les slot libres sont terminés.

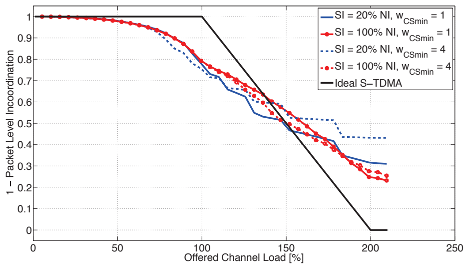


FIGURE 79 – Packet Level Coordination pour $t_{min} = 3$ et $t_{max} = 7$

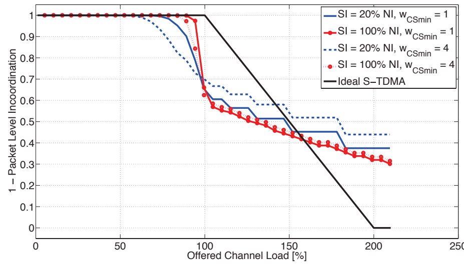


FIGURE 80 – Packet Level Coordination pour $t_{min} = 1$ et $t_{max} = 10^5$

STDMA et SH-STDMA : résultats de simulation

Figure 81 illustre la probabilité de réception pour STDMA (soit en considérant et négligeant l'effet du half duplex) et des extensions protocolaires OSTDMA et SH-STDMA. Le scénario prévoit un canal allouant 900 slots/s sur 300 sous-trames, ce qui signifie 3 slots pour chaque sous-trame. Les terminaux transmettent 10 paquets/s : valeurs croissantes de OCL sont obtenus en augmentant le nombre de terminaux dans le système. Dans ce cas statique, les utilisateurs sont générés en positions aléatoire, tous entre portée respective, et ne bougent jamais. On peut observer comme la simulation valide les résultats analytiques obtenus dans ce travail, et au même temps les avantages apportés par les extensions protocolaires par rapport à STDMA.

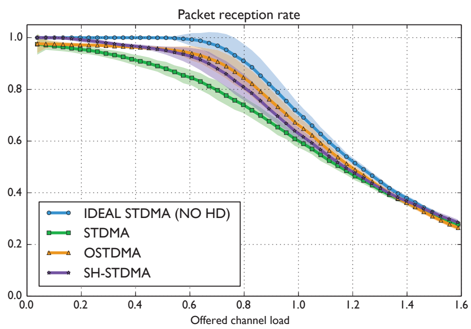


FIGURE 81 – Évaluation statique : OSTDMA vs SH-STDMA vs STDMA. Les surfaces colorées autour des courbes représentent l'intervalle de confiance à 95%

B.6.2 *Évaluation dynamique : résultats*

Dans les figures 82 et 83 les causes des pertes de paquets pour STDMA et SH-STDMA respectivement sont comparées. Dans les deux cas, le scénario est l'autoroute décrite en section B.5.2, avec densité de 240 véhicules/km.

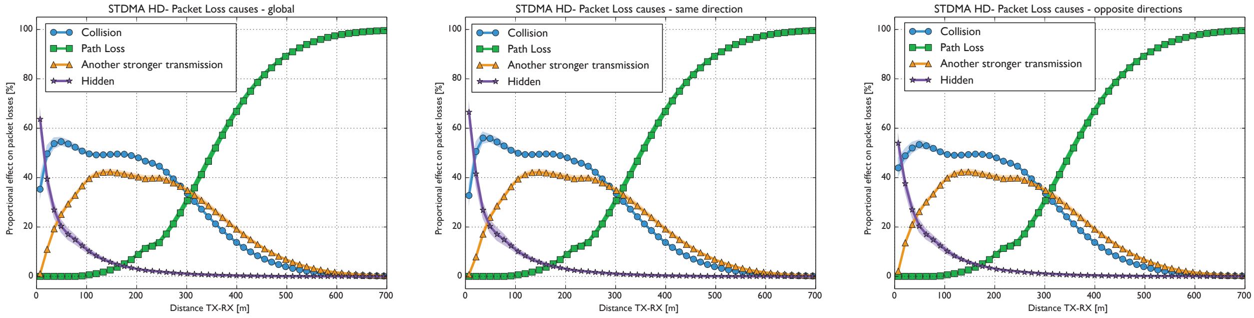


FIGURE 82 – Causes de perte de paquet pour STDMA avec HD, 240 véhicules pour km **Gauche** : tous les véhicules ; **centre** : seulement couples TX/RX procédant dans la même direction ; **droite** : seulement couples TX/RX procédant en directions opposées

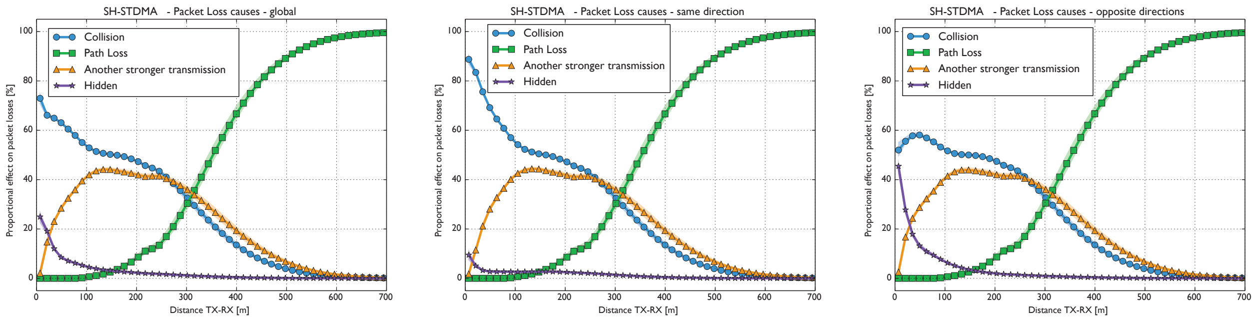


FIGURE 83 – Causes de perte de paquet pour SH-STDMA avec HD, 240 véhicules pour km **Gauche** : tous les véhicules ; **centre** : seulement couples TX/RX procédant dans la même direction ; **droite** : seulement couples TX/RX procédant en directions opposées

En comparant les deux figures, on peut observer comme SH-STDMA peut réduire l'incidence des pertes de paquets due au HD.

B.7 CONCLUSION ET PERSPECTIVES

B.7.1 *Remarques finales*

Nous vivons dans un temps où le développement scientifique et technologique procède plus rapidement que jamais auparavant. Spécifiquement, le secteur de l'automobile est en train de vivre le change de paradigme plus radical dans son histoire plus que centenaire. Le croissant niveau d'automation des voitures est en train de rendre la connectivité une composante fondamentale. De plus, les voitures sont envisagées entrer faire partie du paradigme du IoT, devenant des hôtes de capteurs et des nœds de cache mobiles.

Dans les derniers deux décennies, la communauté scientifique, l'industrie de l'automobile et la standardisation ont travailler pour le développement de 802.11p, une extension de WiFi qui permets la réalisation de communications horizontales directes V2V. 802.11p, cependant, prévoit de fournir connectivité verticale à internet et au cloud, à travers d'un réseau de RSUs couramment non existant, si non dans des déploiements expérimentaux.

LTE, d'autre part, peut déjà compter sur un réseau vaste et en constante expansion qui fournit connectivité verticale. Au début des travaux de cette thèse, toutefois, il n'offrait aucune possibilité de connectivité horizontale, fondamentale pour les applications véhiculaires et objectif de ce travail.

Dans ce travail nous avons donc commencé en étudiant les exigences et l'évolution des services véhiculaires, de façon de montrer la nécessité de les supporter avec LTE. Nous arrivons donc à la conclusion que la modalité non supervisée par le réseau est fondamentale four les connexion horizontales à faible latence. Nous donc avons fait un étude détaillé de l'état de l'art, concernant la recherche, la standardisation et les implications commerciales des communications véhiculaires par LTE-D2D.

Nous avons donc proposé un paradigme de communication partagé en deux phases, la *réservation des ressources* et *ordonnancement distribué*. Pour la phase de réservation des ressources, nous avons explorés les possibilités offertes par le standard pour réserver une canal pour les communications directes V2V/V2P. Pour la phase de ordonnancement distribué, nous avons étudié, de façon mathématique et par simulation, les effets de la configuration de canal LTE-V2X proposée sur les performances de réception. Nous avons étudié deux protocoles, basés sur deux type d'approche différents : OOC, basé sur une sélection aléatoire des slots de transmission ; STDMA, basé sur un mécanisme de réservation qui exploite la connaissance des réservation des autres terminaux en proximité. Ce dernier permets à STDMA d'achever des performance meilleures, mais est plus fortement limité par les pertes due au Half Duplex. Pour cette raison nous avons présenté deux extensions protocolaires (OSTDMA et SH-STDMA) pour réduire son impact.

Dans cette thèse, nous avons exploré, proposé et évalué un paradigme pour les communications véhiculaires basé sur LTE-V2X basé sur un mode d'opérations non supervisé, que nous soutenons être fondamental pour le LTE-V2X. Ce paradigme, complètement nouveau au début de cette thèse en 2013, a été parallèlement développé par la 3GPP et maintenant est incluse dans les standards.

B.7.2 *Perspectives futures*

Dès le premier jour, l'esprit à la base de cette thèse était d'explorer une direction nouvelle, combinant les communication véhiculaires directes et le réseau cellulaire. Cet approche a donc ouvert nombreux nouveaux problèmes et défis, qui méritent d'être traité dans des travaux futurs.

D'un point de vue théorique, les modèle présentés peuvent être améliorés pour en étendre l'applicabilité. Par exemple, le modèle de STDMA peut être étendu à toutes les phases du protocole, et considérer aussi des scénario où les terminaux sont mobiles.

Le déploiement commercial de technologie V2X devient une réalité toujours plus proche : pour cette raison, les test sur des prototypes sont toujours plus appréciés par la communauté. Ce travail est difficile pour LTE-D2D, parce que pour l'instant il n'y a pas de matériel disponible commercialement. Toutefois, un développement très intéressant serait l'implémentation des mécanismes proposés sur Open Air Interface (OAI) [142], une plate-forme de émulationsimulation maintenue par un consortium de universités, centres de recherche et entreprises très dynamique et en croissance, fondé et guidé par EURECOM.

7 ACRONYMS

3GPP	3rd Generation Partnership Project.
5G-PPP	5G Private Public Partnership.
ACK	Acknowledgment.
ADAS	Advanced Driving Assistance Systems.
AIS	Automatic Identification System.
ALOHA	Additive Links On-line Hawaii Area.
AP	Access Point.
ASTM	American Society for Testing and Materials.
BPSK	Binary Phase Shift Keying.
BSM	Basic Safety Message.
BW	Bandwidth.
C2C-CC	Car-2-Car Communications Consortium.
C2X	Car-2-Everything Communications.
CACC	Cooperative Adaptive Cruise Control.
CAM	Cooperative Awareness Message.
CAMP	Crash Avoidance Metrics Partnership.
CBTC	Communication-Based Train Control.
CCA	Clear Channel Assessment.
CCH	Control Channel.
CCTV	Closed Circuit Television.
CDMA	Code Division Multiple Access.
CFR-MAC	Collision Free Reservation MAC.
C-ITS	Cooperative Intelligent Transportation System.
CL	Channel Load.
CP	Cyclic Prefix.
CRC	Cyclic Redundancy Check.
CRS	Cell-Specific Reference Signals.
CS	Candidate Set.
CSA	Common Subframe Allocation.
CSI	Channel State Information.
CSMA	Carrier Sense Multiple Access.

CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance.
CTMAC	Centralized TDMA MAC.
CTS	Clear To Send.
C-UE	Cellular UE.
CW	Contention Window.
D2D	Device-to-Device.
DCC	Decentralized Congestion Control.
DCF	Distributed Coordination Function.
DCI	Downlink Control Information.
DENM	Decentralized Environmental Notification Message.
DFT	Discrete time Fourier Transform.
DIFS	DCF Inter Frame Space.
DL	Downlink.
DMO	Direct Mode of Operation.
DoT	Department of Transportation.
DRx	Discontinuous Reception.
DSRC	Dedicated Short Range Communications.
DTx	Discontinuous Transmission.
EDCA	Enhanced Distributed Channel Access.
eMBMS	evolved Multimedia Broadcast Multicast Service.
eNodeB	evolved Node B.
EPC	Evolved Packet Core.
ETSI	European Telecommunications Standard Institute.
EU	European Union.
E-UTRA	Evolved Universal Terrestrial Radio Access.
FCC	Federal Communication Commission.
FDD	Frequency Division Duplexing.
FDMA	Frequency Division Multiple Access.
FI	Frame Information.
FP5	5th Framework Programme.
FP7	7th Framework Programme.
GLOSA	Green Light Optima Speed Advisory.
GNSS	Global Navigation Satellite System.
GPS	Global Positioning System.
GSM	Global System for Mobile communications.

HAD	Highly Autonomous Driving.
HD	Half Duplex.
HIGHTS	High precision Positioning for Cooperative-ITS.
HSS	Home Subscriber Server.
I2V	Infrastructure-to-Vehicle.
IEEE	Institute of Electrical and Electronics Engineering.
IETF	Internet Engineering Task Force.
IoT	Internet of Things.
IoV	Internet of Vehicles.
IP	Internet Protocol.
IRT	Inter Reception Time.
ISM	Industrial, Scientific, and Medical.
ITS	Intelligent Transportation System.
IVI	Intelligent Vehicle Initiative.
LAA	Licensed Assisted Access.
LBT	Listen Before Talk.
LOS	Line of Sight.
LTE	Long Term Evolution.
MAC	Medium Access Control.
MANET	Mobile Ad-hoc Network.
MBMS	Multimedia Broadcast Multicast Service.
MBSFN	Multicast Broadcast Single Frequency Network.
MCH	Multicast Channel.
MCS	Modulation and Coding Scheme.
M-FUNC	Mapping Function.
MIB	Master Information Block.
MIMO	Multi Input Multi Output.
MO	Management Object.
MS-ALOHA	Mobile Slotted Aloha.
MSI	MCH Scheduling Information.
MSP	MCH Scheduling Period.
MTC	Machine Type Communications.
NEP	Network Entry Packet.
NI	Nominal Increment.
NLOS	Non Line of Sight.

NoW	Network on Wheels.
NS	Nominal Slot.
NSS	Nominal Starting Slot.
NTS	Nominal Transmission Slot.
OAI	Open Air Interface.
OBU	On Board Unit.
OCB	Outside the Context of a Basic Service Set.
OCL	Offered Channel Load.
OFDM	Orthogonal Frequency Division Multiplexing.
OFDMA	Orthogonal Frequency Division Multiple Access.
OOC	Optical Orthogonal Codes.
OSTDMA	STDMA for OFDMA deployments.
PAPR	Peak to Average Power Ratio.
PATH	Partners for Advanced Transit and Highways.
PDR	Packet Delivery Rate.
P-FUNC	Partitioning Function.
PHY	Physical.
PL	Path Loss.
PLC	Packet Level Coordination.
PLI	Packet Level Incoordination.
PLMN	Public Land Mobile Network.
PLMNO	Public Land Mobile Network Operator.
PN	Pseudo Noise.
PRB	Physical Resource Block.
PRE-DRIVE C2X	Preparation for Driving Implementation and Evaluation of C2X Communication Technology.
PROMETHEUS	PROgraM for a European Traffic system with Highest Efficiency and Unprecedented Safety.
ProSe	Proximity Services.
PRR	Packet Reception Probability.
PSBCH	Physical Sidelink Broadcast Channel.
PSCCH	Physical Sidelink Control Channel.
PSDCH	Physical Sidelink Discovery Channel.
PSS	Primary Synchronization Signal.
PSSCH	Physical Sidelink Shared Channel.
PUCCH	Physical Uplink Control Channel.
QAM	Quadrature Amplitude Modulation.
QoS	Quality of Service.

QPSK	Quadrature Phase Shift Keying.
RACH	Random Access Channel.
RATDMA	Random Access Time-Division Multiple Access.
RB	Resource Block.
RBP	Resource Block Pair.
RE	Resource Element.
Rr	Report Rate.
RR-ALOHA	Reliable Reservation ALOHA.
RRC	Radio Resource Control.
RRM	Radio Resource Management.
RSU	Road Side Unit.
RTS	Ready To Send.
RX	Reception.
SAE	Society of Automotive Engineers.
SBA	Safety Broadcast Area.
SBS	Safety Broadcast Service.
SBS-UE	SBS User Equipment.
SC-FDMA	Single Carrier Frequency division Multiple Access.
SCH	Service Channel.
SCI	Sidelink Control Information.
SDMA	Space Division Multiple Access.
SH-STDMA	Selective Hiding STDMA.
SI	Selection Interval.
SIB	System Information Block.
SIFS	Short Inter Frame Space.
SIM^{TD}	Safe and Intelligent Mobility Test Field Germany.
SINR	Signal to Interference and Noise Ratio.
SISO	Single Input Single Output.
SL	Sidelink.
SLA	Speed and Location Aware.
SL-BSR	Sidelink Buffer Status Report.
SL-RNTI	Sidelink Radio Network Temporary Identifier.
SOD	Slot Occupation Distribution.
SR	Scheduling Request.
SSS	Secondary Synchronization Signal.
STDMA	Self-Organizing TDMA.
SYSTUF	Système Télécom pour les Transports Urbains du Futur.

TCMAC	TDMA Cluster-based MAC.
TCP/IP	Transmission Control Protocol / Internet Protocol.
TDD	Time Division Duplexing.
TDMA	Time Division Multiple Access.
TPC	Transmission Power Control.
TR	Technical Report.
TRC	Transmission Rate Control.
T-RPT	Time Resource allocation Pattern.
TS	Technical Specifications.
TTI	Transmission Time Interval.
TX	Transmitter.
UCI	Uplink Control Information.
U-D2D	Unsupervised Device-to-Device.
UE	User Equipment.
UL	Uplink.
UMTS	Universal Mobile Telecommunication System.
USA	United States of America.
UTC	Coordinated Universal Time.
UTRA	UMTS Terrestrial Radio Access.
Uu	User to UTRAN.
V2I	Vehicle to Infrastructure.
V2N	Vehicle to Network.
V2P	Vehicle to Pedestrian.
V2V	Vehicle to Vehicle.
V2X	Vehicle to Everything.
VANET	Vehicular Ad-hoc Network.
VeMAC	Vehicular Ad Hoc Networks MAC.
VeSOMAC	Vehicular Self Organizing Ad Hoc Networks MAC.
VII	Vehicle Infrastructure Integration.
VRU	Vulnerable Road User.
VTL	Virtual Traffic Lights.
V-UE	Vehicular UE.

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