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Self Organizing TDMA over LTE Sidelink

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Abstract

Self-Organizing TDMA (STDMA) is a distributed channel access algorithm developed for position reporting in maritime and airborne domains. Its reliability, semi-deterministic behavior, and context aware scheduling also made it an attractive option considered by the European Telecommunications Standard Institute (ETSI) for vehicular communications in ITS-G5.

In recent times, cellular-based Long Term Evolution (LTE) is arising as a compelling technology to support Vehicle to Everything (V2X) communications. While already providing vertical connectivity via the installed network, standard extensions are being discussed to support horizontal, direct Vehicle to Vehicle (V2V) and Vehicle to Pedestrian (V2P) communications. A dedicated Sidelink (SL) has been defined for the purpose, as opposed to Uplink (UL) and Downlink (DL). In this research report, we propose STDMA as scheduling algorithm for unsupervised, low latency, direct transmissions over SL; we highlight the challenges caused by its channel configuration, and propose two protocol extensions to address them. The performance are then compared against them and against Optical Orthogonal Codes (OOC), a enhanced random access technique: STDMA's packet reception performance finally confirms its role as a valuable candidate technology for direct, LTE-based V2X.

Index Terms

LTE, Long Term Evolution, Sidelink, PC5, V2V, STDMA, Self Organizing TDMA

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Acronyms

3GPP	3rd Generation Partnership Project.
AIS	Automatic Identification System.
BSM	Basic Safety Message.
CAM	Cooperative Awareness Message.
CCA	Clear Channel Assessment.
CL	Channel Load.
CS	Candidate Set.
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance.
DL	Downlink.
DSRC	Dedicated Short Range Communications.
eMBMS	evolved Multimedia Broadcast Multicast Service.
eNB	evolved Node B.
EPC	Evolved Packet Core.
ETSI	European Telecommunications Standard Institute.
FDD	Frequency Division Duplexing.
HD	Half Duplex.
LME	Link Management Entity.
LTE	Long Term Evolution.
MAC	Medium Access Control.
NEP	Network Entry Packet.
NI	Nominal Increment.
NS	Nominal Slot.
NSS	Nominal Starting Slot.
NTS	Nominal Transmission Slot.
OCB	Outside the Context of a Basic service set.
OCL	Offered Channel Load.
OFDM	Orthogonal Frequency division Multiplexing.
OOC	Optical Orthogonal Codes.

O-STDMA	STDMA for OFDMA deployment.
PHY	Physical layer.
PRB	Physical Resource Block.
ProSe	Proximity Services.
RATDMA	Random Access Time-Division Multiple Access.
RB	Resource Block.
RBP	Resource Block Pair.
RE	Resource Element.
Rr	Report Rate.
RX	Reception.
SH-STDMA	Selective Hiding STDMA.
SI	Selection Interval.
SIB	System Information Block.
SINR	Signal to Interference and Noise Ratio.
SL	Sidelink.
STDMA	Self-Organizing TDMA.
TDD	Time Division Duplexing.
TTI	Transmission Time Interval.
TX	Transmission.
UE	User Equipment.
UL	Uplink.
V2P	Vehicle to Pedestrian.
V2V	Vehicle to Vehicle.
V2X	Vehicle to Everything.
WAVE	Wireless Access for Vehicular Environment.

1 Introduction

It is widely agreed that Vehicle to Everything (V2X) communications will be a fundamental component of autonomous vehicles, which are getting every day closer to being a reality available to the public. Extensive research, development, and standardization has been going on the the past two decades to define a common technological platform, which resulted in the definition of 802.11p. 802.11p is an amendment of WiFi that operates Outside the Context of a Basic service set (OCB), which has been adopted as lower layers both by the Wireless Access for Vehicular Environment (WAVE) in the US and by ITS-G5 in the EU.

In parallel, the last decade has seen a spectacular growth of cellular technologies, which brought fast mobile internet connectivity to billions of smartphones and connected devices in the past few years. The increasing performance and availability of cellular networks, have pushed the 3rd Generation Partnership Project (3GPP), the standardization body in charge of the development and maintenance of the cellular technologies, to open towards supporting new types of applications. One of these is indeed the automotive market.

2 Protocol description

Self-Organizing TDMA (STDMA) is a Medium Access Control (MAC) layer protocol already commercially adopted for periodical position reporting in shipping [1] (with the name Automatic Identification System (AIS)) and airline [2] industries. Given its effectiveness proven on the field, and to extensive research works such as [3] and [4], the European Telecommunications Standard Institute (ETSI) considered STDMA as an alternate to Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) [5].

STDMA is a slotted structured access mechanism, in which channel resources are organized into slots, each with duration and bandwidth adequate to host a fixed size packet. For the purpose of this work, we consider Cooperative Awereness Messages packets [6], periodically transmitted by vehicles to report their instantaneous state, which includes position, speed and heading.

In order to support periodical message transmissions, the STDMA medium access policy based on periodical pattern, wherein all the slots within a predetermined time window are organized into a *frame*, as illustrated in Fig. 1.

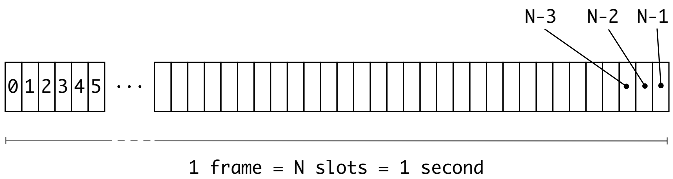

Figure 1: STDMA: channel organization into slots and frames

Frames are repeated periodically, and have a duration of 1 minute in AIS and of 1 second when used in vehicular applications [1] (as considered in this document): the number N of slots that can be hosted within a frame depends on the packet size, and on the transmission parameters, which determine the channel capacity. It is assumed that terminals, which from now on we will refer to as UEs to conform with Long Term Evolution (LTE) nomenclature, are slot synchronous, meaning that the starting and ending moment of each slot must be aligned for all UEs. Frame synchronization, on the other hand, is not required nor necessary.

The STDMA protocol is based on a slot reservation mechanism, in which all of the transceivers are assumed to be in turn transmitters and receivers. The purpose of the protocol is to determine which slots each UE needs to use for transmitting its packets. The protocol is articulated into the following 4 phases:

1. initialization phase;
2. network entry phase;
3. first frame phase;
4. continuous operations phase;

which will be described in detail in the following of this section. For reference, the system parameters, along with their description, are summarized in Table 3

2.1 The initialization phase

The first phase UEs enter is the *initialization phase*, during which they listen to the channel for one whole frame. Since no frame synchronization is required, the starting point is random, and purely dictated by the instant of each UE's startup. In this process, a state is attributed to every slot, based on what the UE receives in it. The possible states defined in [1], and the conditions they are associated to, are:

- *Free*: the current slot is not used by any other UE within range;
- *Externally Allocated*: the current slot is used or reserved for transmission by another UE within range;
- *Internally Allocated*: the current slot is used or reserved for transmission by the current UE.

Needless to say, internally allocated slots will not be encountered in the initialization phase, since they have not been scheduled yet. A fourth state, not listed in [1] but proposed in [7], is necessary for implementation purpose: *Unavailable* slot. A slot is unavailable when a power level higher than a given Clear Channel Assessment (CCA) threshold is detected, but no information could be correctly decoded. This situation typically happen when multiple packets from UEs within range of the current UE collide, and the Signal to Interference and Noise Ratio (SINR) of the received signal is too low for capture effect to take place.

In Fig. 2 a sample scenario is illustrated, wherein the *free* slots are in white, whereas the slots detected to be *externally allocated* are shaded in light blue. The

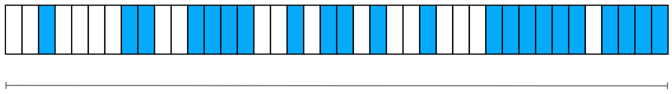

Figure 2: STDMA: initialization phase

initialization phase terminates when all of the N slots have been listened to, and a state has been assigned to each of them. Once this is done, the UE switches to the following phase, the *network entry phase*

2.2 The network entry phase

The purpose of the network entry phase is for the current UE to transmit a Network Entry Packet (NEP), a one time special transmission which is meant to inform all the other UEs within range of the current one that it is about to join the network. The slot for the transmission of the NEP is chosen using the Random Access Time-Division Multiple Access (RATDMA) protocol, which *"is used when a station needs to allocate a slot, which has not been pre-announced"* [1].

In the following, the AIS compliant procedure will be described, as well as a vehicular model proposed in [7], which will be adopted in the work presented in this paper.

2.2.1 The AIS procedure (as in [1])

The meaning of the Link Management Entity (LME) parameters listed in the following is explained in Table 2

A Candidate Set (CS) is defined by including all the free slots within the first `LME.RTCSC`, within which the NEP transmission slot will be chosen according to a p-persistent algorithm. Each slot belonging to the glscs is internally labeled with an index between 0 and `LME.RTES`; each time the current UE is about to reach one slot belonging to the CS it decides whether to transmit the NEP with probability `LME.RTP2`, which is initialized equal to `LME.RTPS`. In [1], the value denominated `LME.RTP1` indicates a uniformly random variable in the assuming a natural value between 0 and 100: if `LME.RTP1` $\leq$ `LME.RTP2`, the transmission will occur. If this is the case, the UE proceeds to selecting the Nominal Transmission Slot (NTS). Otherwise, the `LME.RTCSC` counter is increased by one unit, and the probability `LME.RTP2` is increased by `LME.RTPI`, and the process repeated once the UE reaches the next slot belonging to the CS. At any point in time, the CS shall contain at least 4 slots: if this is not the case, it should be expanded by using the same rules that will be described in section 2.2.3.

Table 2: Network entry Phase parameters (adapted from Table 14 [1, §3.3.4.2.2])

Symbol	Name	Description
`LME.RTCSC`	Candidate Slot Counter	The number of slots available in the CS
`LME.RTES`	End Slot	The index of the slot at the end of the CS for the NEP
`LME.RTPS`	Start Probability	Probability of choosing the first slot of the CS for NEP transmission
`LME.RTP1`	Derived probability	Uniformly distributed random value cast before each slot in the CS to decide whether NEP will be transmitted in it
`LME.RTP2`	Current probability	The current probability that a transmission will occur in the next candidate slot
`LME.RTA`	Current probability	Initial value set to 0. This value is incremented by one each time the p-persistent algorithm determines that a transmission shall not occur
`LME.RTPI`	Probability increment	Each time the algorithm determines that transmission should not occur, LME.RTP2 should be incremented with LME.RTPI. Please check [1, §3.3.4.2.2] for details on the computation, which will not be described in this document since it is specific to the AIS implementation.

2.2.2 Vehicular procedure (as in [7])

The procedure described by Gaugel et al. in [7] is better adapted to vehicular applications than the one in section 2.2.1. Denoting with $p(k)$ the probability of transmitting the NEP in the k^{th} slot belonging to the CS, and with $n(k)$ the number of remaining slots in the CS after the k^{th}, the probability of transmitting the NEP in the next slot is computed as in eq. (1).

$$\begin{aligned} p(0) &= \frac{1}{n(0)} \\ p(k) &= p(k-1) + \frac{1-p(k-1)}{n(k)}, \quad k > 0 \end{aligned} \tag{1}$$

Right before each slot belonging to the CS, a UE computes $p(k)$, then casts a uniformly distributed random value in $[0, 1]$: if such value is lower than $p(k)$, the

NEP transmission is scheduled for the next slot, and the UE proceeds to selecting the NTS. Otherwise, it moves on to the next slot.

It is worth reminding that UEs in the network entry phase, as well as in any of the following phases, continue to monitor the slot, updating the internal representation of their state.

2.2.3 Selecting the first NTS

In this last part of the network entry phase, the UE needs to elect and reserve the NTS, its first transmission slot. To do so, some further intermediate step is required: the NTS must in fact be chosen among the slot belonging to a new CS, that needs to be computed as follows:

1. a Nominal Increment (NI) is defined as $NI = \lfloor N/r \rfloor$, representing the ideal interval between two consecutive transmitted packets;

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

3. a Selection Interval (SI) is defined as the set of all the slots around the NSS: its cardinality is determined by the parameter s, which represents the ratio between the width of the SI and the one of the NI, with $0 < s \leq 1$. Denoting with $\sigma_0, \ldots, \sigma_{N-1}$ the slots within each frame as numbered by the current terminal, the set of the slots belonging to the first SI (hence, with index 0) is given by (2), and illustrated in Fig. 3.

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

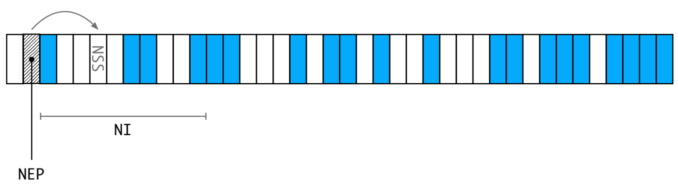

Figure 3: STDMA: network entry phase: choice of the NEP slot and of the NSS

The parameter s is fixed to a value equal to 0.2 in AIS, whereas it is a variable system parameter for vehicular applications (see [7]).

4. within the so-defined SI, a CS is compiled, according to the following rules (and illustrated in Fig. 4):

- *free* slots are automatically included in the CS;
- the minimum size for the CS is w_{CSmin}. If less than w_{CSmin} free slots are available in the SI, a suitable number of *externally allocated* ones must be included in the CS. These are selected starting from the ones allocated by the users more distant from the current transmitter;
- the designated slot for the first packet transmission, which we mark as σ_{nts_0} , is randomly chosen from the ones in the CS with uniform probability, regardless of its state.

In case the NTS is an externally allocated slot, the current terminal will not be able to reuse slots allocated by that same user in the current frame. For this reason, in [1] §3.1.6 the states *available* and *unavailable* for externally allocated slots are defined.

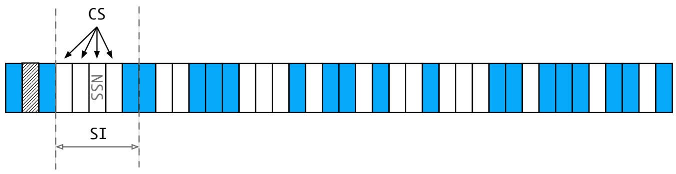

Figure 4: STDMA, network entry phase: SI and CS compilation.

Finally, the UE transmits the NEP, to which it appends he offset between σ_{nep} (the next slot), and the σ_{nts_0}, as in Fig 5. The UE subsequently waits for theσ_{nts_0}, then moves to the next phase, the *first frame phase*.

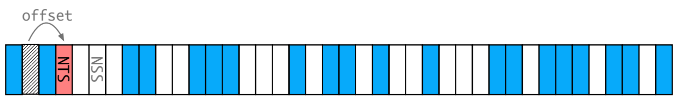

Figure 5: STDMA, network entry phase: NTS selection and NEP transmission

2.3 The first frame phase

As the name suggests, this phase lasts until (approximately) one frame after the transmission of the NEP. Its purpose is the preparation and the reservation of all the NTSs to satisfy the communication needs of a UE. To do so, further $r - 1$ NTSs (beside the first one, reserved during the previous phase) need to be reserved, by repeating the procedure described in the *network entry phase* for the NTS #0, with some further attention required to adapt the protocol to mobile environments.

Right before transmitting the first packet, the UE needs to perform two further actions:

Table 3: STDMA system parameters: [1, Table 16, §3.3.4.4.2]

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

1. attach a timeout t_0 to the NTS #0;
2. reserve the next NTS (NTS #1), so to attach its offset to the packet transmitted in NTS #0.

The timeout represents the number of consecutive frames which this slot is reserved for. Every frame, when in correspondence of $\sigma_{nts,0}$, the current UE will decrease the timeout by one unit, right before transmitting a packet. When the timeout reaches 0, a new slot must be reserved as indicated in section 2.4 *"The continuous operation phase"*. The initial value of the timeout is randomly picked, with uniform probability, between t_{min} and t_{max}.

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

1. select a NS #1, NI slots after the NSS;

2. construct a SI around the NS, defined as:

$$SI_1 = \left\{ \sigma_{(j \mod N)} \right\}, \quad \text{where:}$$
$$\sigma_{nss} + NI - \left\lfloor \frac{N}{2r} s \right\rfloor \quad \leq \quad j \quad \leq \quad \sigma_{nss} + NI + \left\lfloor \frac{N}{2r} s \right\rfloor \tag{3}$$

3. compile a CS from the slots within the SI as in section 2.2.3, point 4.

4. select the NTS #1 randomly among the slots within the CS

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

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

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

The procedure illustrated above is then repeated until all the r NTS have been successfully allocated., as illustrated in Fig. 6. Once this is done, the UE moves

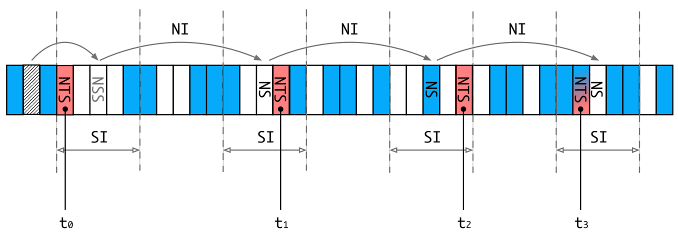

Figure 6: STDMA, network entry phase: NTS selection and NEP transmission

to the *continuous operations phase*.

2.4 The continuous operations phase

This phase represents the steady state of a UE, in which it enters after the network entrance is completed, and other neighboring UEs are well aware of its presence and its reservation pattern.

In continuous operations, the UE transmits a packet whenever a NTS is reached. Right before the transmission, the timeout associated to that NTS is decreased by one unit. When 0 is reached, a new slot must be reserved, applying the same mechanism as illustrated before. A new timeout is then associated to the newly appointed NTS. In continuous operations, the same parameters, offset and timeout, are transmitted piggybacked to each packet. However, the semantics of the *offset* changes with respect to the previous phases. The offset transmitted in NTS #i, in fact, does no longer represent the offset with respect to NTS #(i+1). Instead, it now indicates the offset with respect to the NTS #i in the next frame. This means that for values of the timeout $t_i > 0$, the offset is set equal to 0. When the timeout reaches 0, it indicates the offset relative to the newly reserved slot for the next frame(s).

In the continuous operations phase, the NSS acts like NS #0.

2.5 Considerations on slot reuse

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

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

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

As it is shown in [7], packet losses in STDMA have a broader effect than just missing a generic CAM / Basic Safety Message (BSM), i.e. some status information about the transmitting UE. They also imply the loss of reservation information, which will therefore affect the decisions taken by neighboring UEs. If a packet containing the offset to a new reservation is lost, another UE might choose the same exact slot at the same time, causing a collision. And since slots are reserved for at least t_{min} consecutive frames, this means that at least t_{min} consecutive collisions are caused, assuming the colliding UEs stay within range proximity for all that time.

3 LTE Vehicle to Vehicle (V2V) / Vehicle to Pedestrian (V2P) channel configuration

STDMA has already been widely studied when applied on top of Orthogonal Frequency division Multiplexing (OFDM), the Physical layer (PHY) layer of Dedicated Short Range Communications (DSRC) / ITS-G5. In it, packet slots occupy the whole bandwidth for one slot time, which is dependent on the channel rate, and on the packet size. According to the ETSI [5, §5.2.3.1]. This value, for a 6 Mbps channel, is in Table 4, along with the number of frames available per frame. In such configuration, the slots occupy the whole bandwidth and are multiplexed only in time: however, in the remainder of this section we will show this will not necessarily be the case in LTE V2X.

Table 4: ETSI slot duration for 6 Mbps 802.11p channel

PHY Packet length	Duration of one slot	Number of slots per frame
300 bytes	496 µs	2016
800 bytes	1163 µs	859

3.1 Channel configuration for LTE V2X

In our previous works [8] and [9], we proposed a novel paradigm to support V2V/V2P communication based on LTE. As opposed to 802.11p, LTE legacy transmissions are coordinated by a basestation, named evolved Node B (eNB), which authorizes and allocates the resources for each communication within the cell it controls. All transmission must pass through the core network (Evolved Packet Core (EPC)), up until reaching the endpoint of the communication, for which the eNB the receiving UE is attached to will allocate a set dedicated Downlink (DL) resources. Unfortunately, this infrastructure-centric communication paradigm poorly adapts to the requirements and the traffic patterns of safety critical vehicular communications. Extensions to the standard are thus required to support unsupervised, direct, broadcast communications. A further challenge is imposed by the network topology, which contemplates vehicles within respective TX/RX spanning over multiple cells. We identified that allowing them without introducing complex network-side coordination was a challenge, and claimed that a constant, semi-static resource pool commonly allocated by a group of neighboring cells was required to support V2V and V2P underlying LTE.

In [8], we introduced a paradigm based on evolved Multimedia Broadcast Multicast Service (eMBMS), which was already available since Rel. 8, the earliest day of LTE, and allows multi-cell multi-point to multi-point communications. The interesting part of eMBMS is its resource reservation protocol, in which multiple neighboring eNBs allocate a subset of their available subframes, according to a periodical pattern. This system, allows UEs to identify a common resource pool which they will than be able to organize into a slotted system. Similarly to STDMA over 802.11p, slot occupy a portion of the channel resources sufficient to host a fixed size CAM / BSM packet. In this way, the problem is reduced to a distributed tdma-like scheduling one.

In [9], we proposed a novel mechanism for LTE-based V2X that exploited new standard extensions introduced by 3GPP under the name of Proximity Services (ProSe). A new link, denominated Sidelink (SL) was introduced, as opposed to DL and Uplink (UL), that connects UEs directly. The SL is defined as a subset of the UL resources[1], organized based on a periodical subframe pool, in time domain, which contains a Resource Block (RB) resource pool, as illustrated in Fig. 7.

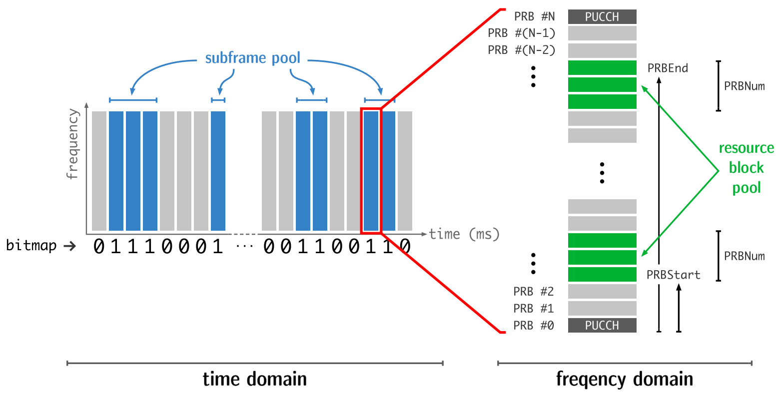

Figure 7: LTE SL resource reservation

In time domain, subframe pools are laid out according to a periodical pattern, determined by a bitmap (`subframeBitmap-r12` within `SL-FR-ResourceConfig` in [10, §6.3.8]). The length of the bitmap is fixed to 40 subframes in Frequency Division Duplexing (FDD) deployments, whereas it varies from 4 to 42 according to the configuration in Time Division Duplexing (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 Physical Resource Block (PRB) #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. 7. All the parameters for the resource pool allocation are periodically broadcast by the eNodeB enclosed within the System Information Block

[1] although the possibility of its allocation in external bands, such as the 5.9 GHz ITS band is actively being discussed

(SIB) 18 for communications and SIB 19 for discovery [10, §6.3.1], which are accessible by UEs in both RRC_CONNECTED and RRC_IDLE states.

The so allocated SL, can then be independently organized by UEs into a slotted system in time and frequency as illustrated in Fig. 8. Thanks to the higher spectral

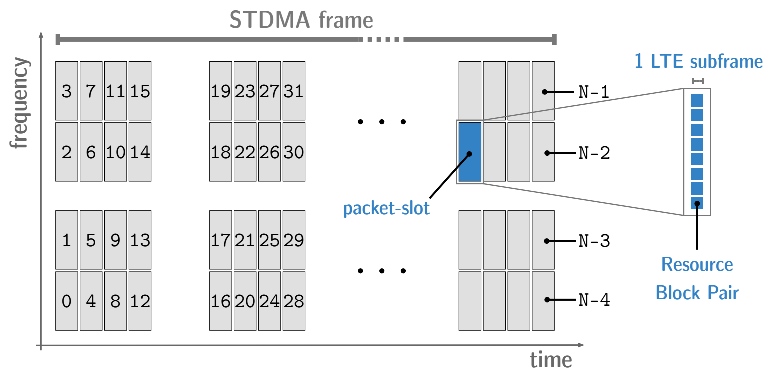

Figure 8: Construction of slotted system over the LTE SL. It is worth mentioning that "STDMA frame" and the "LTE subframe" are unrelated entities: the former is the basic period of the STDMA protocol, whereas the latter refers to the set of RBs contained in the whole bandwidth in one TTI

.

efficiency of LTE than 802.11p, in LTE SL configuration, slots are distributed both in time and in frequency, which represents a further challenge to be taken care of, considering the UEs operate on Half Duplex (HD).

3.2 HD impairment

Half Duplex operations means that UEs can only be in TX or RX mode at any given time. This means that a transmitting UE is not able to receive all the slots located in the same subframe as its NTS. We refer to this phenomenon as "HD impairment", and to the slots that cannot be received because of it as *hidden slots*. As mentioned in section 2.5, the loss of a packet in STDMA also implies the loss of reservation information, which might negatively impact the future scheduling decision: in the case of hidden slot, their loss will certainly affect the future scheduling, as they belong to the SI, as illustrated in Fig. 9. Packet loss due to HD impairment are equivalent to "internal collisions", as they disrupt one (or more) receptions exactly like collision would do, but they only affect individual UEs depending on the state of the transceiver, without affecting others.

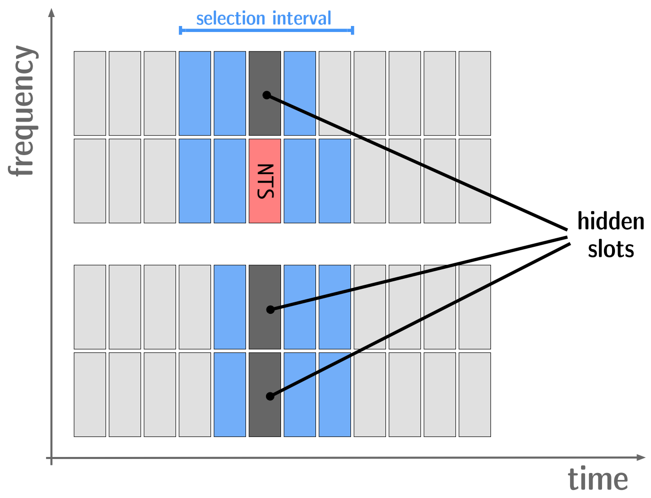

Figure 9: Hidden slots within the SI

4 Performance: static analysis

In this section, we analyze the effect of the HD impairment on the STDMA reservation protocol by means of simulation. In order to be able to support the newly introduced channel structure based on SL, we developed a custom-built simulator in python. In order to isolated the effect of HD impairment on MAC layer, we consider a perfect PHY layer, and selected the parameters as in Table 5. We consider a scenario wherein all the UEs are within respective TX/RX range.

In Fig. 10, the curves for STDMA are compared with and without considering the HD impairment, against the Offered Channel Load (OCL). The OCL is a channel-side metric that accounts for the communication needs of all the UEs in a given area. In a slotted system, it represents the ratio between the number of slots needed to satisfy the communication needs of all the UEs in range of a given point and the number of slots available per second. Referring to the parameters in Table 5, with 900 slots available per second, and a report rate of 10 packets per second per UE, a OCL = 1.0 is obtained with 90 UEs within respective range.

4.1 STDMA without HD impairment

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

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

In the *low-to-mid* region ($0.6 < OCL < 1.0$), the progressive reduction of free slots within the SI means that externally allocated slots are progressively added to the CS. Once they belong to it, they get the same probability of being chosen than

Table 5: STDMA over LTE V2X: system parameters

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

free ones, which leads to increasing collisions. As mentioned in section 2.5, since slots are reserved for multiple consecutive frames, this causes recurrent collisions. The random nature of the selection is what causes the 95% confidence interval to be wider in this interval, as raw performance is very much dependent on every instance.

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

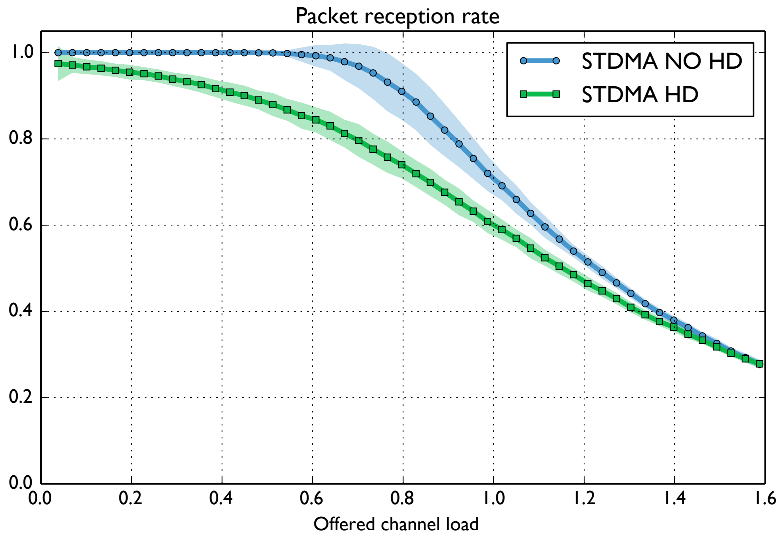

Figure 10: STDMA comparison with and without HD impairment. The shaded area around the curves represents the 95% confidence interval

4.2 STDMA with HD impairment

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

4.3 Comparison with Optical Orthogonal Codes (OOC)

We proposed OOC as a distributed scheduling algorithm for LTE V2X in [8] and [9]. OOC are a blind channel access system that provides reliability by re-transmitting multiple copies of each packet. Alike STDMA, OOC are based on a periodical structure, albeit with a shorter period of 100 ms, to support a maximum transmission rate of 10 packets/s. In the configuration of our choice, within each period, UEs re transmits $w = 2$ times each packet. The distinctive characteristic of OOC codesets makes it such that two separate UEs will collide at most $\lambda = 1$ times per period, thanks to their cross-correlation properties.

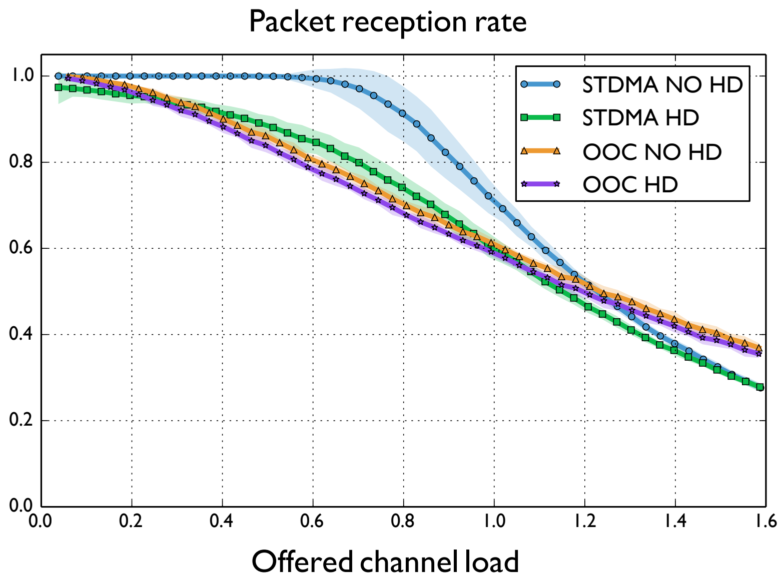

Figure 11: STDMA and OOC comparison with and without HD impairment. The shaded area around the curves represents the 95% confidence interval

The results of the comparison of OOC and STDMA versus the OCL, both with and without taking into consideration the effects of HD, are shown in Fig. 11. The OOC parameters are summarized in Table 6.

Table 6: OOC over LTE V2X: system parameters

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

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

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

5 STDMA protocol extensions for LTE V2X

In this section, we propose two protocol extension of STDMA, which aim at mitigating the effects of HD on it. We refer to them as STDMA for OFDMA deployment (O-STDMA) and Selective Hiding STDMA (SH-STDMA), and describe them in the following of this section.

5.1 O-STDMA

O-STDMA deals with the fact that the UE, when performing a re-reservation, has no information about what is happening in the slots hidden to it. This includes:

- the presence of some NTSs of other users which will keep on reusing the same slot in the next frame;
- the presence of some NTSs of other users which will reserve a new slot for the next frame; however, the offset to the new slot cannot be received.

O-STDMA aims at avoiding the former of these, by simply removing from the CS all of the slots that were hidden in the frame where the re-reservation definition is taken. The current slot, however, is maintained in it, as no other UE would reserve it before knowing the re-reservation information of the one currently occupying it.

5.2 SH-STDMA

SH-STDMA is conceived with the purpose of selectively avoid hiding the NTS of the vehicles closer to it, which are those whose state information (content of the CAM/BSM packet) is most relevant. To do this, the procedure of compilation of the candidate set is modified as follows:

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

   $$P_i = \sum_{j=0}^{n_s} g(d(\sigma_j)) \tag{4}$$

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

- it must contain exactly the number of slots w_{CSmin} (the minimum for STDMA)
- free slots are added starting from the subframes with lower penalty P_i
- if less than w_{CSmin} free slots are available in the SI, the remaining slots are picked by progressively choosing them from the subframes with lower penalty, and choosing the one allocated by the farthest UEs first.[2]

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

$$g(d(\sigma_j)) = \begin{cases} \frac{1}{d(\sigma_j)} & \text{if } \sigma_j \text{ is externally allocated} \\ 0 & \text{else} \end{cases} \tag{5}$$

5.3 Performance comparison

In Fig. 12, the performance of STDMA, O-STDMA, and SH-STDMA are compared in a LTE V2X channel system as in Table 5, against the ideal case. The

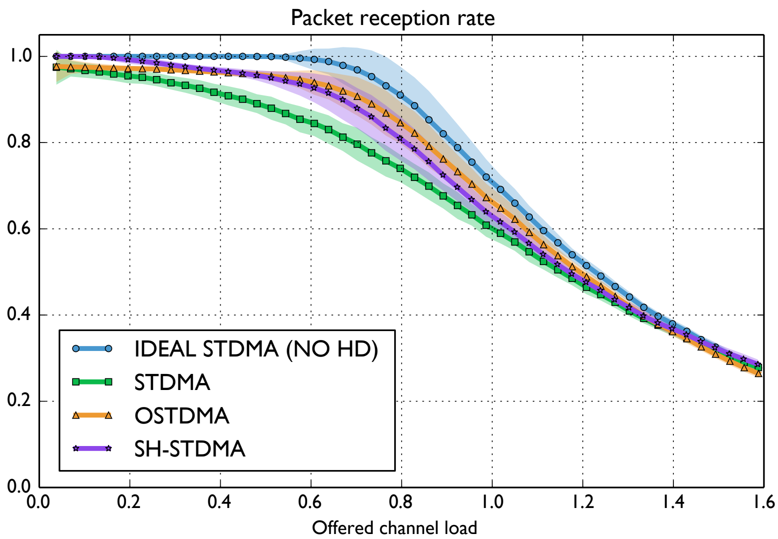

Figure 12: Protocol extensions: O-STDMA and SH-STDMA vs STDMA. The shaded area around the curves represents the 95% confidence interval

first thing we can observe, it that for lower OCL SH-STDMA provides optimal or near-optimal performance, thanks to its mechanism that avoids hiding users, allowing for a more efficient use of the channel's time dimension. When the OCL exceeds 25%, it becomes increasingly difficult to have subframes within the CS that are entirely made of free slots. It is worth noting that the 25% quote is dependent of

[2] The case wherein less than w_{CSmin} slots are available within the CS is very unlikely, thus neglected in this work. This situation would

the ratio between n_s and N. The considered scenario has the purpose of illustrating this phenomenon: realistic deployments might have much larger N (for instance, 3000 slots per second), and consequently larger SIs, which might move this point at higher OCL.

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

In the *mid-to-high* region, one can observe a crossing between the SH-STDMA and the O-STDMA curves, with the latter starting to performing slightly better than the former. This phenomenon is very dependent on this specific simulation scenario, and might be attributed to the choice of function $g(x)$ made for SH-STDMA, which does not assign a penalty to unavailable slots, those affected by collisions. The purpose of this perfect PHY configuration was to isolate the MAC layer performance; in a realistic implementation, however, those are also affected by the behavior of lower layers. Specifically, when fading is considered, in case of collision, the transmission coming from the closest UEs is likely to be received thanks to capture effect. In the scenario considered in this section, on the other hand, any kind of slot reuse makes a slot unavailable, hence considered by SH-STDMA as a viable slot to be hidden, by scheduling the NTS in a free slot located within the same subframe. The evaluation in a more realistic scenario will be done in a future work.

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

6 Conclusion

In this research report, we first provided a detailed description of the STDMA protocol, which we propose as a distributed scheduling algorithm for LTE V2X communications. We highlighted, by means of simulation, how the distribution of slots both in time and in frequency represents a challenge, and proposed two STDMA protocol extensions to cope with them. The performance are compared in a scenario that isolates the MAC layer, and show that STDMA, with some modifications to adapt to a novel channel configuration, represents a suitable candidate technology for unsupervised V2X over LTE.

References

[1] ITU, *Rec. M.1371-5 - Technical characteristics for an automatic identification system using time-division multiple access in the VHF maritime mobile band.* International Telecommunications Union, Feb. 2014.

[2] Eurocontrol, "Vhf digital mode 4," Eurocontrol, Tech. Rep. [Online]. Available: http://www.eurocontrol.int/services/vhf-digital-mode-4

[3] K. Sjöberg, "Medium access control for vehicular ad hoc networks," Ph.D. dissertation, Chalmers University of Technology, 2013.

[4] A. Alonso and C. Mecklenbrauker, "Stabilization Time Comparison of CSMA and Self-Organizing TDMA for Different Channel Loads in VANETs," in *ITS Telecommunications (ITST), 2012 12th International Conference on*, Nov 2012, pp. 300–305.

[5] ETSI, "TR 102 861 Intelligent Transport Systems (ITS); STDMA Recommended Parameters and Settings for Cooperative ITS; Access Layer Part," ETSI, Tech. Rep., January 2012.

[6] ——, "TS 102 637-2 Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service," ETSI, Tech. Rep., March 2011.

[7] T. Gaugel, J. Mittag, H. Hartenstein, S. Papanastasiou, and E. G. Strom, "Indepth Analysis and Evaluation of Self-Organizing TDMA," in *Vehicular Networking Conference (VNC), IEEE*, 2013, pp. 79–86.

[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, December 2013, pp. 166–169.

[9] L. Gallo and J. Härri, "Analytic performance comparison of unsupervised LTE D2D and DSRC in a V2X safety context," Eurecom, Tech. Rep. EURECOM+4499, December 2014. [Online]. Available: http://www.eurecom.fr/publication/4499

[10] 3GPP, "TS 36.331; Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Resource Control (RRC); Protocol Specification v13.0.0," 3GPP, Tech. Rep., Jan. 2016.