Unsupervised LTE D2D - Case Study for Safety-Critical V2X Communications

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***Abstract*—This article explores the recent 3GPP LTE D2D rel. 14 Radio Resource Management specification to identify the challenges and evaluate the potentials of Unsupervised LTE D2D (mode 2) for Safety-critical V2X Communications. It also proposes two distributed resource allocation strategies for unlicensed band access. Complementary to DSRC/ITS-G5, unsupervised LTE D2D is an opportunity to provide redundancy for ultra-reliable systems, such as safety-critical V2X communications.**

I. INTRODUCTION

Connected vehicles are expected to be a major milestone in journey toward future Highly Autonomous Driving (HAD) vehicles. To this objective, a ultra-reliable V2X communication service is critical, capable of providing vehicular awareness hundreds of meters away, and in severe Non-Line-of-Sight (NLOS) conditions. Since 1999, the IEEE 802.11p has been chosen for such service by the Dedicated Short Range Communication (DSRC) in the US, and by the ETSI ITS-G5 in Europe. At the time of writing, IEEE 802.11p-based DSRC/ITS-G5 deployments are ongoing, both in the US and in EU, and both in vehicles and as road infrastructures.

The 3GPP Long Term Evolution (LTE), already since its Release 12, provides specifications for Device-to-Device (D2D) communication to Proximity Services (ProSe) [1]. Under the pressure of cellular operators and chip manufacturers, this specification has been refined in subsequent releases. LTE rel.14 currently provides a solid specification for LTE D2D, making LTE technology a candidate also for ultra-reliable V2X communication services.

It is yet necessary to evaluate the true capabilities of LTE D2D to fulfill such service requirements. Since January 2016, LTE Rel. 14 is available and D2D aspects, such as service discovery or resource allocation in single, multi-cell or in roaming conditions. However, this specification mostly relates to the case of a supervised D2D by an eNB/ePC (evolved Packet Core). A limited unsupervised D2D specification is reserved to First Responders and environments lacking cellular coverage.

Supervised LTE-D2D is yet not sufficient for safety-critical V2X communications, first as the LTE UTRAN/EPC still remain bottlenecks and single-points of failure, and second as they add non negligible delays for multi-cells and multi-operators vehicular awareness. Also, V2X 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 are therefore neither required nor necessary. Yet, considering the lack of specifications, unsupervised LTE-D2D remains challenging for safety-critical V2X communications.

In this paper, we overview the state-of-art of the Radio Resource Management of the recent LTE-D2D rel. 14 standard, and emphasize the lack of specifications related to the unsupervised LTE-D2D mode. We address key challenges from the absence of network supervision, and identify potential mechanisms available for secured and efficient unsupervised LTE D2D. We finally describe two fully distributed resource allocations schemes for unsupervised LTE-D2D: (i) a blind access developed for opportunistic access in strongly changing topology; (ii) a Self-Organized TDMA (S-TDMA) scheme providing higher reliability in stable topology. Jointly or separately, these two mechanisms are capable to provide reliable V2X communication, and complementary to DSRC/ITS-G5, are a critical strategy to provide communication redundancy for Safety-critical ITS applications.

II. BACKGROUND ON LTE-D2D

A. LTE D2D - State of the Standard

In order to support proximity-based discovery, communication and applications, ProSe introduced a novel D2D extension to the legacy LTE architecture. Fig. 1 illustrates this extension for the general case, where the communicating User Equipments (UEs) are attached to different Public Land Mobile Networks (PLMNs) (i.e. Operators).

Alongside the legacy interfaces such as the "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 I 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 [1], §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 as "Sidelink" (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[1], where D2D communications can take place; in the current specification

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[1] In the current 3GPP specification, Uplink resources have been preferred for SL due to their lower peak-to-average power ratio (PAPR).

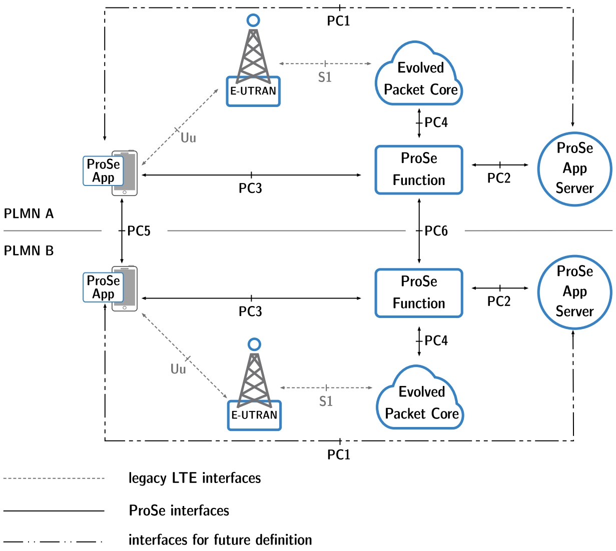

Fig. 1. ProSe architectural extension - adapted from [1, §4.2]

TABLE I
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 "Sidelink" user plane and control plane communications
PC6	connects ProSe Functions of different PLMNs, when ProSe-enabled UEs are attached to different cellular networks

it is allowed to operate within the frequency bands listed in [2, Table 5.5D-1]. The bandwidths that can be 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 [2, §A6.2 - §A6.5]).

As illustrated in Fig. 2, 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 [3, §6.3.8]). The length of the bitmap is fixed to 40 subframes in 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 block pool is defined by the parameters `prb-Num`, `prb-Start` and `prb-End`: the latter two respectively indicate the index of the first and last RBs allocated to SL within the subframe, relative to PRB (Physical Resource Block #0). `prb-Num` indicates how many RBs are assigned after `prb-Start` and before `prb-End`, resulting in the two-striped structure illustrated in Fig. 2. All the parameters for the resource pool allocation are periodically broadcast by the eNodeB enclosed within the System Information Block 18 (SIB18) for communications and SIB19 for discovery [3, §6.3.1], which are accessible by UEs in both `RRC_CONNECTED` and `RRC_IDLE` states.

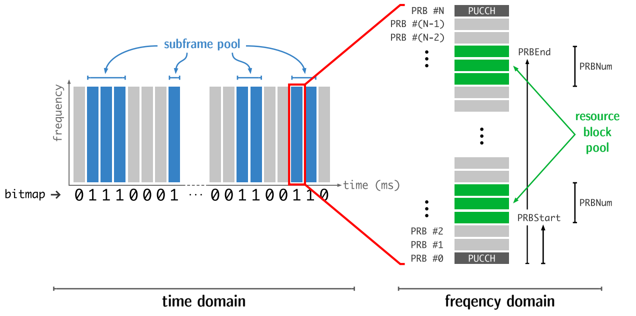

Fig. 2. Resource Allocation in time/frequency domain - Subframe and Resource Block pools

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 RX and up to 4 in TX (`max-SL-RXPool` and `max-SL-TXPool` in [3, §6.4]). Separate resource pools are created to support newly defined PHY layer channels:

- "PSBCH", Physical Sidelink Broadcast Channel, which carries system information and synchronization signals;
- "PSCCH", Physical Sidelink Control Channel, which carries UE-to-UE control plane data;
- "PSDCH", Physical Sidelink Discovery Channel, which supports UE direct discovery transmissions;
- "PSSCH", Physical Sidelink Shared Channel, used for user plane data transmissions.

A detailed description how these PHY channels are mapped onto transport and logical channels is available in [4], 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 [1, §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 [5, §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 [6, §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 Sidelink Control Information (SCI, see [7, §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 eNB 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.

Visually, a Sidelink implementation for transmission mode 2 would result in a channel organization such as the one in Fig. 3, wherein the (different) periods of control/communication and discovery services are highlighted.

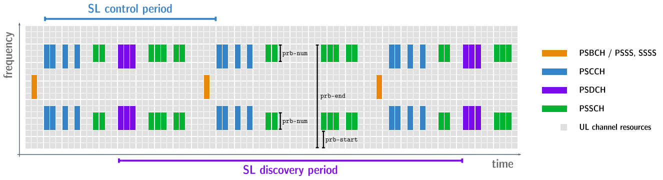

Fig. 3. Example of SL channel for transmission mode 2

B. State of the research

In recent years, extensive research efforts have been done towards the support of direct V2X communications underlying cellular networks. However, the results currently available in literature propose centralized schemes, that rely on the infrastructure for scheduling assignment, albeit tackling the problem by following different approaches. For instance, in [8], a separate RB assignment and power control algorithm is proposed, wherein cellular users (C-UEs) and vehicular users (V-UEs) share the commercial LTE bands, with the purpose of maximizing the C-UEs sum rate, while supporting V-UEs with given reliability constraints. In [9], the authors designed a centralized scheduling mechanism based on the position of the vehicles within a single cell, then extended to cover multicell deployments in [10]. Knowledge of the geographical position of vehicles is also exploited in [11] which considers a single cell inband scenario, wherein multiple vehicular UEs on a single road share the resources with a single cellular UE in a single cell.

III. UNSUPERVISED LTE D2D FOR SAFETY-CRITICAL V2X

Safety Critical V2X applications are characterized by specific network topology and transmission patterns, which challenge the current ProSe architecture. Safety critical messages need to be periodically broadcast by each UE to all other UEs in its local geographical scope, irrelevantly to the cellular coverage of one or multiple operators[2]. This aspect is illustrated on Fig. 4, where three vehicles are in immediate safety-related ranges, but are not under the coverage of the same cells. The blue vehicles ("V1" and "V2") are under two different partially overlapping cells of a same operator, while the orange vehicle ("V3") is under the cellular coverage of another operator. Whereas specific interfaces exist, such as PC5 and PC6, enabling ProSe between UEs connected to two different eNB or different PLMNs, they represent overhead and delay in the D2D discovery/communication[3], and as such to Safety-critical V2X applications. Moreover, any functional element required to conduct such process is considered as a single point of failure that Safety-critical V2X applications cannot tolerate. Only fully dedicated and distributed D2D resource allocations may be relied on, and thus irrelevantly to the operator. Safety-critical V2X communication having only a local scope, a distributed resource allocation is also more efficient for optimal resource usage than a centralized scheduler, which would require to cope with specific resource allocations between different eNBs and operators.

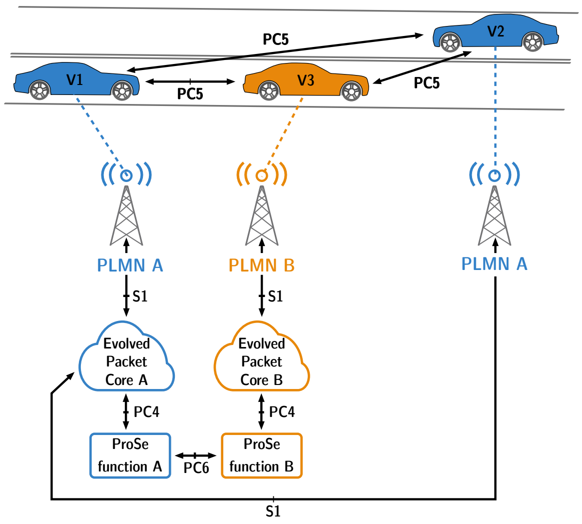

Fig. 4. Illustration of vehicles under different cells and operators

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[2] The 3GPP ProSe supports one-to-many communications, but are strictly reserved to Public Safety UEs operating as an independent network, when the regular one is absent, i.e. in case of catastrophic events.

[3] At the time of writing, the standard is not well defined enough to provide a numerical evaluation: the numerous network entities that need to be involved and the level of coordination needed are however unsuitable for safety critical communications

Obviously, such unsupervised resource allocation schemes cannot be conducted in the operators commercial bands, but are also not required. When common resources must be made available over a large geographical area and irrelevantly to the operator, using licensed bands is an inefficient strategy. Similarly to DSRC/ITS-G5, LTE-D2D safety-critical V2X communication must be done on a common shared band. As described in [12], and illustrated on Fig.5, a variety of unlicensed bands are available. The two most prominent are the ITS (Intelligent Transportation Systems) band between 5875 and 5905 MHz, and the Radio LAN (ISM) band between 5470 and 5725 MHz. The RLAN band is even currently considered for LTE Licensed Assisted Access (LAA), where LTE eNB/UEs may use these bands by adopting a mandatory listen-before-talk access [5, §15]. The results and considerations presented in this paper, however, remain valid independently from the use of a dedicated or a shared band.

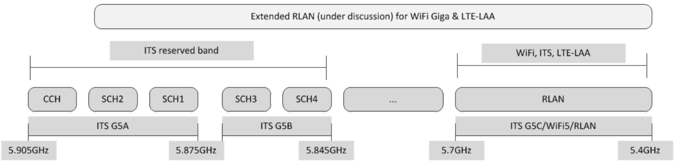

Fig. 5. Spectrum Sharing and Co-existence in the RLAN and ITS bands

An intensive lobbying is ongoing, both a the US FCC and at the EU ETSI, for co-existence mechanisms between WiFi and DSRC/ITS-G5 in a future extended RLAN band integrating almost all the ITS channels. Yet, according to FCC watchdogs, any co-existing technology shall not interfere with safety-critical V2X communications. Operating **unsupervised LTE D2D** for Safety-related applications in these bands would make LTE **the primary user**, hence **protecting it from other technologies** and traffic types.

Unsupervised LTE-D2D should yet not be considered as a competitor to the current DSRC/ITS-G5. First, DSRC/ITS-G5 is currently the only available technology for safety-critical V2X communication, and will be deployed before the unsupervised LTE-D2D will be available. Second, it should be considered as an opportunity to rely on two different technologies on different bands, and as such capable of either adding redundancy or doubling the communication capacity as function of the objectives of safety-critical V2X applications.

IV. CHALLENGE OVERVIEW

Although no strong normative bounds prevent unsupervised LTE D2D for safety-critical V2X communication, technical challenges remain due to the reduction of the supervision by the network. We identify and describe next critical challenges, which should be addressed by Unsupervised LTE D2D:

- **Synchronization -** The timing of UEs transmissions and reception is adapted to a time reference established by the eNodeB. In LTE D2D unicast, synchronization signals are defined to align the time reference of pairs of users; in an unsupervised broadcast scenario, however, the time reference needs to be shared by all the UEs. This can be achieved, for instance, by using GPS and by applying a guard time during the last symbol (or half symbol) of each subframe, which compensates for interference due to propagation delay. A dependable availability of GNSS coverage even in challenging scenarios such as urban canyons and tunnels will be required for future autonomous vehicles. In cases where GNSS coverage would be absent, UEs would however be able to maintain synchronization by relying on the network-provided timing, compensating internally for its mismatch with GNSS time. The edge cases, where none of the above would be available, future studies would be required on advanced techniques to reliably exploit UEs internal clock.
- **Distributed Resource Allocation -** LTE D2D UEs in mode 2 need to independently detect and handle contention with proximity UEs: LTE LAA already provides such a scheme, but also leaves room for further optimization. Distributed resource allocation schemes envisioned for unsupervised LTE D2D will require UEs to be able to monitor the channel load and control congestion by themselves, both to guarantee coexistence and to avoid collision with other UEs competing for the same resources. Decentralized Power / rate control strategies similar to those for ITS-G5 could be used for this purpose [13].
- **Half Duplex (HD) operations -** The LTE air interface, as illustrated in [14], allows multiple packet-slot to be positioned in adjacent sub-bands within the same transmission time interval. This means that UEs that select one of them to transmit a packet will not be able to receive in the ones time co-located to it, causing a further impairment that affects RX performance.
- **Cooperative Multi-hop LTE Resource Sharing -** Well known in ad-hoc and vehicular networks, channel conditions strongly vary in space and in time. Any channel condition locally measured does not reflect the condition of the UEs, which will be impacted by transmitting LTE D2D UE. LTE D2D UEs will need to cooperate and exchange information. The ETSI ITS Geonetworking [15] could be an approach to that objective for two main reasons: first, the relay of local channel monitor, which greatly helps UEs into taking optimal TX rate / power decision based on one-hop channel knowledge; second, for its ability to support mobile relay nodes.
- **Security and Privacy-** Without an eNB, distributed security and privacy mechanisms are required. Aspects like TMSI (anonymous ID), certificates, as well as mechanisms to exchange them are required. Also in this case, IEEE 1609.2 and ETSI ITS security specifications[4] provide a full specification for cryptography and authentication that could be applied.

All these challenges are important, but it can be mentioned that all of them have been studied already under different conditions and technologies. Accordingly, Unsupervised LTE D2D may freely integrate them when and wherever required. Yet, joint frequency-time distributed resource allocation is one challenge remaining insufficiently charted. All studies

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[4] among others: TS 102 687; TS 102 940; TS 102 731.

investigating these allocation strategies assumed either pure TDMA, FDMA or CSMA. Distributed resource allocations for unlicensed LTE D2D is a combination of all of them, and specific aspects, such as joint frequency/time resource block allocations in half duplex conditions, yet requires to be investigated.

V. DISTRIBUTED RESOURCE ALLOCATION FOR UNSUPERVISED LTE D2D

We provide in this Section a few hints on promising strategies for joint frequency/time distributed resource allocations for Unsupervised LTE D2D.

The Sidelink structure described in section II-A and its periodical nature can be efficiently exploited to convey V2X safety critical traffic. We propose to organize channel resources as illustrated in Fig. 6. The D2D V2X period is a further periodicity which is related to the maximum envisioned TX rate: in the case of the standard CAM/BSM 10Hz TX rate, this period is equal to 0.1 seconds. UEs can retrieve the SL time and frequency coordinates from the SIBs 18 and 19[5], then organize all the resources into slots, each containing a number of Resource Block Pairs sufficient to carry a packet (e.g. CAM or BSM). The number of slots L available per D2D V2X period depends on many factors, such as the amount of channel resources dedicated to the V2X pools, the modulation and coding scheme used, and the packet size.

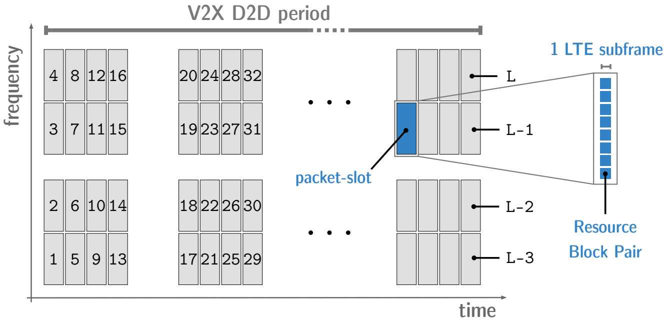

Fig. 6. Resource reservation for unsupervised LTE V2X

GPS synchronization and the SL time / frequency information received from the network will ensure that UEs all associate the same resource block pairs to the same slots. Assuming that all the eNodeBs in a wide region do share the same allocation scheme, these same slots can be exploited to transmit between multiple cells without requiring further intercell coordination. Allocating the SL V2X pool in a shared band such as the ITS or RLAN bands, and linking the subframes timing to UTC time coordinates will allow UEs from multiple operators to exploit that same set of resources, without needing inter-operator coordination, but only the definition of new, RRC messages for the configuration of the UEs.

We briefly describe two mechanisms for distributed scheduling: (i) Optical Orthogonal Codes (OOC), a retransmission-based system as in [14], [16] and reference therein, and (ii) Self Organizing TDMA (S-TDMA) [17], a reservation-based distributed multiple access scheme designed for position reporting applications.

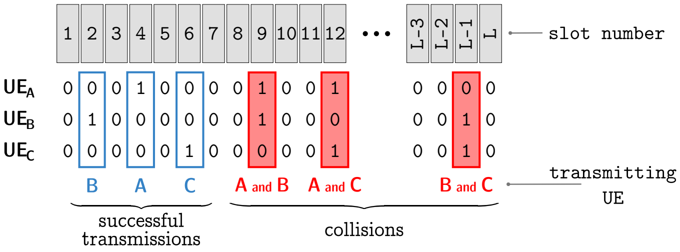

Fig. 7. Optical Orthogonal Code for distributed resource scheduling

As depicted on Fig. 7, OOCs are sets of binary codewords which UEs can locally generate and use to regulate channel access. OOC codewords must have length L bits, of which w are `1`s and $L-w$ `0`s. The UEs generate one codeword per period, then map every bit in exact order to the L available slots: the transceiver is then set in TX mode in correspondence of `1` bits and in RX state in correspondence to the `0` bits. This results in w retransmissions per period for each UE. The beneficial property of OOC is that the cross correlation between pairs of codewords is upper bounded to $\lambda < w$. This means that two UEs can collide at most in λ slots per period, which improves the transmission reliability.

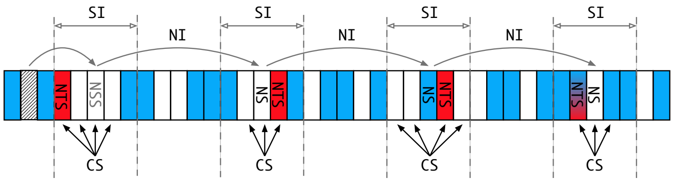

Fig. 8. Self-Organizing TMDA (S-TDMA) for distributed resource scheduling

S-TDMA, on the other hand, is a protocol in which UEs exploit the knowledge of other UEs CAM/BSM transmissions, and accordingly also their positions, to reserve slots for their transmissions. UEs trying to gain access to S-TDMA resources first need to listen to a full STDMA frame. Based on this, UEs will obtain a representation of available and busy slots as illustrated on Fig.8. Then, UEs will autonomously choose enough slots to support their TX rate. In the case not enough free slots are available, UEs will rely on spatial reuse by using slots occupied by the geographically most distant UEs. The UE finally announces its reserved slots for all other UEs to become aware of it. The slot reservation pattern is periodically updated to compensate for variations of the topology due to users' mobility.

In Fig. 9, the MAC-layer performance of OOC and STDMA are compared by means of simulation against a metric called *Offered Channel Load (OCL)* in a static scenario, wherein 900 packet slots per seconds are available per second and allocated over 300 subframes, each containing 3 packet-slots co-located in time. A transmission rate of 10 Hz per second is assumed for both schemes, with OOC transmitting $w = 2$ instances of each packet.

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[5] SIB 18/19 infos may be preloaded as well, considering they would not change over time/space

The reservation-based, context aware STDMA shows to provide the best performance in ideal conditions (neglecting the HD impairment). However, when HD is factored in, a notable drop in performance is observed due to collisions caused by the missed receptions of the re-reservation information attached to the packets. On the other hand, the blind channel access mechanism, and the multiple re-transmissions performed by OOC offer a worse baseline ideal performance, which however is less affected by the RX impairment caused by HD. The price of multiple re-transmissions is a higher OCL per user.

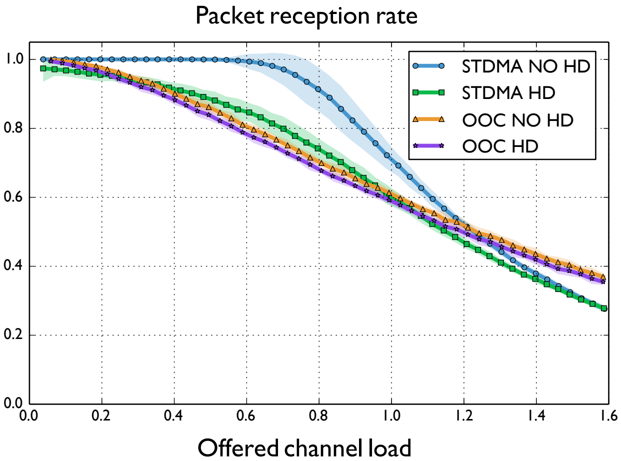

Fig. 9. LTE V2X distributed scheduling: OOC vs S-TDMA. The lightly colored area surrounding the curves represent the 95% confidence interval

These two conceptually different approaches provide better results in different scenarios: while the re-reservation pattern of S-TDMA performs better in slowly changing environments, wherein the re-reservation parameters vary faster than the network topology does, the OOC approach provides better performance for fast changing topologies, thanks to re-transmissions and to limited cross correlations, which influence the delivery reliability.

VI. CONCLUSION

Considering LTE D2D-based safety-critical V2X communication, network supervision is neither required nor necessary. It is not required, as operating in LTE unlicensed band supports dedicated access, and it is not necessary as it adds delay and points-of-failure. Unsupervised LTE D2D yet remains challenging, as key network supervision functions need to be distributed. This article listed them, and notably introduced two Radio Resource Management strategies capable of allocating LTE D2D resources in a fully distributed way. Complementary to DSRC/ITS-G5, Unsupervised LTE D2D is a promising approach to increase the capacity and add redundancy for safety-critical V2X communications.

VII. ACKNOWLEDGMENTS

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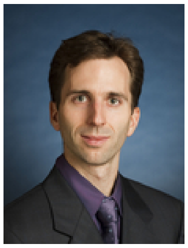

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