EURECOM
Department of Communication Systems
Campus SophiaTech
CS 50193
06904 Sophia Antipolis cedex
FRANCE

Research Report RR-14-298

Analytic performance comparison of unsupervised LTE D2D and DSRC in a V2X safety context

December 2014
Last update July 21st, 2016

Laurent Gallo and Jérôme Härri

Tel : (+33) 4 93 00 81 00
Fax : (+33) 4 93 00 82 00
Email : {gallo, haerri}@eurecom.fr

[1]EURECOM's research is partially supported by its industrial members: BMW Group Research and Technology, IABG, Monaco Telecom, Orange, Principauté de Monaco, SAP, SFR, ST Microelectronics, Symantec.

Analytic performance comparison of unsupervised LTE D2D and DSRC in a V2X safety context

Laurent Gallo and Jérôme Härri

Abstract

3GPP LTE specified for 5G the support for Device-to-Device (D2D) communication in either supervised mode (controlled by the network) or unsupervised mode (independent from network). This article explores the potential of LTE D2D in a fully unsupervised mode for the broadcast of safety-of-life automotive messages. After an overview of the Proximity Service (ProSe) architecture and new D2D interfaces, it introduces a framework and the required mechanisms for unsupervised LTE D2D broadcast on the new SideLink (SL) interface, composed of (i) a multi-cell and pan-operator resource reservation schema (ii) a distributed resource allocation mechanism (iii) decentralized channel congestion control for joint transmit power/scheduling optimization. The proposed scheme is first evaluated independently, then benchmarked against IEEE 802.11p. Complementary to IEEE 802.11p, unsupervised LTE D2D is an opportunity to provide redundancy for ultra-reliable broadcast of automotive safety-of-life messages.

Index Terms

Automotive 5G, Congestion control, Distributed resource allocation, ITS, LTE D2D, LTE-direct, Mode 2, ProSe, Safety-related communications, V2X

Contents

List of Figures

Nomenclature

3GPP	3rd Generation Project Partnership
BSM	Basic Safety Message
CAM	Cooperative Awareness Message
CPS	Cyber Physical System
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
D2D	Device to Device
DCC	Decentralized Congestion Control
DIFS	DCF (Distributed Coordination Function) Inter Frame Space
DSRC	Dedicated Short Range Communication (802.11p)
DSRC	Dedicated Short Range Communications
E-UTRA	Evolved UMTS Terrestrial Radio Access
eNB	cfr. eNodeB
eNodeB	evolved Node B
EPC	Evolved Packet Core
HD	Half Duplex
IRT	Inter Reception Time
ITS	Intelligent Transportation System
ITS-G5	Intelligent Transportation System - [band] G5
LTE	UTMS Long Term Evolution
M2M	Machine to Machine
OOC	Optical Orthogonal Codes
PLMN	Public Land Mobile Network
PRB	Physical Resource Block
ProSe	Proximity Services
RB	Resource Block
RBP	Resource Block Pair

RRC	Radio Resource Control
RRM	Radio Resource Management
SBA	Safety Broadcast Area
SBS	Safety Broadcast Service
SL	Sidelink
TPC	Transmission Power Control
TRC	Transmission Rate Control
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
V2V	Vehicle to Vehicle
V2X	Vehicle to Everything

1 Introduction

Safety-related applications of future Connected Vehicles are based on the periodic exchange of vehicular status (GNSS position, speed, control instructions, etc..). One leading message, called Cooperative Awareness Message (CAM) in EU or Basic Safety Message (BSM) in the US, aims to assess potential road hazards by announcing the presence of a vehicle to other surrounding vehicles or any other vulnerable road users. This type of traffic yet significantly differs from traditional data exchange, as it is periodically transmitted, has only a local scope, need to be broadcast, and must provide ultra-reliable and low latency communications. After ten years of research, the automotive industry standardized a WiFi extension called IEEE 802.11p[1] (a.k.a ETSI ITS-G5 in EU, DSRC[2] in the US) to address the communication requirements of safety-related applications for connected vehicles.

Recently, the adoption of cellular technologies to support vehicular applications has gathered increasing attention, as it offers high speed Internet connectivity and includes standard extensions supporting Device to Device (D2D) communications. While legacy LTE is found capable of supporting infotainment and driver comfort applications [1], it has been deemed as unsuitable [2] or not worth the expense w.r.t ITS-G5 [3] for safety-critical applications. The new D2D extensions to the standard overcomes the limitations of the LTE legacy architecture by eliminating the latency caused by the core network: a new Sidelink (SL) is defined alongside the Downlink and the Uplink, that allows User Equipments (UEs) to transmit directly to each other, without the involvement of the basestation or of the core network. In this way, LTE becomes a candidate technology for complementing ITS-G5 in supporting safety critical V2X communications, while also offering connectivity to the Internet, Cloud-based services and Professional Mobile Radio.

In the current LTE specification for Proximity Services (ProSe), features such as one-to-many communications and UEs transmitting without supervision of a basestation (autonomous resource selection) are reserved to Public Safety UEs only. Non public safety UEs are currently limited to unicast transmissions that need to be individually scheduled by the basestation (named eNodeB or eNB in LTE) via a complex procedure. We believe that reducing the dependence on the eNB is a key for reducing latency and for improving the system robustness against failure in V2X safety critical scenarios.

In this report, we propose an unsupervised LTE D2D protocol supporting safety-related V2X communication and fully compatible with the recent LTE rel.13/14 Sidelink architecture extensions. Specifically, our contributions are threefold: (i) we formulate the V2X system requirements and compare them with the characteristics of the ProSe architecture and PC5 Slidelink interface (ii) we propose a distributed resource allocation mechanism and evaluate it against IEEE 802.11p (iii) we formulate a joint scheduling / power optimization for D2D as a decentralized

[1]Although the IEEE 802.11p amendment is now integrated into IEEE 802.11-2012, we keep referring to it in this work from the lack of an unanimous naming recognized in all standards/countries.

[2]DSRC is an American acronym standing for Dedicated Short Range Communications.

channel congestion control problematic. We first justify how unsupervised LTE D2D is the necessary to support the safety-related V2X system requirements. We then show that the proposed unsupervised LTE D2D distributed resource allocation performs at least as good as IEEE 802.11p, and can even outperforms it through a joint scheduler and power control mechanism keeping the LTE D2D Sidelink load below a given threshold.

The rest of this document is organized as follows: In section 2, we describe the system requirements for safety-related vehicular communication, and in Section 3, we introduce the new LTE-A Proximity Services and the LTE D2D Sidelink. Section 4 introduces the 5G Sidelink broadcast framework, distributed resource allocation and decentralized congestion control. Section 5 evaluates its performance, and then benchmarks it against IEEE 802.11p. Finally, in Section 7, we provide directions in related D2D work, while in Section 8 we summarize the benefits of the proposed D2D architecture and shed lights on its impact on 5G automotive.

2 System Requirements

Safety critical V2X transmission are a communication paradigm characterized by a specific set of features and requirements, which need to be carefully considered, as neither WiFi (the foundation of 802.11p) nor LTE were originally created to support them:

- *periodic*: cooperative traffic applications require road users to continuously report their state;
- *high transmission rate*: for the state information to be as fresh as possible: differently from typical M2M traffic, V2X requires transmission rates of 10 Hz or more per user;
- *broadcast*: all the road users in proximity of the transmitter are intended recipient of each packet;
- *low latency*: since state information ages very quickly with high users mobility, latency shall be minimized: the lowest possible transmission time ($\sim$1 ms) and end-to-end delay as low as 10 ms [4] for applications such as platooning shall be achieved;
- *distributed operations mode*: UEs shall be able to transmit and adapt transmission power and range without the constant need for a centralized coordinator, which would represent a single point of failure;
- *receiver centric perspective*: in V2X, the performance perceived by the application, such as the Inter Reception Time, are more relevant than protocol metric like the successful reception probability.

3 Proximity Services

3.1 Architecture

In the recent years, the 3GPP defined a new LTE/5G standard extension to support D2D communications under the name of Proximity Services (ProSe). From an application perspective, the objective of ProSe is to provide similar proximity services as WiFi-Direct or Bluetooth. From an architecture perspective, ProSe proposes an extension to the LTE reference architecture with a new set of entities and interfaces, portrayed in Fig. 1 for the general case in which the UEs are camping under different Public Land Mobile Networks (PLMN).

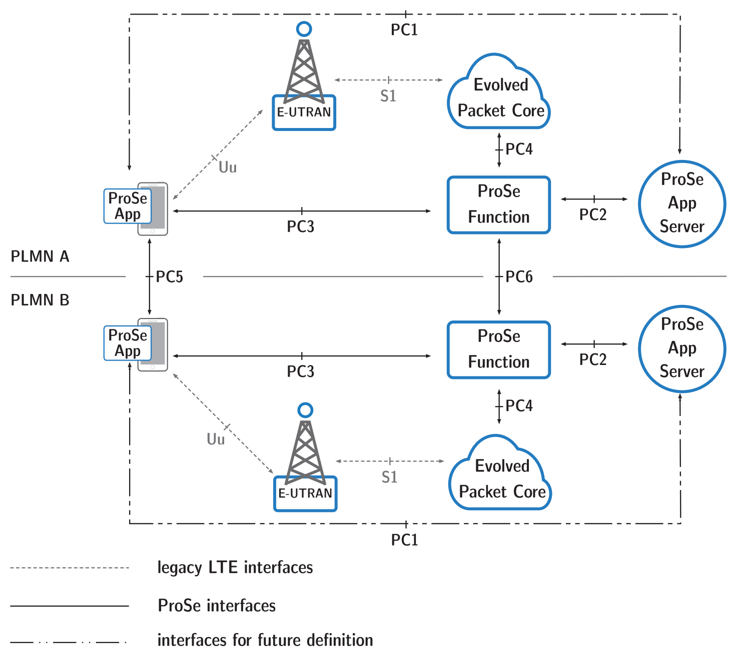


Figure 1: ProSe architecture (inter-PLMN scenario, adapted from [5], Fig.4.2-2)

The newly defined interfaces are [5, §4.3.1]:

PC1, connecting the *ProSe App* to the *ProSe App Server*: it is introduced but not yet specified in the current release;

PC2, connecting the *ProSe App Server* to the *ProSe Function*, which is used to define the interactions for Direct Discovery and EPC-level ProSe Discovery;

PC3, the reference point between *UE* and *Prose Function*, used to authorize discovery functions, perform allocation of Application Codes and User IDs used for discovery, and define the authorization policies for discovery;

PC4, the reference point between the *ProSe Function* and the *EPC*, providing geolocation and EPC-related user data;

PC5, the reference point between *ProSe-enabled UEs*, carrying the “Sidelink” user-plane communications;

PC6, the reference point between *ProSe Functions of different PLMNs*, used when the ProSe-enabled UEs are attached to different cellular networks.

The focus of this work will be on the PC5 link, representing the direct air interface between ProSe enabled UEs; the analysis of the impact of V2X application on the remaining interfaces and entities is left to future study.

3.2 The PC5 Sidelink Interface

As opposed to legacy LTE, in which all the UL and DL transmissions pass through the eNB via the Uu interface, in ProSe UEs can communicate directly via the PC5 interface, also known as “Sidelink” (SL).

The SL air interface is located within the UL frequency bands, parts of which are assigned by the eNodeB to D2D transmissions through the creation of resource pools. Resource pools support basic functions for D2D communications, such as control, discovery and, in some specific configuration, also communications. In time domain, resource pools follow a periodical pattern, as illustrated in Fig. 2, 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 [6, §6.3.8].

In frequency domain, the resource pool occupies a subset of the resource blocks within these subframes, as determined by three parameters [6, §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 ([7, §5]), as illustrated in Fig. 2:

- PSBCH (Physical Sidelink Broadcast Channel), used for the UE to UEs broadcast of control signals;
- PSCCH (Physical Sidelink Control Channel), dedicated to the transmission of the Sidelink Control Information (SCI);

- PSDCH (Physical Sidelink Discovery Channel), used by UEs to discover the presence of other UEs in proximity;

- PSSCH (Physical Sidelink Shared Channel), which carries the UE to UE data transmissions.

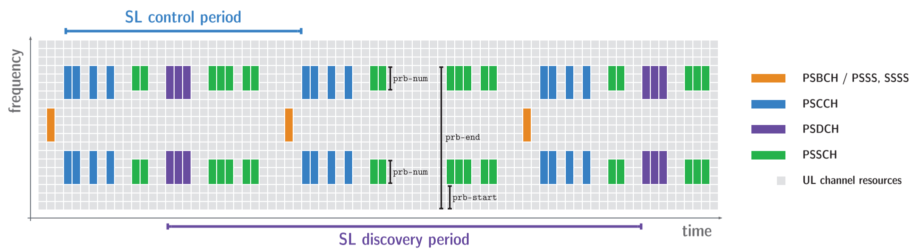


Figure 2: Example of Sidelink channels allocation for transmission mode 2

The allocation of SL resources for D2D transmissions can be made according to 2 different allocation modes:

- `Mode 1 - scheduled`: the eNB handles the resource allocation for every single D2D transmission through a dedicated radio resource management procedure;

- `Mode 2 - autonomous`: the UEs autonomously select the resources to use for their transmissions by picking them randomly from a resource pool. This mode is currently restricted to public safety.

As a result, only Mode 2 requires the reservation of a dedicated PSSCH resource pool (as in Fig. 2), whereas in Mode 1 the resources for D2D data transmissions are dynamically allocated upon request. As opposed to Mode 1, UEs do not need to be RRC_CONNECTED to the eNB in order to transmit on the SL while in Mode 2.

4 5G Sidelink Broadcast of Safety Messages

ProSe currently supports one-to-many type of transmissions, although only for Public Safety UEs [5]. One-to-many communications are E-UTRA only, connectionless, and do not make use of control signaling on the PC5 interface. When happening under the control of a serving cell, the UEs make use of dedicated resource pools, whereas a common pre-configuration is required when outside coverage. In this section, we modify and expand the mechanism proposed in [8], to exploit the novelty introduced in the meantime by the standard (namely, the PC5 interface and the SL channel definition), to enable unsupervised V2V broadcast of vehicular safety messages on the PC5 interface.

The adoption of the unsupervised mode of operations represents a paradigm shift with respect to legacy LTE, which centralizes the management of the radio resources and wherein the network manages the traffic generated by the UEs. In the mechanism proposed in this report, the traffic and channel load management is a challenge, as it needs to be done locally: UEs become active actors in the radio resource management process, by taking decisions based on their local perception.

Such mechanism is described in the remainder of this section, organized in two phases: the *Resource Reservation* phase and the *Distributed Allocation* phase, of which only the former relies on the network infrastructure.

4.1 Resource Reservation phase

The resource reservation phase consists of 3 stages: the definition of a Safety Broadcast Service (SBS) and a Safety Broadcast Area (SBA), the reservation of a common SL resource pool within the SBA, and the definition of a common periodical structure of transmission slots.

4.1.1 Safety Broadcast Service and Safety Broadcast Area

The first step is the definition, within the network, of a *Safety Broadcast Service* (SBS), whose function is to enable road users to broadcast and receive CAM/BSM packets. The SBS is enabled on the *Safety Broadcast Area* (SBA), including the set of neighboring cells over which vehicular UEs shall be able to broadcast safety messages. All the eNBs belonging to the same SBA shall allocate a novel type of resource pool, denominated "SBS resource pool", following the standard Sidelink practices. The resulting scenario is illustrated in Fig. 4. The SBS resource pool

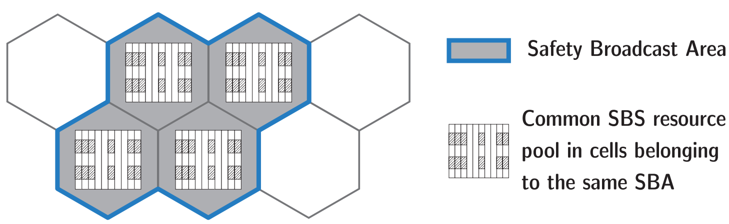
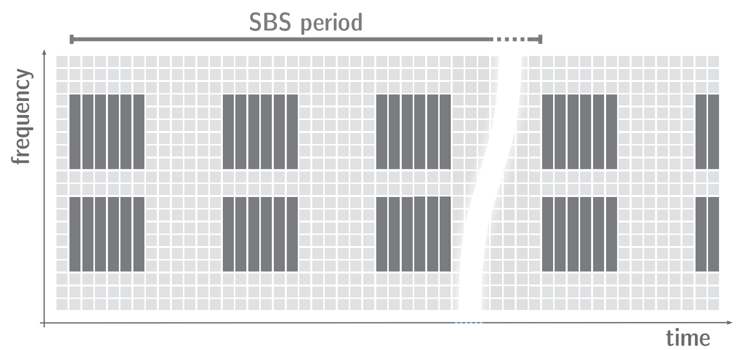


Figure 4: Safety Broadcast Area and common SBS resource pool

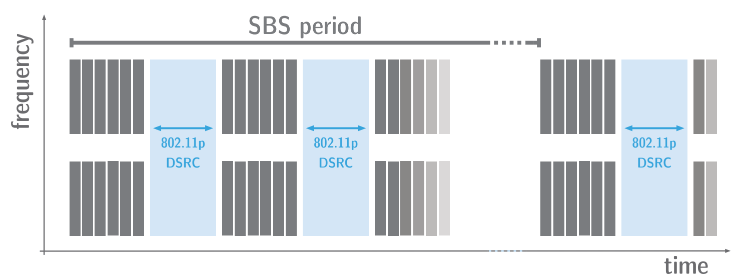
must be configured with the same set of parameters on all the cells in the SBA. In this way, assuming the eNBs are phase synchronous, a common set of channel resources can be exploited for inter-cell broadcast, without requiring coordination from the network. This is particularly important in a vehicular scenario, in which highly mobile UEs can be spread over multiple neighboring cell, and need to reach each other with their CAM/BSM messages.

4.1.2 Reservation of an SBA-wide Common SL Resource Pool

In frequency domain, the SBS resource pool can be reserved according to 2 different modes, as illustrated in Fig.5. In the band sharing mode (5a), the SBS resource pool sharing is reserved like a standard SL resource pool, thus occupying a subset of the UL resources. The second mode (5b) sees the reservation of the



(a) Commercial UL band sharing



(b) Dedicated 5.9 GHz ITS band

Figure 5: SBS resource pool reservation modes

SBS resource pool in the 5.9 GHz ITS band. The benefit of this latter approach is twofold: first, it does not require Public Land Mobile Network Operators to reallocate part of their UL bands; second, it allows the coexistence of LTE D2D with other technologies, such as IEEE 802.11p.

In time domain, the SBS resource pool is repeated every SBS-period, which represents the maximum transmission rate for CAM/BSM packets. Assuming a maximum transmission rate of 10 Hz as in [9], the SBS-period will be 100 ms long. As for the regular Sidelink operations, SBS-periods are assumed synchronous: it starting and ending instants are thus identical for each SBS-UE.

This channel structure of LTE D2D makes it possible to achieve channel rates comparable to or higher than IEEE 802.11p by only occupying the channel a fraction of the time, which creates the following opportunities:

- **In-band deployment -** In absence of commercial LTE traffic to transmit or receive, the LTE transceiver may fall back idle state to save energy. In this way, an energy saving mode based on discontinuous TX / RX can be implemented without causing loss of awareness. This is particularly beneficial considering the extension of safety critical applications to battery-powered hand-held devices;

- **In-band deployment -** The remaining time fraction can be used by the terminal to transmit legacy LTE traffic;
- **Out-band deployment -** Frequency band such (e.g. ITS bands) can be exploited in the remaining time interval by other access technologies (e.g. IEEE 802.11p) as illustrated in Fig. 5b. Day two safety applications such as highly automated driving, which require transmission rates superior to 10 Hz, can use this channel portion to go beyond the 10 Hz transmission rate currently offered by Unsupervised LTE D2D.

4.1.3 Packet-slots Definition

The next step is for SBS-UEs to partition the resources within the SBS pool into blocks, each able to carry a fixed-sized packet such as a CAM or a BSM, as illustrated in Fig. 6. We refer to this blocks as "packet-slots", or simply "slots"[3]. Under the fixed packet size assumption, SBS-UEs can autonomously compute the number l_{RBP} of Resource Block Pairs necessary to form a slot. Starting from the beginning of the SBS-period, and from the frequency bottom-end of the SBS-resource pool, SBS-UEs shall progressively group chunks of l_{RBP} consecutive RBPs in frequency, all of which must belong to the same subframe. This setup is

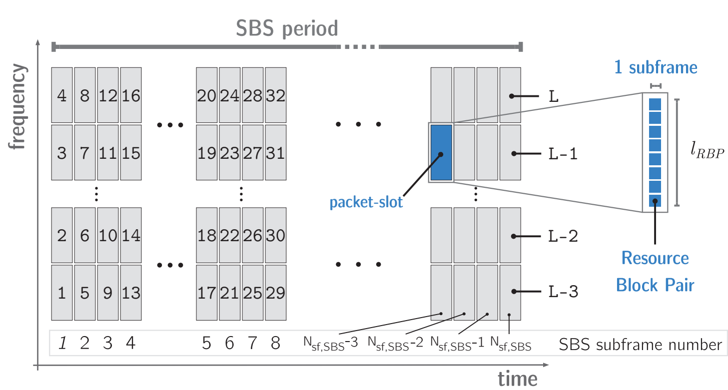


Figure 6: Partition of the SBS resource pool into slots

beneficial in two ways: the impairment effect caused by half duplex (that will be evaluated in section 5), as well as the transmission time of a packet are minimized, which reduce latency. This procedure is applied until the whole SBS pool within

[3]"slot" in LTE terminology is a term indicating a 0.5 ms time division, 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

a SBS-period is covered. The number of slots available within each SBS-period is denoted with L. Its value can be computed starting from l_{RBP}, which is given by (1), wherein l_{PKT} is the size of a fixed-size safety packet, μ is the spectral efficiency in bits/symbol and n_{RE} is the number of Resource Elements (symbols) available in each RBP:

$$l_{RBP} = \lceil 8 \cdot l_{PKT}/(\mu \cdot n_{RE}) \rceil \tag{1}$$

where $\lceil x \rceil$ is the smallest integer larger than x. Denoting with N_{SBS} the number of subframes within each SBS-period belonging to the SBS subframe pool (cfr. Fig. 6), L can be obtained as in (2):

$$L = \lfloor BW_{SBS} \cdot N_{SBS}/l_{RBP} \rfloor \tag{2}$$

where $\lfloor x \rfloor$ is the largest integer smaller than x, and BW_{SBS} is the aggregated bandwidth of the SBS-pool expressed in RBs, $BW_{SBS} = 2 \cdot \texttt{prb-num}$ (cfr. Fig. 2).

This structure is repeated every following SBS-period, during which another L slots will be available. In the next section a distributed allocation mechanism is illustrated, according to which SBS-UEs independently choose in which slots to transmit their packets.

4.2 Distributed Allocation Phase

The solution proposed in this work and in [8] for the distributed allocation is based on Optical Orthogonal Codes (OOC) [10]. It is 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 performing multiple transmission to improve reception reliability was already investigated in [11] 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 adopted as a mechanism to regulate channel access [12, 13]. The definition, properties, and algorithm for their generation are described in detail in [10]. The most desirable property of OOC is the maximum cross-correlation between pairs of codewords belonging to the same set, which is limited to a threshold value denoted with λ. Considering any couple of codewords u and v, L bits long, belonging to the same OOC set, (3) holds true:

$$\sum_{j=1}^{L} u_j \cdot v_j \leq \lambda \quad \forall u \neq v. \tag{3}$$

The number of codewords that can belong to the same OOC set is limited by the choice of parameters L, λ and w: an expression to compute the exact number is not known; however, upper bounds are available, as described in [13].

Similarly to [12], 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. SBS-UEs shall generate an L-bits long OOC codeword before the beginning of each SBS period. Each of the bits is then associated in order to one of the slots 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 Fig. 7. The Hamming weight w of the codewords corresponds to the number of retransmissions performed by an 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[4].

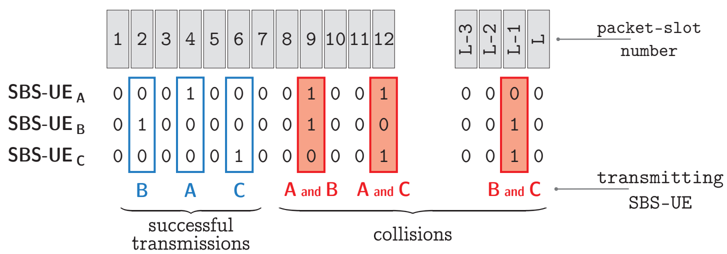


Figure 7: Distributed Allocation: OOC-based access to slots

Fig. 7 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 OOC codes help by increasing the probability that at most one of the transmissions is successfully received, as evaluated in section 5.

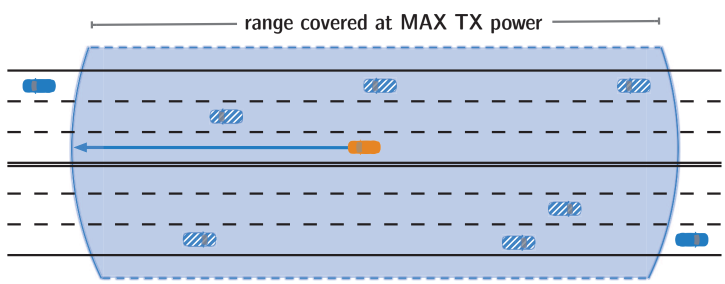
4.3 Decentralized Channel Congestion Control

In most of ProSe scenarios, the LTE eNBs schedule the D2D RBs and allocate the respective D2D transmit power for each D2D UE. In a V2X safety critical scenario, UEs need to be able to independently take action to maintain the channel load under control, first as these scenarios cannot depend on the availability of eNBs, and second as RB scheduling and transmit power allocations depend D2D "Sidelink" local perceptions. Controlling the load on the channel, called Decentral-

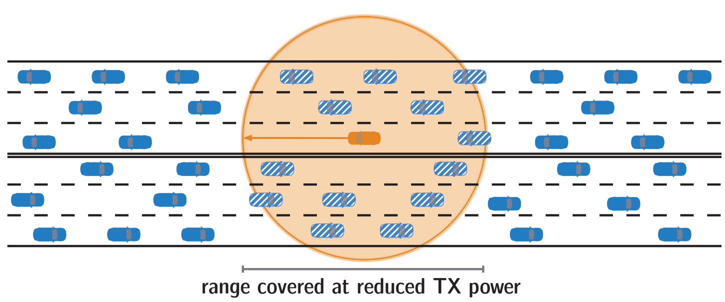
[4]excluding the case in which multiple SBS-UEs generate the same codeword in the same SBS period. In this work we will focus on scenarios wherein parameters are such that this event is highly improbable, thus we will not consider it

ized Channel Congestion Control (DCC) thereafter, is necessary in V2X networks to avoid performance degradation under varying network topology and density. We invite the reader to refer to [14], which contains a detailed overview on challenges, algorithms and standardization related to the DCC in vehicular networks.

DCC is usually operated in two ways, by Transmission Power Control (TPC), as illustrated in Fig. 8 and by Transmission Rate Control (TRC), as depicted in Fig. 9. TPC modifies the emission power to control the transmission range to adjust the spatial reuse of D2D SL resources. In low density scenarios, SBS-UEs can transmit at full power, increasing the range which their packets are able to reach, as illustrated in Fig. 8a. When the channel load is perceived to be above a critical threshold, SBS-UEs can reduce their transmission power. As a consequence, the range reduction will cause its packet to only reach other SBS-UEs in closer proximity (as in Fig. 8b), with the positive effect of globally reducing the channel congestion.



(a) Higher transmission power



(b) Lower transmission power

Figure 8: Transmission Power Control

TRC, on the other hand, operates on the transmission rate and adjusts the temporal reuse of the D2D SL resources. As illustrated in Fig. 9, we propose to implement TRC by introducing "mute" SBS periods. Mute periods are periods in which a given SBS-UE refrains from transmitting, and stays in RX mode only. The TX rate is determined by how many mute periods are inserted between regular TX ones. Each SBS-UE autonomously decides if and when to apply a rate reduction.

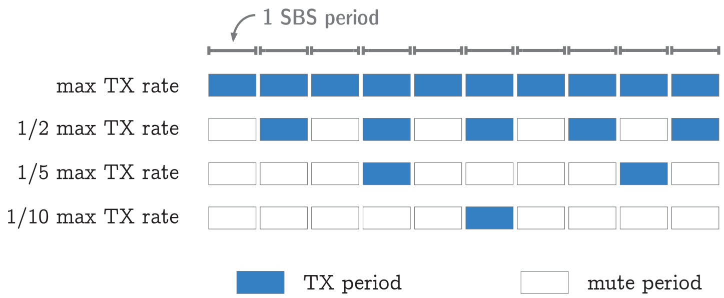


Figure 9: Transmission Rate Control

From an application perspective, TPC and TRC have different repercussions on the awareness perceived by the upper layers. Reducing power reduces the distance to which a vehicle can be ”seen” through its safety-related messages; reducing the rate increases the average uncertainty about the transmitter's position. The choice between which systems to adopt and in which context, is outside the scope of this work. But this decision can only be taken by SBS-UEs alone and not by eNBs, as the required 'awareness' range and freshness is specific to each SBS-UE. Also, TPC and TRC require a cooperative strategy between SBS-UEs, as reducing its own transmit rate or power only benefits neighboring UEs. Perceiving such benefit, these UEs may take an opposite choice and increase their transmit power or rate, leading to unstable TRC and TPC strategies.

From physical perspective, TPC and TRC impact the available SL RB for LTE D2D communication, which must be kept sufficiently high to guarantee dependable unsupervised LTE D2D communications. DCC is therefore required to adjust transmit parameters satisfying the V2X applications, yet maintaining an optimal usage of the SL RBs (i.e. SL channel load). Such mechanism is modeled in our work as a cyber-physical system (CPS) illustrated on Fig. 10, where the cyber-layer adjusts the transmit parameters (i.e. transmit power, rate, modulation, ...) as function of the physical-layer (i.e. SL channel load, number of neighbors, ...). Unsupervised LTE D2D must therefore individually monitor the CPS physical-layer to stabilize the CPS control loop.

In the slotted system presented in this work, the LTE D2D SL *Channel Load* as in Eq. (4), as the ratio between the number of occupied slots and the total number of slots within a reference time interval Δt equal to the SBS-period. All the variables are defined in Table 1. Vehicular SBS-UEs constantly listen the channel in all slots (except when they are in transmission mode themselves), which provides them with the information necessary to estimate the SL channel load.

$$CL^{SL}(\Delta t) = \sum \frac{1 \forall slot^{\text{busy}}}{n_s \cdot N_{SBS}} \tag{4}$$

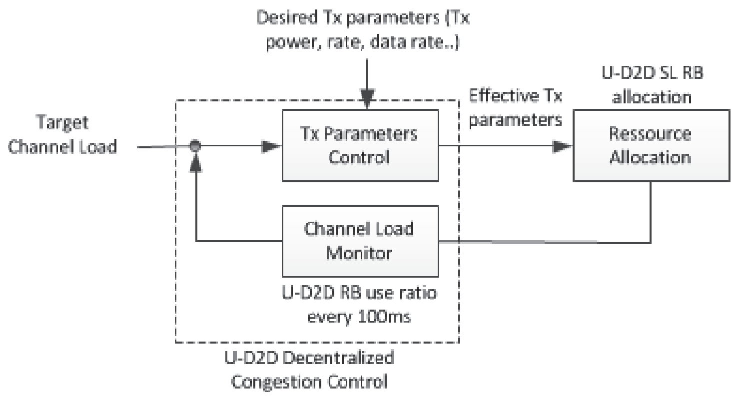


Figure 10: Unsupervised D2D Decentralized Congestion Control

5 Performance model

5.1 Packet-level performances

The scope of this work is to evaluate the MAC-layer performances of the distributed access protocol: the PHY layer will therefore be considered perfect, and no capture effect will be taken into account. Packets that are affected by collision will be considered lost. With such premises, the reception performances are limited by two factors: collisions and Half Duplex (HD) 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 slots being 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-UE cannot to receive packets transmitted within slots that are located within the same subframes as its own TX slots, as illustrated in Fig. 11. A basic scenario is considered with two SBS-UEs,"A" and "B", each transmitting into $w = 2$ slots, thereafter labeled TX_{A1}, TX_{A2}, TX_{B1}, and TX_{B2} respectively. 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 the potential missed receptions due to HD impairment 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, the probability of having at least one of the TX slots free from collisions within a SBS-period is presented for any choice of w and λ. Next, the effects of HD impairment are evaluated, by computing the probability of successful reception for a configuration with $w = 2$ and $\lambda = 1$. This choice of parameters is very important for real applications, as it represents a good com-

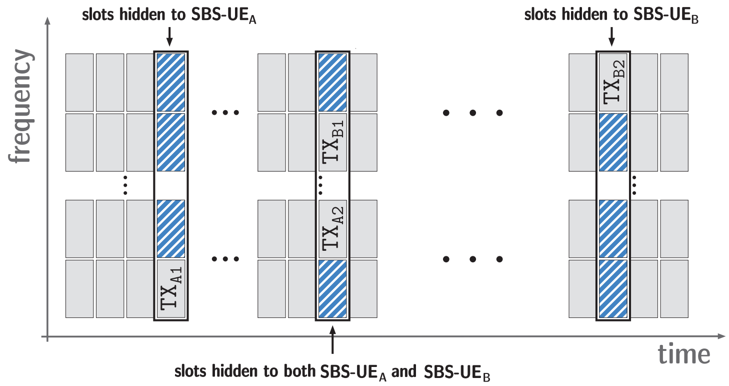


Figure 11: Half duplex impairment: relative position of TX slots of two SBS-UEs

promise between improving reception probability, not saturating the channel with excessive retransmissions, and integrates the energy cost of the protocol, while also greatly simplifying the tractability of the problem, and allowing for the generation of large codesets. As the proposed distributed allocation technique does not listen to the channel 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 identical TX/RX range.

5.1.1 Probability of collision-free transmission within a SBS-period

Let us consider the perspective of a transmitting SBS-UEs. We denote with P_{cf} the probability for at least one of its w TX slots not to be also used for transmission by any of the other $N-1$ SBS-UEs within range. Considering the assumption of synchronous SBS-periods for all SBS-UEs, the formulation of P_{cf} can thus be obtained as in [8], from the case of synchronous frames in [12], as follows:

$$P_{cf} = \sum_{k=1}^{w} (-1)^{k+1} \binom{w}{k} \left[1 - \sum_{j=1}^{w} p_j \sum_{i=1}^{\min(j,k)} \binom{k}{i} \binom{w-k}{j-i} \right]^{N-1} \tag{5}$$

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

$$p_j = \mu_p \frac{\binom{L-w}{w-j}}{\sum_{l=0}^{\lambda} \binom{w}{l} \binom{L-w}{w-l}}, \quad 0 \leq j \leq \lambda. \tag{6}$$

The maximum cross-correlation between OOC codewords being limited to λ and the frame alignment make it such that $p_j = 0$ for $j > \lambda$. For each pair of SBS-UEs, $\binom{w}{j}$ interference patterns of size j exist: p_j represents the probability for each of

Table 1: Mathematical notation (Unsupervised LTE D2D)

Symbol	**Description**
BW_{SBS}	bandwidth assigned to the SBS pool expressed in RBs
$CL^{SL}(\Delta t)$	Channel Load for the Sidelink SBS pool in a time window equal to Δt
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}	length of a slot in RBPs
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
$slot^{\text{busy}}$	slot in a busy state (used by a SBS-UE for transmission)
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)

them to happen. μ_p is a parameter which assumes values in $0 \leq \mu_p \leq 1$, used to model the mean transmission rate as a fraction of a reference maximum value. With $\mu_p = 1$, SBS-UEs transmit packets in every SBS-periods; lower values of μ_p mean that more and more SBS-period are mute ones. $\mu_p = 0.5$ 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, which corresponds to being mute in respectively 50% and 80% of the total SBS-periods.

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

We hereby 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 Fig. 11, labeled "A" and "B", one of which seen from the transmitter's perspective (SBS-UE$_A$) and the other from the receiver's (SBS-UE$_B$). Since every SBS-UE is in turn both, the evaluation also holds when their role is switched. The successful reception of a packet by SBS-UE$_B$ depends on:

- the numbers of TX$_{A1}$ and TX$_{A2}$, which are collision-free;
- whether TX$_{A1}$ and 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 of impairment caused by half duplex:

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:

$$Pr\{E_1\} = (1 - 2p_1)^{N-1} \tag{7}$$

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:

$$Pr\{E_2\} = 2(1 - 2p_1) \cdot \sum_{n=1}^{N-2} \binom{N-2}{n} {p_1}^n (1 - 2p_1)^{N-n-2} \tag{8}$$

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$_{A2}$:

$$Pr\{E_3\} = 2p_1 \cdot \sum_{n=0}^{N-2} \binom{N-2}{n} {p_1}^n (1-2p_1)^{N-n-2} \tag{9}$$

It is worth noting that $Pr\{E_1\}+Pr\{E_2\}+Pr\{E_3\}$ is equal to P_{cf} in (5) evaluated for $w=2$ and $\lambda=1$.

Half duplex impairment depending 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, we recall N_{SBS}, the number of subframes allocated to the SBS within each SBS-period. Let us denote with n_s the number of slots that fit into a subframe:

$$n_s = \lfloor BW_{SBS}/l_{RBP} \rfloor. \tag{10}$$

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

Event E^*: occurs with probability:

$$\begin{aligned} Pr\{E^*\} &= Pr\{\text{TX}_{A1} \in \text{SF}_i, \text{TX}_{A2} \in \text{SF}_i\} \\ &= N_{SBS} \cdot \binom{n_s}{2} / \binom{L}{w}, \end{aligned} \tag{11}$$

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

$$\begin{aligned} Pr\{E^{**}\} &= Pr\{\text{TX}_{A1} \in \text{SF}_i, \text{TX}_{A2} \in \text{SF}_j, i \neq j\} \\ &= 1 - Pr\{\text{TX}_{A1} \in \text{SF}_i, \text{TX}_{A2} \in \text{SF}_i\}. \end{aligned} \tag{12}$$

where in (11) and (12) 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:

$$E_k^* = E_k \cap E^*, \qquad Pr\{E_k^*\} = Pr\{E_k\} \cdot Pr\{E^*\}; \tag{13}$$

$$E_k^{**} = E_k \cap E^{**}, \qquad Pr\{E_k^{**}\} = Pr\{E_k\} \cdot Pr\{E^{**}\}. \tag{14}$$

The desired probability of successful reception P_s can thus be obtained from (13) and (14) as follows:

$$P_s = \sum_{k=1}^{3} [(1 - Pr\{loss_{hd} \mid E_k^*\}) Pr\{E_k^*\} + (1 - Pr\{loss_{hd} \mid E_k^{**}\}) Pr\{E_k^{**}\}] \quad (15)$$

where the terms $Pr\{loss_{hd} \mid E_k^*\}$ and $Pr\{loss_{hd} \mid E_k^{**}\}$ are computed in (16)-(21) 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.

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:

$$Pr\{loss_{hd} \mid E_1^*\} = \frac{(n_s - 2)(L - n_s) + \binom{n_s - 2}{2}}{\binom{L-2}{2}} \quad (16)$$

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:

$$Pr\{loss_{hd} \mid E_1^{**}\} = \frac{(n_s - 1)^2}{\binom{L-2}{2}}. \quad (17)$$

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 re-transmissions 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:

$$Pr\{loss_{hd} \mid E_2^*\} = \frac{(n_s - 2)(L - n_s) + \binom{n_s - 2}{2}}{\binom{L-2}{2}} \quad (18)$$

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

$$Pr\{loss_{hd} \mid E_2^{**}\} = \frac{(n_s - 1)(L - n_s - 1) + \binom{n_s - 1}{2}}{\binom{L-2}{2}} \quad (19)$$

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:

$$Pr\{loss_{hd} \mid E_3^*\} = 1 \tag{20}$$

On the other hand, if TX_{A1} and TX_{A2} are on different subframes, the transmissions from SBS-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:

$$Pr\{loss_{hd} \mid E_3^{**}\} = \frac{n_s - 1}{L - 1}. \tag{21}$$

5.2 Application-level performance

The application-layer performances are the effect perceived at the application layer as a result of packet losses on the radio channel.

5.2.1 Inter Reception Time (IRT)

is a receiver-side metric that represents the mean time between consecutive successful packet receptions from one given transmitter. Since CAMs and BSMs contain information about vehicles' state, longer mean IRTs lead to a lower quality awareness.

For the purpose of evaluating the mean IRT, we maintain the perfect PHY layer assumption, in which packet reception are only affected by collisions and half duplex. Furthermore, we will assume that consecutive packet losses are uncorrelated, which allows us to model it as a function of the probability of successful packet reception in (15) according to a geometric law:

$$IRT = T_{SBS} \cdot \left(1 + \sum_{n=0}^{\infty} n \cdot P_s (1 - P_s)^n\right) = \frac{T_{SBS}}{P_s} \tag{22}$$

where T_{SBS} is the duration of the SBS-period, i.e the inverse of the maximum TX rate. The model in eq. (22) considers a reception successful if at least one of the $w = 2$ transmissions within a SBS period is correctly received.

6 Performance evaluation

6.1 System parameters

We consider a LTE D2D system, wherein UEs are equipped with a single antenna (SISO configuration). Each RB contains 12 subcarriers with 15 kHz spacing (resulting bandwidth: 180 kHz / RB); a normal cyclic prefix configuration is assumed, carrying 14 Resource Elements (symbols) per subcarrier per millisecond, resulting in a total of 168 symbols per Resource Block Pair. QPSK modulation is adopted, i.e. every symbol carries 2 bits.

In such a scenario, a protocol slot is formed by $l_{RBP} = 8$ RBPs consecutive in frequency, allowing a total capacity of 336 bytes per packet, including pilots and PHY layer overhead, able to fit a 300 bytes CAM/BSM packet.

6.2 Retransmission Impact Evaluation

The Hamming weight w of the OOC codewords, representing the number of transmission that an SBS-UE makes in a SBS-period, is relevant to determine the MAC performances. In Fig. 12 P_{cf} as in eq. (5) 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. A higher number of retransmissions is shown providing

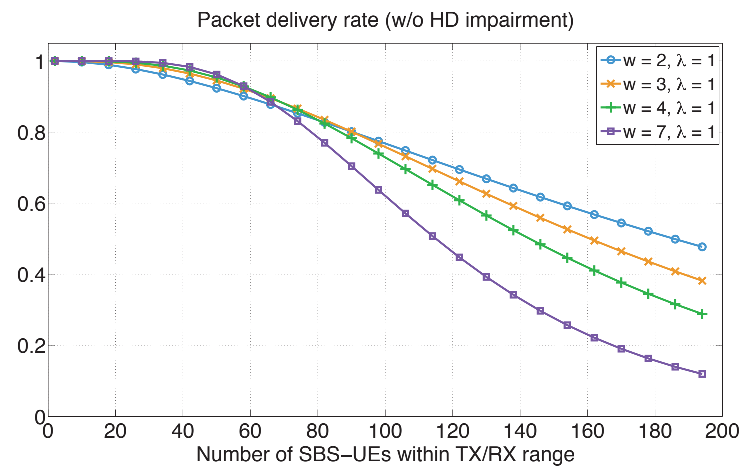


Figure 12: Frame-basis probability of collision-free slot vs w (for TX rate 10 packets/s, with $L = 300$ slots available per SBS-period = 100ms)

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 compensated for with noticeable losses in higher SBS-UE densities. By increasing w, the crossover point between the curves moves leftward to lower number of neighboring SBS-UEs. It is worth noting, as remarked in sec. 4.2 and in [13], that the maximum size of the OOC codeset decreases with w and λ: higher values of w also require to tolerate higher cross correlation, in order to be able to generate a codeset large enough to make the probability for multiple SBS-UEs to pick the same codeword at the same time negligible.

6.3 Half-Duplex Impact Evaluation

Fig. 13 compares 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 with

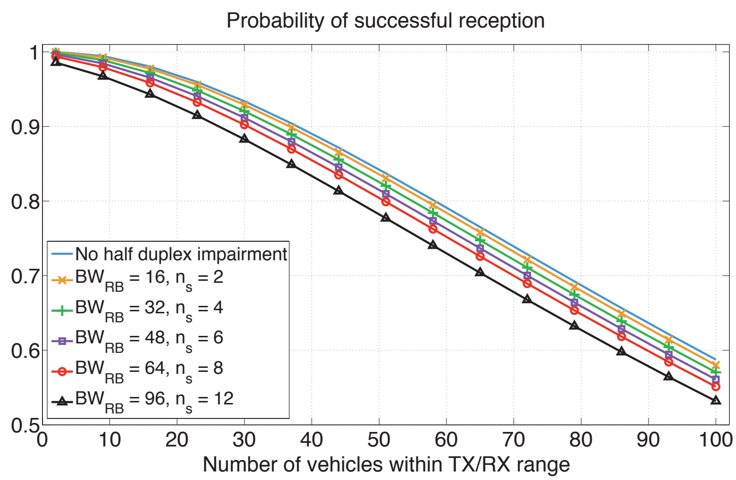


Figure 13: Frame-basis probability of collision-free slot vs w and λ

$w = 2$, $\lambda = 1$ and $L = 192$. This value allows for a fair comparison between all the cited values of n_s, while fitting in a 100ms (100 LTE subframes) SBS-period. Table 2 describes the time and frequency occupation of each of the considered configurations. Out of these configurations, those containing multiple slots in the same

Table 2: Time / Frequency occupation of SL configurations (100 ms SBS-period)

n_s	BW_{SBS} [RBs]	BW [MHz]	Time occupation
2	16	2,88	96%
4	32	5,76	48%
6	48	8,64	32%
8	64	11,52	24%
12	96	17,28	16%

subframes have indeed larger bandwidth and require less subframes to be allocated to SBS, hence reducing the total time occupation of the SL. At the same time, they are also more affected by half duplex impairment, because of the larger number of slots co-located per subframe. The choice of the ideal configuration is an open challenge for future work. Reducing the time interval allows for discontinuous reception cycles, wherein the transceiver can be switched off and saving energy. This 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.

6.4 Impact of Decentralized Channel Congestion Control

In Sec. 2 and Sec. 4.3, it is described how D2D UEs must locally find a trade-off between the Tx rate and Tx range (mapped to #UEs) given a target maximum SL channel load. This trade-off is visually illustrated on Fig. 14, with a plotted optimal transmit rate / #UEs curve for a target SL channel load of 65%, for a reference case wherein 6000 slots are allocated to LTE D2D every second.

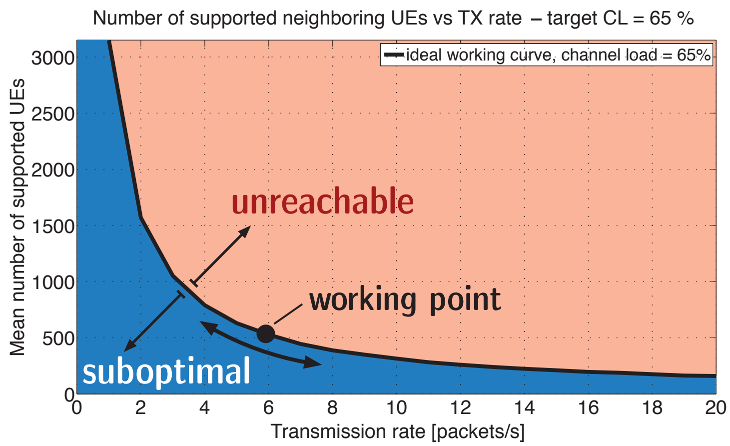


Figure 14: Transmission rate vs Number of neighboring SBS-UEs for channel load 65%

The number of supported users (#UEs) on the vertical axis, can directly be related to the vehicular density once a transmit power is fixed. The curve in Fig. 14 was plotted by means of Monte Carlo simulations, generating a set of OOC codewords using the *greedy algorithm* in [10], and progressively adding SBS-UEs to the network up to the point in which the critical channel load is reached. Fig. 14 depicts a curve separating two zones: (i) a first zone situated below the curve corresponds to a combination of *Tx rate-#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-#UEs* (i.e. leading to a SL channel load higher than the target). The curve is therefore the optimal operational point for unsupervised LTE D2D resource allocations, which may only select one parameter (Tx rate or Tx power), the second being automatically extracted from this curve.

Fig. 15 illustrates the impact of TRC on the probability of successful reception (PSR). The curves represent plots of Eq. (5) for different values of the parameter μ_p in (6), with values corresponding to the Tx rate as in Table 3. Given the finite number of available SL RBs, trying to transmit more packets per SBS-UE, less of

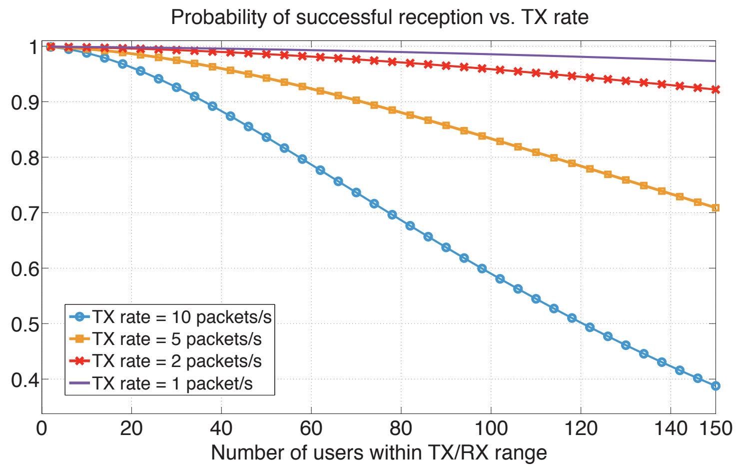


Figure 15: Tx Rate Adaptation in Unsupervised LTE-D2D

them may be allocated on the LTE D2D SL without impacting the communication reliability. When the #UEs is dynamically changing (e.g. mobility, channel fading), adjusting the transmit rate therefore allows more UEs to successfully transmit on the LTE D2D SL.As shown on Fig. 15, given a target 90% PSR, while a Tx rate of 10Hz may only allocate ≈40 UEs in Tx range, reducing it to 5Hz and 2Hz will lead to ≈70 UEs and ≈160 UEs in Tx range, 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 SL channel load in order to support the number of UEs in a given Tx range required by a V2X critical safety application.

Table 3: Correspondence μ_p in (6) ⇔ TX rate

$\mu_{\mathbf{p}}$	**TX rate**
1	10 packets/s (max)
0.5	5 packets/s
0.2	2 packets/s
0.1	1 packet/s

6.5 Benchmarking with IEEE 802.11p

We hereby compare the performance of the unsupervised D2D LTE scheme presented in this work with IEEE 802.11p.For this purpose, we consider the IEEE 802.11p analytic model introduced by Yin et al. in [15], 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 Fig. 16.

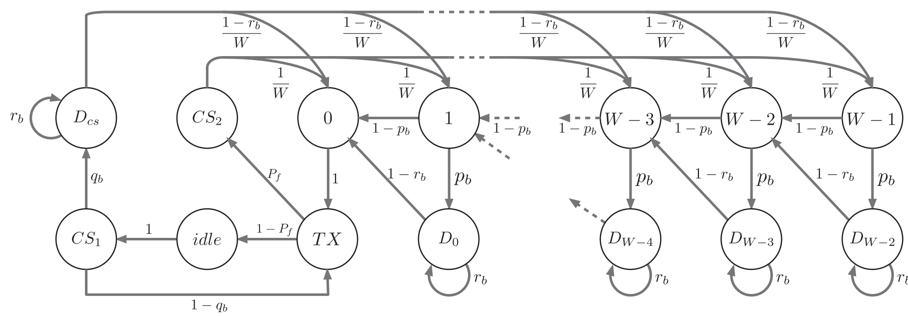


Figure 16: Semi Markov Process state diagram of DSRC, adapted from [15]

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 (DCF Interframe Space). 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:

- 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 [15] 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-D2D, and for the analytic derivation of the IRT for IEEE 802.11p.

6.5.1 Probability of successful reception in IEEE 802.11p

For reasons of analytic tractability, vehicles in [15] are distributed along a single lane according to a Poisson point process, whose parameter β is the mean

Table 4: Mathematical notation (IEEE 802.11p model in [15])

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

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 Eq. (23): the meaning of all the variables therein is defined in Table 4.

$$P_{s,11p}(x) = \exp\Big(-2\pi_{TX}\beta x - 2\frac{\pi_1}{\pi_{TX}}\Big[1 - e^{-\beta\pi_{TX}(R-x)}\Big] - \beta x\pi_1\Big) \quad (23)$$

$P_{s,11p}$ 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 $x \in [0, R]$:

$$\overline{P}_{s,11p} = \frac{1}{R}\int_0^R P_{s,11p}(x)dx. \quad (24)$$

No closed form exists for the integral in (24), hence it must be approximated with numerical methods.

6.5.2 Probability of successful reception: comparison between unsupervised LTE D2D and IEEE 802.11p

Fig. 17 compares the probability of successful packet reception, as a function of the network density, for five different configurations of LTE D2D against IEEE 802.11p. The evaluation parameters for both IEEE 802.11p and unsupervised LTE

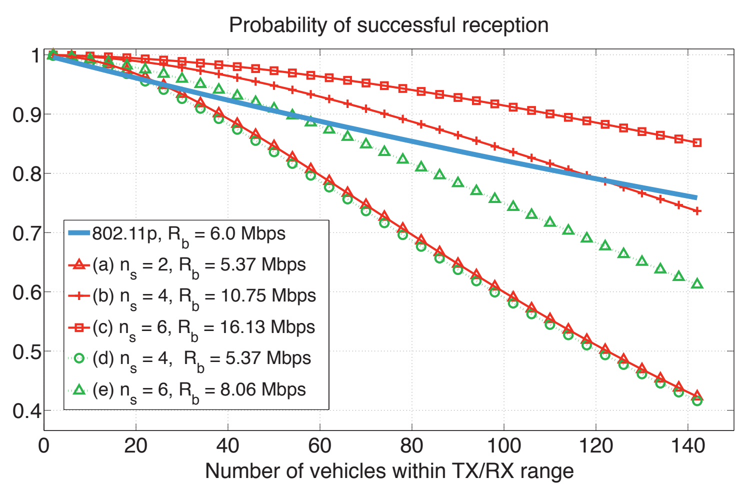


Figure 17: Successful reception probability LTE D2D vs. IEEE 802.11p

D2D are listed in Table 5. Configurations (a), (b), and (c) for LTE D2D feature the SBS pool on all of the 100 subframes available per SBS-period, causing the LTE

Table 5: Probability of successful reception: system parameters

Packet type: Cooperative Awareness Message
Packet size: 300 bytes

802.11p

modulation	QPSK
bandwidth	10 MHz
TX and RX range	500 m
TX rate	10 packets/s
channel rate R_b	6 Mbps
CSMA/CA slot duration	13 µs
SIFS	16 µs
DIFS	42 µs
contention window width W	16

Unsupervised LTE D2D

modulation	QPSK
w	2
λ	1
cyclic prefix config.	normal (14 REs / subcarrier / subframe)
# of REs per RBP (n_{RE})	168
SBS-period	100 ms (10 Hz TX rate)

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

D2D transceiver to be always on. These three configurations have increasingly large bandwidths, allowing to respectively stack 2, 4 and 6 slots within each subframe, resulting in an increasingly higher capacity in terms of number of available slots. Configuration (a) clearly suffers from insufficient capacity, offering performance comparable to IEEE 802.11p, but only for the lowest network densities. Above 25 vehicles within range, the effect of the channel saturation due to the multiple retransmissions becomes evident. As opposed to configuration (a), LTE D2D in configurations (b) and (c) offers enough bandwidth to provide consistently better probability of successful reception than IEEE 802.11p: (b) outperforms it up until the crossing point at 120 vehicles in range, at which point (a) still retains a 10% advantage over IEEE 802.11p.

On the other hand, configurations (d) and (e) only allocate the SBS pool in $N_{sf,SBS} = 50$ out of the 100 subframe available, allowing the LTE transceiver to go in idle mode in the remaining subframes. These configurations offer performance comparable to IEEE 802.11p for densities respectively up 25 and 55 neighboring vehicles.

It is worth noting that the lower perceived densities are the most relevant ones, as the congestion control mechanism illustrated in section 4.3 of this report constantly operates to maintain the working point within this region.

6.5.3 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 D2D described in section 5.2.1, thus having:

$$IRT_{11p} = T + T \cdot \sum_{n=0}^{\infty} n \cdot \overline{P}_{s,11p} \cdot (1 - \overline{P}_{s,11p})^n = \frac{T}{\overline{P}_{s,11p}} \tag{25}$$

where T is the inverse of the transmission rate.

6.5.4 IRT: Comparison between unsupervised LTE D2D vs IEEE 802.11p

Fig. 18 compares plots of the mean Inter Reception Time for IEEE 802.11p, from Eq. (25) and for unsupervised LTE D2D, from Eq. (22), with the configurations and system parameters as in Table 5. The retransmission-based access technique in unsupervised LTE D2D, which allows for improved probability of successful reception over IEEE 802.11p in configurations (b) and (c), consequentially provides lower mean IRTs, which translate to higher position accuracy perceived by the applications.

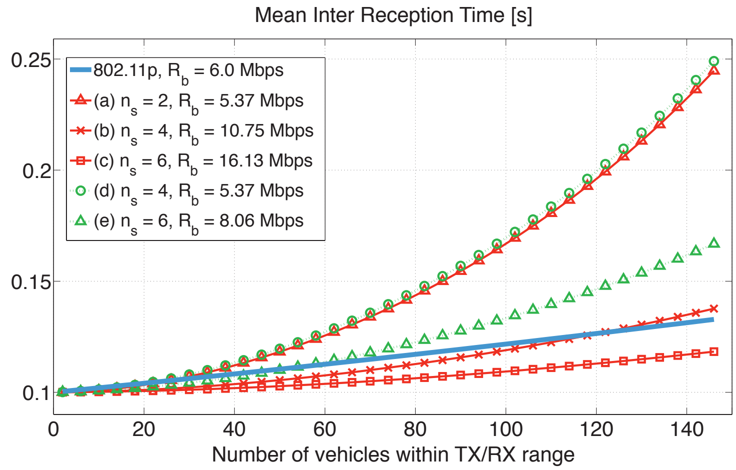


Figure 18: Inter Reception Time: unsupervised LTE D2D vs IEEE 802.11p

7 Related Works

7.1 State of the art

D2D communications underlying the LTE cellular network have been researched since the earliest stages of the specification [16]. [17] contains an extensive review of the literature on cellular D2D communications until 2014 classified by type. Based on the portion of spectrum they occupy, D2D communications can in fact be "inband" or "outband". In the former case, D2D transmission share the frequency bands (typically the UL one) with legacy cellular use, whereas in the latter they are assigned a separated band. Inband D2D can be further split into "overlay" and "underlay", with overlay D2D users being assigned orthogonal resources to the 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 allows to improve spectral efficiency exploiting proximity gain. On the other hand, outband D2D can be a "controlled" or "autonomous" type: controlled D2D are scheduled by the basestation, despite happening on a separate band. This is the case when the basestation decides to re-route transmission between nearby UEs to a different interface, such as WiFi-direct on the ISM bands [18]. On the other hand, autonomous outband communications are completely self-organized by the 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 [19] 3G/LTE cellular communications are compared to WiFi for vehicular networking, and LTE D2D is featured as an appealing solution. Radio Resource Management (RRM) is stressed as the key aspect to ensure an adequate coexistence of legacy cellular and V2V communications. In [20] 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 [21], 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 V2V2D to extend safety safety communications classes of devices (smartphones, IoT *things*) other than vehicles. The same concept is also envisioned in this work. In [22] the authors evaluate the influence that V2V specific PHY and MAC configuration, and traffic patterns have on the performances of LTE D2D: the conclusion is that LTE D2D offers performances (in upper bound) adequate to support this type of traffic. In [23], the performance evaluation focuses entirely on the PHY layer, using multiple 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 [24] 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.

In very recent years, several works have proposed techniques to improve cellular D2D to specifically support vehicular communications, mostly focusing on RRM (scheduling) and power control. In [25], 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 [26], 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, whereas vehicles within range of a single broadcast transmission are likely to be spread over multiple cells, which is one of the issues we addressed in this report. The authors in [27] designed a centralized RB allocation scheme for inband underlay 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. The same authors extended and improved the paradigm to a multicell deployment in [28]. The knowledge of geographic position of vehicular UEs is also exploited in [29], 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 [30] apply vehicle UEs clustering and refine the power control algorithm to relax the full CSI knowledge requirement.

7.2 State of the standard

Beside technical works, standardization has also been very active. Standardization works on LTE ProSe started in the early stages of the Rel. 12 specification with [31] and [32], respectively in 2012 and 2013. The former represents the preliminary study of the scenarios and use cases for ProSe, whereas the latter explores the architecture and protocol extensions to support them. The results of these studies originated [5], which is the current reference specification for ProSe: it contains 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, both at EPC and E-UTRA level. This very latter case is the most relevant for this work, as it involves the PC5 Sidelink. The eligible frequency bands and channel widths that can be assigned to the SL are specified in [33], while its organization into PHY layer channels, and how they map onto transport-level and logical-level channels is defined by [7] (§5, §5.3.1, and §6.1.3.3 respectively).

The discovery services can either be handled by the core network (EPC-level discovery, [5, §5.5]) or directly between ProSe-enabled UEs (direct discovery, [5, §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, [34, §8] defines the two allocation procedures supported for ProSe direct discovery: autonomous resource selection (Type 1) and scheduled resource allocation (Type 2B). Type 1 requires the definition of a discovery resource pool, whose PHY layer characteristics are specified by [35, §14.3.3]. Type 2, on the other hand, allocates discovery channel resources via dedicated RRC signaling.

In ProSe, both broadcast and unicast communication paradigms are envisioned, but currently the former is only loosely specified, and reserved to Public Safety UEs. Chapter 4 in [36] (*"From DMO to D2D"*) discusses the use of LTE D2D for public safety applications, and provides a more detailed description of the Sidelink operations.

ProSe support two resource allocation paradigms for ProSe, standardized in [34, §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 eNB. A specific Downlink Control Information (DCI) format 5 ([37, §5.3.3.1.9]) and a specific Sidelink Control Information format 0 ([37, §5.4.3.1]) were defined for the purpose. Mode 2 on the other hand requires the definition of a PSSCH resource pool as in [35, §14.1.3], but does not specify a policy for UEs to select resources within the pool for transmissions. The definition of such a policy, in a broadcast vehicular safety scenario, is one of the contributions of this work.

8 Conclusion

The recent 3GPP LTE support for Device-to-Device (D2D) communication is not sufficient for safety-critical V2X applications. First the supervision requirement by the LTE network constitutes bottlenecks and single-points of failure, and second adds delays for multi-cells and multi-operators D2D communications. This report investigated LTE D2D communications without the supervision of the LTE network, and proposed a distributed resource allocation and a decentralized congestion control framework for D2D-based safety-critical V2X broadcast communications.

The distributed D2D Sidelink (SL) resource allocation has been analytically formulated and evaluated by simulation. It illustrated that resource allocations should integrate half-duplex considerations, but it also showed to perform at least comparably to IEEE 802.11p, in terms of packet reception probability and packet inter-reception time. It managed to even outperform IEEE 802.11p, by offering up to 12% better probability of successful reception and shorter inter reception time, when the number of broadcast packets or the number of neighbors in D2D range are controlled by a decentralized congestion control mechanism.

Yet, D2D communications without the supervision of the LTE network create challenges to cellular operators. However, V2X safety-critical communications being fundamentally different from standard cellular traffic, they are not expected to be transmitted on commercial bands, but instead on the unlicensed bands between 5.7GHz and 5.9GHz. A strict supervision in these bands is therefore neither required nor necessary. According to this work, unsupervised LTE D2D is therefore a important and promising strategy for future safety-critical V2X applications, such as autonomous vehicles/platooning, or the detection of vulnerable road users.

References

[1] C. Lottermann, M. Botsov, P. Fertl, and R. Mllner, "Performance evaluation of automotive off-board applications in lte deployments," in *Vehicular Networking Conference (VNC), 2012 IEEE*, Nov 2012, pp. 211–218.

[2] A. Vinel, "3gpp lte versus ieee 802.11p/wave: Which technology is able to support cooperative vehicular safety applications?" *Wireless Communications Letters, IEEE*, vol. 1, no. 2, pp. 125–128, April 2012.

[3] T. Mangel, T. Kosch, and H. Hartenstein, "A Comparison of UMTS and LTE for Vehicular Safety Communication at Intersections," in *Vehicular Networking Conference (VNC), 2010 IEEE*, 2010, pp. 293–300.

[4] "5G Automotive Vision," 5G-PPP, the 5G Infrastructure Public Private Partnership, Tech. Rep., October 2015.

[5] 3GPP, "Universal Mobile Telecommunications System (UMTS); LTE; Proximity-based services (ProSe); Stage 2 (3GPP TS 23.303 version 13.3.0 Release 13)," 3GPP, Tech. Rep., Apr. 2016.

[6] ——, "TS 36.331; Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Resource Control (RRC); Protocol Specification v13.0.0," 3GPP, Tech. Rep., Jan. 2016.

[7] ——, "TS 36.300 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2 (Release 12)," 3GPP, Tech. Rep., March 2015.

[8] L. Gallo and J. Härri, "Short paper: A LTE-direct broadcast mechanism for periodic vehicular safety communications," in *VNC 2013, IEEE Vehicular Networking Conference (VNC)*, Boston, USA, Dec. 2013.

[9] ETSI, "ES 202 663, intelligent transport systems (ITS); european profile standard for the physical and medium access control layer of intelligent transport systems operating in the 5 ghz frequency band," ETSI, Tech. Rep., November 2009.

[10] F. Chung, J. Salehi, and V. Wei, "Optical Orthogonal Codes: Design, Snalysis and Applications," *Information Theory, IEEE Transactions on*, vol. 35, no. 3, pp. 595–604, May 1989.

[11] Q. Xu, T. Mak, J. Ko, and R. Sengupta, "Vehicle-to-vehicle safety messaging in dsrc," in *Proceedings of the 1st ACM International Workshop on Vehicular Ad Hoc Networks*, ser. VANET '04. New York, NY, USA: ACM, 2004, pp. 19–28. [Online]. Available: http://doi.acm.org/10.1145/1023875.1023879

[12] F. Farnoud, B. Hassanabadi, and S. Valaee, "Message broadcast using optical orthogonal codes in vehicular communication systems," *Wireless Networking for Intelligent Transportation Systems, ICST QSHINE Workshop*, Aug. 2007.

[13] F. Farnoud and S. Valaee, "Repetition-based broadcast in vehicular ad hoc networks in rician channel with capture," in *INFOCOM Workshops 2008, IEEE*, April 2008, pp. 1–6.

[14] D. Smely, S. Rührup, R. K. Schmidt, J. Kenney, and K. Sjöberg, *Decentralized Congestion Control Techniques for VANETs*. Cham: Springer International Publishing, 2015, pp. 165–191. [Online]. Available: http://dx.doi.org/10.1007/978-3-319-15497-8_6

[15] X. Yin, X. Ma, and K. S. Trivedi, "MAC and application level performance evaluation of beacon message dissemination in DSRC safety communication," *Performance Evaluation*, vol. 71, pp. 1–24, 2014.

[16] K. Doppler, M. Rinne, C. Wijting, C. Ribeiro, and K. Hugl, "Device-to-device communication as an underlay to LTE-advanced networks," *IEEE Communications Magazine*, vol. 47, no. 12, pp. 42–49, December 2009.

[17] A. Asadi, Q. Wang, and V. Mancuso, "A Survey on Device-to-Device Communication in Cellular Networks," *IEEE Communications Surveys & Tutorials*, vol. 16, no. 4, pp. 1801–1819.

[18] A. Asadi and V. Mancuso, "WiFi Direct and LTE D2D in action," in *Wireless Days (WD), 2013 IFIP*. IEEE, 2013, pp. 1–8.

[19] G. Araniti, C. Campolo, M. Condoluci, A. Iera, and A. Molinaro, "LTE for vehicular networking: a survey," *IEEE Communications Magazine*, vol. 51, no. 5, pp. 148–157, 2013.

[20] X. Cheng, L. Yang, and X. Shen, "D2D for Intelligent Transportation Systems: A Feasibility Study," *IEEE Transactions on Intelligent Transportation Systems*, vol. 16, no. 4, pp. 1784–1793.

[21] A. Khelil and D. Soldani, "On the suitability of Device-to-Device communications for road traffic safety," in *Internet of Things (WF-IoT), 2014 IEEE World Forum on*. IEEE, 2014, pp. 224–229.

[22] G. Piro, A. Orsino, C. Campolo, G. Araniti, G. Boggia, and A. Molinaro, "D2D in LTE vehicular networking: System model and upper bound performance," in *Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT), 2015 7th International Congress on*. IEEE, 2015, pp. 281–286.

[23] D. W. Matolak, Q. Wu, J. J. Sanchez-Sanchez, D. Morales-Jimenez, and M. C. Aguayo-Torres, "Performance of LTE in Vehicle-to-Vehicle Channels," in *2011 IEEE Vehicular Technology Conference (VTC Fall)*. IEEE, pp. 1–4.

[24] C. Lottermann, M. Botsov, P. Fertl, R. Müllner, G. Araniti, C. Campolo, M. Condoluci, A. Iera, and A. Molinaro, *Vehicular ad hoc Networks: Standards, Solutions, and Research*. Springer International Publishing, 2015, ch. LTE for Vehicular Communications, pp. 457–501. [Online]. Available: http://dx.doi.org/10.1007/978-3-319-15497-8\textunderscore16

[25] W. Sun, E. Strom, F. Brännström, K. Sou, and Y. Sui, "Radio Resource Management for D2D-based V2V Communication," *IEEE Transactions on Vehicular Technology*, pp. 1–1.

[26] W. Sun, D. Yuan, E. G. Strom, and F. Brännström, "Cluster-Based Radio Resource Management for D2D-Supported Safety-Critical V2X Communications," *IEEE Transactions on Wireless Communications*, vol. 15, no. 4, pp. 2756–2769.

[27] M. Botsov, M. Klugel, W. Kellerer, and P. Fertl, "Location dependent resource allocation for mobile device-to-device communications," in *2014 IEEE Wireless Communications and Networking Conference (WCNC)*. IEEE, pp. 1679–1684.

[28] ——, "Location-based Resource Allocation for mobile D2D communications in multicell deployments," in *Communication Workshop (ICCW), 2015 IEEE International Conference on*. IEEE, 2015, pp. 2444–2450.

[29] Y. Ren, C. Wang, D. Liu, F. Liu, and E. Liu, "Applying LTE-D2D to Support V2V Communication Using Local Geographic Knowledge," in *Vehicular Technology Conference (VTC Fall), 2015 IEEE 82nd*. IEEE, 2015, pp. 1–5.

[30] Y. Ren, F. Liu, Z. Liu, C. Wang, and Y. Ji, "Power Control in D2D-Based Vehicular Communication Networks," *IEEE Transactions on Vehicular Technology*, vol. 64, no. 12, pp. 5547–5562.

[31] 3GPP, "TR 22.803 3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; Feasibility study for Proximity Services (prose) (release 12)," 3GPP, Tech. Rep.

[32] ——, "TR 23.703 3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; Study on architecture enhancements to support Proximity Services (ProSe) (release 12)," 3GPP, Tech. Rep.

[33] ——, "TS 36.101 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access E-UTRA; User Equipment (UE) radio transmission and reception (release 13)," 3GPP, Tech. Rep., March 2016.

[34] ——, "TR 36.843 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Study on LTE Device-to-Device Proximity Services; Radio Aspects; v12.0.1," 3GPP, Tech. Rep., March 2014.

[35] ——, "TS 36.213 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Layer procedures (Release 13) v13.0.0," 3GPP, Tech. Rep., January 2016.

[36] D. Câmara and N. Nikaein, *Wireless public safety networks 1*. Elsevier, November 2015, ISBN: 9781785480225, 11 2015. [Online]. Available: http://www.eurecom.fr/publication/4833

[37] 3GPP, "TS 36.212 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Multiplexing and channel coding (Release 13) v13.0.0," 3GPP, Tech. Rep., January 2016.