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Resource Allocation for LTE-Direct Broadcast of Periodic Vehicular Safety Messages

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Abstract

Direct Device-to-Device (D2D) communications underlaying the cellular network are receiving increasing attention lately: LTE-A standard will adopt them for unicast proximity services. So far, no application has been envisioned for broadcast transmissions. In this work, we propose an eMBMS-inspired mechanism to allocate a *quasi-static* pool of resources over multiple eNodeBs (eNBs) for D2D broadcast transmissions to take place. The mechanism does neither require any connection procedure with the eNB nor any additional network-side mobility management. Further, we propose multiple access according to a distributed *TDMA-like* scheme. We apply this concept to the periodic broadcast of CAMs / BSMs and show that the system's flexibility and extensibility make LTE-Direct a good complementary technology to DSRC for periodic vehicular safety communications.

Index Terms

LTE-Direct, broadcast, eMBMS, periodic vehicular communications, resource allocation, distributed resource access scheduling

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Nomenclature

BPSK	Binary Phase Shift Keying
BSM	Basic Safety Message
CAM	Cooperative Awareness Message
CSA	Common Subframe Allocation
D2D	Device to Device
DL	Downlink
DSRC	Direct Short Range Communications
eMBMS	evolved Multimedia Broadcast Multicast Service
eNB	evolved Node B
FDD	Frequency Division Duplexing
LTE	UMTS Long Term Evolution
LTE-A	UMTS Long Term Evolution - Advanced
MBSFN	Multicast Broadcast Single Frequency Network
MCH	Multicast Channel
MIB	Master Information Block
MSI	MCH Scheduling Information
MSP	MCH Scheduling Period
OFDM	Orthogonal Frequency Division Multiplexing
OOC	Optical Orthogonal Code
PMR	Professional Mobile Radio
PSS	Primary Synchronization Signal
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase-Shift Keying
RB	Resource Block
SIB	System Information Blocks

SSS	Secondary Synchronization Signal
TDD	Time Division Duplexing
TDMA	Time Division Multiple Access
TETRA	Terrestrial Trunked Radio
UE	User Equipment
UL	Uplink
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle

1 Introduction

The current scenario of V2V or V2I communications shows a fragmentation into different transmission technologies serving different categories of users.

Cars and public transportation vehicles, for instance, are connected to each other and to the road side infrastructure using DSRC (a.k.a IEEE 802.11p), an extension of the WiFi standard for communications in a vehicular environment, characterized by high user mobility and challenging propagation scenarios.

PMR communication in the *railroad* environment are currently based on the Terrestrial Trunked Radio (TETRA). However, more and more manufacturers of professional radio equipment are proposing solutions based on LTE, given the capability of new generation cellular systems to satisfy the strict requirements of such mission-critical applications.

First responders as ambulances and firetrucks are also adopting a high speed networking system for public safety based on LTE.

Finally, roads are also populated by *vulnerable users* such as pedestrians and cyclists, who can be reasonably assumed carrying mobile devices equipped with some radio technology for proximity communications like Bluetooth or WiFi Direct and a cellular interface as LTE.

We believe that including all the aforementioned categories of road users in a unique framework for safety communications will be beneficial for all the subjects involved. We thus envision the convergence of all the listed communication technologies into a unified safety communications system based on LTE. From a network perspective, the LTE infrastructure is already available in many areas and the coverage is in fast expansion, while the network of DSRC road side units is only expected to be deployed in few years. Furthermore, LTE features signals optimized for high mobility scenarios and designed to be energy efficient, while providing good performance in terms of spectral efficiency. The adoption of LTE for the transmission of safety messages (CAMs / BSMs) will then automatically provide the users with an internet connection interface, which will open to a new set of applications that exploit connectivity to the web.

On the other hand, the LTE standard currently requires the mobile User Equipments (UEs) to be connected to an eNodeB (eNB) in order to be able to transmit. In [1] it is shown that in a urban scenario, the uplink and downlink of CAMs to and from the eNB can be very expensive in terms of bandwidth usage, even at reduced transmission rates. Moreover, each eNodeB represents a *single point of failure* that would interrupt all the transmissions in the cell area in case of failure. A further issue is raised by the need for the UEs to stay in a connected state to transmit: in the considered case of high mobility users, this would require the network to handle numerous conteporary handover procedures, which could result in additional undesired latency.

Proximity Services (ProSe), currently being discussed in the Rel. 12 of the LTE standard, adress the aforementioned issues by allowing direct communications between UEs, without going through the eNB. However, these communications can only take place in some ad hoc eNB-allocated Resource Blocks (RBs) and only after a *service discovery* phase [2], itself network-reliant. Most importantly, these direct communications are *unicast* only.

In this document it is then proposed a *broadcast* scheme for LTE-direct transmissions divided in two phases, a) *Resource Allocation* and b) *Distributed Resource Access Scheduling*, of which only the former requires the intervention of the network. The resource allocation is inspired by a novel interpretation of the eMBMS service, while the distributed multiple access is handled according to a *TDMA-like* scheme.

The rest of the document is organized as follows: in section 2 the eMBMS service of LTE is introduced, then in section 3 the resource allocation and distributed multiple access mechanisms are presented. Finally, the discussions and outcomes presented in section 4 conclude the document.

Part of the work presented in this report was published on the proceedings of the *2013 IEEE Vehicular Networking Conference*, 16-18 December 2013, Boston, USA [3].

2 Multimedia Broadcast Multicast Service

eMBMS is the LTE implementation of the Multimedia Broadcast Multicast Service (MBMS) available since UMTS rel. 6, which allows the network to broadcast or multicast multimedia content over a wide area. eMBMS transmissions take place over a *Multicast Broadcast Single Frequency Network* (MBSFN), meaning that the set of resources dedicated to them has to be the constant all over the area of interest, as illustrated in figure 1. Inside each cell belonging to the eMBMS area, a sample LTE frame is depicted: the dashed subframes put into evidence the identical set of dedicated resources.

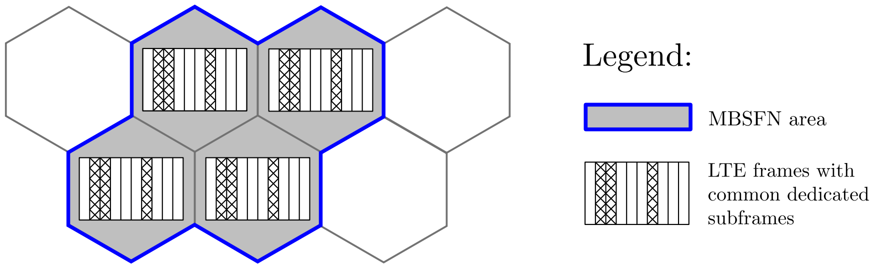

Figure 1: MBSFN area over multiple cells with common allocated resources.

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

MCH channels are organized according to a periodic scheme as illustrated in figure 2.

The base period is the *Common Subframe Allocation* (CSA) which corresponds to the minimum time lapse during which all the services are scheduled, one after the other and without overlapping. CSA can be set from a minimum of 80 ms to a maximum of 10.24 s. In the example in figure 2 it is set equal to 80 ms. Within the CSA period, services are time multiplexed according to the *CSA pattern*: in the figure, MCH1 occupies the first 3 frames of the CSA period, while MCH2 is assigned the following two.

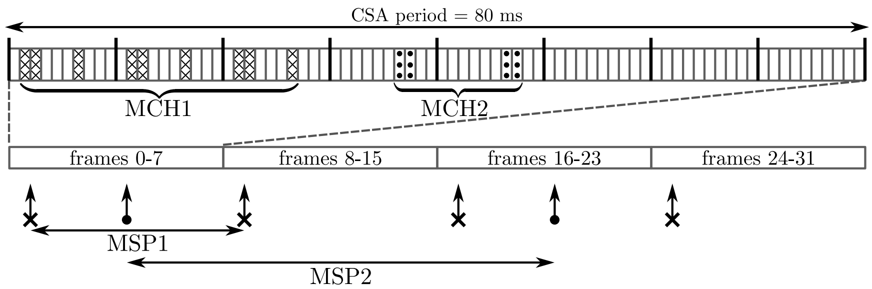

Figure 2: Time distribution of eMBMS services.

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

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

UEs can acquire the location of the MCH channels by reading the SIB13 (System Information Block 13) periodically transmitted by the eNBs. In table 1 are listed the operations every UEs must perform to receive an eMBMS service of interest (for further details please refer to [4]).

Table 1: UE procedure to receive an eMBMS service

1:	Synchronize to the eNB using PSS (Primary Synchronization Signal) and SSS (Secondary Synchronization Signal);
2:	Decode the MIB (Master Information Block), to find the location of SIB (System Information Blocks);
3:	Read SIB13 to find the location of MCHs;
4:	Receive the MCH of interest.

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

3 LTE-direct broadcast

eMBMS provides a flexible and connectionless system to define quasi-static resources over a wide area. In this work, we propose to use the same concept for LTE-Direct broadcast resource allocation. These resources can then be accessed applying a distributed resource access scheduling scheme, currently in phase of investigation.

3.1 Resource Allocation

Let the network allocate the resources for the broadcast LTE-direct transmissions in the same way it allocates resources for one eMBMS service (MCH channel). The specific MBSFN area can be calibrated according to the needs of the specific service: for instance, to allow broadcast communications between urban public transportation vehicles, this area can be set to cover the surface of a city. After allocating them, the network will not use these resources (*i.e.* no data is transmitted by the eNB in the allocated resources).

In the present work, we assume that the UEs transmit in said dedicated resources using the same waveform and cyclic prefix configuration the eNB would use to perform eMBMS tranmsissions. Further, in this work we neglect the effects of propagation delay, by assuming istantaneous propagation.

In the considered scenario, every LTE Resource Block is composed by 12 subcarriers, each carrying 12 OFDM symbols. The first two symbols of all the subcarriers are reserved to the network for the transmission of control plane information, leaving the D2D users with a time-frequency grid of 12 subcarriers by 10 exploitable OFDM symbols. We can thus compute the capacity of one RB as perceived by a D2D UE as:

$$C|_{fr} = 120 \cdot \mu \cdot BW_{RB} \cdot N_{sf} \qquad \text{[bits/frame]} \tag{1}$$

where:

- μ is the spectral efficiency of the chosen modulation scheme in bits per symbol;
- BW_{RB} is the cell bandwidth expressed in number of resource blocks;
- N_{sf} is the number of subframes per frame the network allocates to the LTE-direct transmissions.

In the hypothesis of using BPSK, QPSK, 16QAM or 64QAM it will be $\mu = \{1, 2, 4, 6\}$ bits per symbol. According to the eMBMS standard, it is $N_{sf} \in [1, 5]$ for TDD systems and $N_{sf} \in [1, 6]$ for frequency division duplexing LTE. Finally, the values that BW_{RB} can assume depend on the standard bandwidths supported by LTE, summarized in table 2.

Table 2: LTE standard bandwidths in MHz and Resource Blocks

bandwidths in MHz	bandwidths in RBs (BW_{RB})
1.4	6
3	15
5	25
10	50
15	75
20	100

As there are 100 frames per second, the total rate R_b in bits per second is obtained as

$$R_b = 100 \cdot C|_{fr} \quad \text{[bits/s]} \tag{2}$$

In case the resources were allocated for a fraction of the time, *i.e.* the MCH occupies only a part of the CSA period, or the MSP period is superior to once per frame, the rate must be reduced proportionally.

The following example configuration:

- 20 MHz channel ($BW_{RB} = 100$);
- $N_{sf} = 1$ subframe per frame dedicated to LTE-direct transmissions (10% of the total DL capacity);
- QPSK modulation, $\mu = 2$ (as adopted by DSRC);
- allocation continuous in time (one subframe allocated every subframe, no rate reduction to be applied)

will provide the LTE-Direct UEs with a $R_b = 2.4$ Mb/s shared rate. If in this same configuration the eNB allocated 60% of its totally downlink capacity ($N_{sf} = 6$), the maximum rate would increase to 14.4 Mb/s. The achievable rates in function of the amount of DL resources allocated and of the modulation scheme are shown in table 3.

Adopting the proposed technique, the network has the flexibility to adapt the allocation parameters over time in case of necessity, respecting the modification intervals and rules imposed by the eMBMS standard. The UEs will be informed of these changes by applying the procedure illustrated in table 1 without the need to go through the protocol steps to set up a connection with the eNB.

The proposed technique will then allow the direct communications to take place also in case of temporary loss of network coverage, due for example to the failure of an eNB. In fact, UEs will be able to continue exploiting that same set of periodical resources, provided that they received the information necessary to identify it at least once and that they can maintain time and frequency tuning locally.

Table 3: Achievable capacity vs. modulation scheme and RB allocation [Mbit/s]

	DL resources allocated to LTE-direct					
	10%	20%	30%	40%	50%	60%
BPSK	1.2	2.4	3.6	4.8	6.0	7.2
QPSK	2.4	4.8	7.2	9.6	12	14.4
16-QAM	4.8	9.6	14.4	19.2	24	28.8
64-QAM	7.2	14.4	21.6	28.8	36	43.2

3.2 Distributed resource access scheduling

The procedure described in the previous section allows the LTE network to allocate a quasi-static shared pool of resources for the LTE-direct broadcast transmissions. In this section, we propose a mechanism to organize these resources, distributed both in time and frequency, into a structure which can be accessed according to a *TDMA-like scheme*. Three classes of scheduling algorithm are then compared. Half-duplexing is assumed, *i.e.* every UE can either transmit or receive at any given time instant.

3.2.1 Resource organization into frames and slots

Let us partition the time domain into *frames* (not to be confused with the LTE frames). Since the CAM specification sets the maximum frequency of transmissions to 10 Hz [5], we choose the frames to be 100 ms long. In this way, UEs can achieve the 10 Hz transmission rate by *transmitting one message per frame*. Every frame is then divided into L slots, each one the size of a CAM packet, as described in figure 3. In this work we will assume all the CAMs to have the same size.

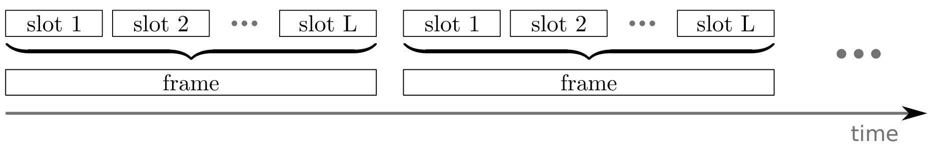

Figure 3: Time domain division into *frames* and *slots*

The number of slots L available per frame depends on several factors, for instance:

- the amount of resources allocated (total capacity);
- the size of a CAM packet;
- the modulation and coding scheme adopted by the UEs.

Since the UEs get the timing from the LTE network and can be assumed being equipped with a GPS unit, we can consider the frames being synchronous among all the UEs. This means that the exact instants of start and end of each frame are known and shared by all the UEs.

The following step consists in mapping the Resource Blocks allocated by the LTE network into the slots of our proposed *TDMA-like* scheme, as suggested in figure 4:

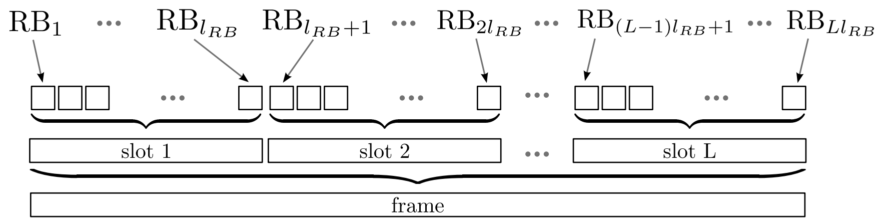

Figure 4: Mapping *RBs* into *slots* and into *frames*

As illustrated in figure 4, groups of l_{RB} Resource Blocks are combined to form one slot. The number l_{RB} of RBs necessary to form a slot depends on the modulation scheme (which determines the capacity of a single RB) and the size of the CAM packets. Specifically, we can compute its value as follows:

$$l_{RB} = \left\lceil \frac{l_B}{120 \cdot \mu/8} \right\rceil \tag{3}$$

where $\lceil x \rceil$ is the smallest integer larger than or equal to x, l_B is the physical layer size of a packet *in bytes* and μ is the number of bits per symbol carried by the chosen modulation scheme.

Let assign every RB in a frame a univocal number x (thus labeling them RB_x) and assume that RBs are taken in the order to form slots (*i.e.* RB_1 to $RB_{l_{RB}}$ form slot 1, $RB_{l_{RB}+1}$ to $RB_{2l_{RB}}$ form slot 2 and so on). This process is responsible for the mapping of a two dimensional resource (RBs in time-frequency) into a logical one dimensional scheme (TDMA-like slots and frames structure).

The choice of an optimal RB mapping scheme requires further research and is out of the scope of this document. In the following we thus present a sample technique. Figure 5 shows, for reasons of space, a 10 ms slice of a frame, in which 3 subframes -shadowed in gray- are allocated to LTE-Direct transmission (specifically, subframes number 1, 2 and 7).

In this example, we adopt the following numbering policy:

1. numbering starts from the *earliest* subframe in time;
2. start from RB *higher in frequency*;
3. increase by one unit moving one RB *down* in frequency (proceeding downwards in the figure) until the bottom of the bandwidth is reached;
4. move to the successive subframe and apply steps (2-3);

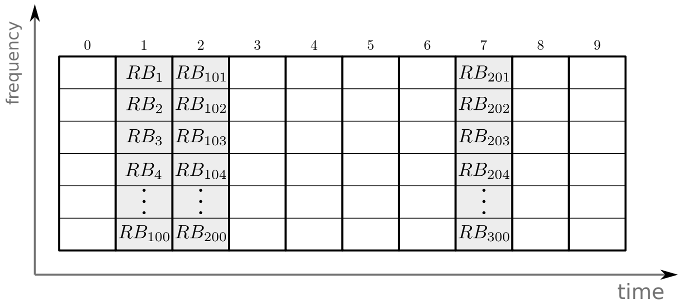

Figure 5: Example of RBs numbering policy

5. repeat steps (2-4) until the end of the 100 ms frame is reached.

The same technique is then applied to all the following frames. Since all the UEs are assumed synchronized, as long as they share the same RB mapping policy, they all identify the same RBs with the same numbers. Furthermore, they all locally build slots in the same fashion.

3.2.2 Distributed scheduling algorithm

Once a common scheme for mapping RBs into slot and frames has been established, a distributed scheduling technique must be defined, to allows UEs to locally decide which slot(s) to access. This specific aspect is still under research, thus in the following we compare three different techniques to obtain a first evaluation of the system performance.

For this preliminary analysis, we consider an isolated network of N UEs, all within transmission/reception range. Since the purpose of the work is to evaluate the performance of the medium access mechanism, we assume a perfect physical layer. A packet is thus correctly received if no collision takes place and it is lost in case of collision. The considered metric is the *probability of successuful broadcast transmission in a slot*, *i.e.* the probability of no collision taking place in a given slot. More precisely, it is the probability for a UE to transmit in one specific slot and for all the other $N-1$ UEs to be in reception mode in that same slot. We will refer to this probability as P_s from now on.

3.2.3 Optimal Resource Access

The Optimal Resource Access (ORA) mechanism in terms of channel utilization is obtained when every user is univocally assigned one slot in each frame: in this way, the system is able to support up to L users with $P_s = 1$, as no collision ever takes place:

$$P_s = 1 \qquad \text{if} \quad N \leq L.$$

The expression of P_s for number of users N greater than the number of slots per frame L requires further decisions. The optimality of this configuration can be maintained by reducing each UE's transmission frequency to a value low enough to allow the reservation of one slot per every user in the transmission range. In this way it keeps being $P_s = 1$ at the price of controllably increased inter-packet delay. For instance, by reducing the transmission rate from 10 Hz to 5 Hz, every UE only needs to transmit one message every *two* frames, allowing the system to support up to $2L$ users.

While ensuring optimal performance, this technique is unrealistic as it would require either a centralized scheduler, which is out of the hypotheses of this document, or a static *a priori* slot assigment to UEs, which poorly adapts to ad hoc vehicular networks.

3.2.4 Random Slot Choice (RSC)

The simplest decentralized solution requires every user to randomly choose, within a frame, one random slot to transmit in according to a uniform distribution. In this configuration P_s can be computed vs. the number of slots L and number of UEs N as follows:

$$P_s = \left[1 - \mu_p \cdot \frac{1}{L}\right]^{N-1} \tag{4}$$

μ_p represents the probability of transmitting a packet in a frame, and it models the transmission frequency. $\mu_p = 1$ corresponds to one packet per frame (10 Hz), while lower values correspond to lower statistical rates.

3.2.5 Retransmission-based techniques: Optical Orthogonal Codes

Optical Orthogonal Codes (OOC) take advantage of multiple retransmissions per frame of the same message to increase the probability of its successful reception P_s. They were initially developed for optical fiber applications, then applied as a TDMA access scheme for broadcast vehicular communications in [6].

OOC are a subset of the binary codewords of length L and Hamming weight w generated so that the maximum cross-correlation between two OOC words u and v is less than or equal to a given integer value λ:

$$\sum_{j=1}^{L} u_j \cdot v_j \leq \lambda \quad \forall u \neq v \tag{5}$$

Let us consider OOC codewords of length L, equal to the number of slots per frame, with Hamming weight w, equal to the number of retransmissions per frame we want the UEs to perform. Let then fix the λ parameter as the maximum number of collisions per frame we tolerate between a pair of users. Every UE must generate on OOC codeword and associate it to each frame, making every bit correspond in the order to a slot. Then, every UE will set itself in *transmission mode* in the slots

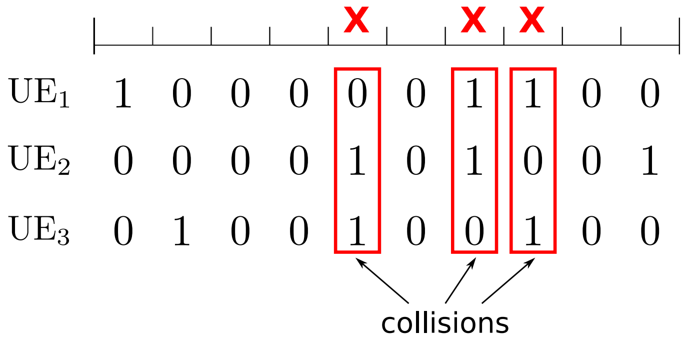

Figure 6: Example of OOC multiple access, $L = 10, w = 3, \lambda = 1$.

corresponding to 1 bits of the OOC codeword, and in *reception mode* in the slots corresponding to 0 bits. An example of this procedure is illustrated in figure 6.

Here one frame of length $L = 10$ slots, accessed by $N = 3$ UEs, is considered. Each UE is associated with an OOC codeword with $w = 3$ (3 retransmissions per frame are performed) and $\lambda = 1$, meaning that every pair of codewords can have at most one overlapping '1'. In the figure we can observe that the successful transmissions take place in the first, second and last slots, in which respectively only UE_1, UE_3 and UE_2 are in transmission mode, while the other users are receiving.

On the other hand, when more than one user is in transmission mode in the same slot, multiple packets collide.

Applying this technique, P_s can be computed as follows [6]:

$$P_s = \sum_{k=1}^{w} (-1)^{k+1} \binom{w}{k} \left[1 - \sum_{j=1}^{w} p_j \sum_{i=1}^{\min(j,k)} \binom{k}{i} \binom{w-k}{j-i} \right]^{N-1} \tag{6}$$

where p_j is the probability of having an interference pattern with weight j:

$$p_j = \mu_p \frac{\binom{L-w}{w-j}}{\sum\limits_{l=0}^{\lambda} \binom{w}{l} \binom{L-w}{w-l}}. \tag{7}$$

In this expression of p_j it appears the parameter μ_p, that similarly to the *Random Slot Choice* case models the transmission rate.

It can be observed that choosing a set of codewords such that a single transmission (*i.e.* no retransmission) is performed per frame is equivalent to apply the Random Slot Choice scheme. In fact, by substituting $w = 1$ and $\lambda = 1$ in (6) and (7), the espression (6) reduces to (4).

The advantage of OOC codewords over the use of random codewords with the same length and Hamming weight stands in the upper limit λ to the cross correlation between a pair of words, which provides an advantage in terms of probability of successful reception. The price to pay is a limitation in the number of available codewords and an additional cost required for their generation. Severals algorithms to generate OOC codes are proposed in [7]: among them, a *greedy* depth first search algorithm is available in pseudocode in [8].

The cardinality N_c of an OOC code depends on the word length and on the maximum desired cross correlation and must be carefully evaluated at design time. In the considered scenario, in which frames are synchronous, the size of the code is upper bounded by [7]:

$$N_c \leq \frac{(L-1)\cdots(L-\lambda)}{w(w-1)\cdots(w-\lambda)}$$

3.3 Performance comparison

In this section are compared the performaces in terms of probability of successful reception of the proposed distributed resource access techniques. Since the purpose of the CAM transmissions is to communicate to neighboring vehicles one's position and speed, P_s can also be interpreted as the average *awareness*. P_s will be analytically computed from equations (4) and (6) and the respective curves compared for different transmissions setups.

Let us consider a scenario in which all the UEs desire to transmit identical size CAM packets, defined as in table 4:

Table 4: CAM packets characteristics

size	300 bytes
maximum frequency	10 Hz
modulation	QPSK
DSRC channel:	CCH

The following parameters are also considered:

- Channel bandwidth of 20 MHz, $BW_{RB} = 100$;
- Allocation of 10% of the cell resources, $N_{sf} = 1$ (networks dedicates 1 subframe every 10 to the shared pool of resources for LTE-direct transmissions);
- QPSK modulation, in accordance with the DSRC standard, $\mu = 2$;
- resouce allocation continuous in time (no rate reduction to be applied).

The maximum rate that can be achieved with the given configuration can be computed using (1) and (2) and substituting the parameters:

$$R_b = 100 \frac{\text{LTE frames}}{\text{s}} \cdot 1 \frac{\text{subframe}}{\text{LTE frame}} \cdot 100 \frac{\text{RBs}}{\text{subframe}} \cdot$$
$$\cdot 120 \frac{\text{symbols}}{\text{RB}} \cdot 2 \frac{\text{bits}}{\text{symbol}} = 2.4 \text{ Mbps}$$

In this configuration, the network allocates 1000 Resource Blocks every 100 ms to the LTE-Direct resource pool. The number of RBs l_{RB} necessary to carry a CAM packet (slot size) can be computed by substituting the size of the CAM packet ($l_B = 300$ bytes) in equation (3):

$$l_{RB} = \left\lceil \frac{300}{120 \cdot 2/8} \right\rceil = 10 \frac{\text{RBs}}{\text{CAM}}$$

The number of slots per 100 ms frame is then:

$$L = \frac{1000}{l_{RB}} = 100 \frac{\text{slots}}{\text{frame}}$$

In figure 7 the performances of the Optimal Resource Access (ORA), Random Slot Choice (RSC) and Optical Orthogonal Codes (OOC) schemes are compared.

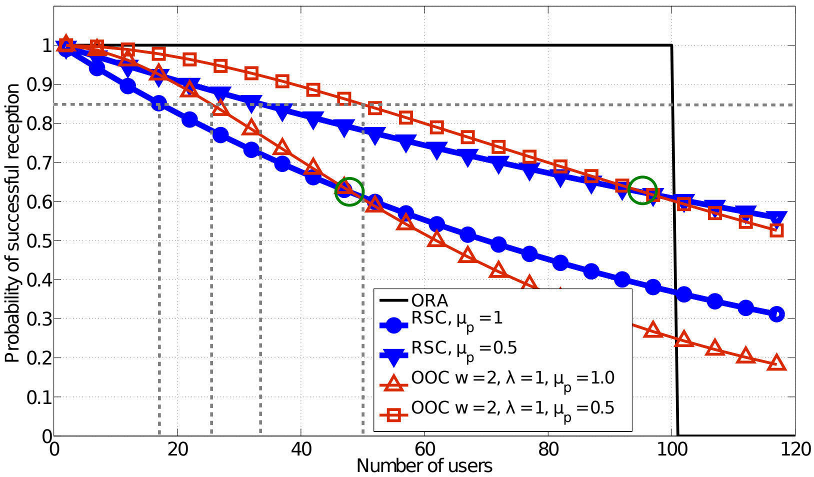

Figure 7: P_s versus number of users. $L = 100$.

The probabilities of successful reception obtained by applying the different paradigms are the compared to the DSRC threshold of $P_s = 0.85$, represented in figure by the horizontal dashed line.

The Optimal Resource Allocation scheme can be observed providing $P_s = 1$ for any amount of users less than or equal to the number of available slots.

Two curves are generated for both Random Slot Choice and Optical Orthogonal Codes, one with $\mu_p = 1$ and the second with $\mu_p = 0.5$. OOC are designed so that two retransmissions per frame are performed ($w = 2$) and the maximum cross-correlation between two codewords λ is equal to 1.

It can be observed that in both cases the OOC technique provides better results in terms of P_s for lower number of users, while RSC maintains better performances when the number of neighbors grows. For increasing number of users, in fact, retransmission-based techniques tend to saturate the available resources, causing a rapid performance drop.

In the considered channel scenario, by transmitting once every frame (10 Hz; $\mu_p = 1$), the RSC technique is able to support up to 17 UEs with $P_s \geq 0.85$, while OOC can support 25 UEs, *i.e.* 47% more.

Lowering the statistical periodicity to one transmission every two frames (5 Hz; $\mu_p = 0.5$), RSC can support up to 33 UEs, with $P_s \geq 0.85$, while OOC can support up to 49, *i.e.* 48% more.

The number of UEs corresponding to which the RSC curve and the OOC curve (with $w = 2$ and $\lambda = 1$) cross (for the same values of μ_p) are circa 45 UEs for $\mu_p = 1$ and circa 95 UEs for $\mu_p = 0.5$. The crossing points are circled in green in figure 7.

Even if for larger number of users RSC is the decentralized mechanism able to provide the best performances, it is worth noting that those performance are well below the tolerable threshold $P_s = 0.85$ set by the DSRC standard. When the number of neighbors grows too large, it is then more convenient to properly adapt the variables discussed in section 3.4.

3.4 Analysis of the design parameters

The resource allocation technique presented in section 3.1 allows the LTE network to allocate a common *quasi-static* pool of resources for LTE-direct broadcast transmission to take place.

The distributed mechanism for the definition of *TDMA-like* scheme presented in section 3.2 provides UEs with a technique to locally organize said pool of resources into a common periodical structure composed by *slots* and *frames*. In the same section are presented three different classes of scheduling methods, according to which the UEs locally decide in which slots to transmit and consequently, in which slots to receive.

The performance of the presented scheduling algorithms depend on the number N of users within transmission/reception range. Unfortunately, vehicular networks are by definition composed by high mobility nodes, therefore is difficult to control this variable. In this section, we thus discuss the system parametes we can modify to optimize the network performance in case of variations of network density, *i.e* in case of increase or reduction of number of UEs within interference range.

The design philosophy of the proposed access scheme make it possible to optimize the performances applying the *Decentralized Congestion Control* mechanism defined for DSRC [9]. Specifically, the following parameters can be adapted:

- *transmission rate*

- *transmission power*

The effects of these parameters will be discussed in the following of this section, as well as the effects of the *codeword selection*, which is specific for the Optical Orthogonal Codes access scheme.

3.4.1 Transmission rate

The 100 ms frame length defined for the proposed multiple access system was chosen so to reflect the maximum generation rate defined for the CAM messages (10 Hz) [5]. In order to transmit 10 CAMs per second, each UE must transmit one message per frame. The probability of successful reception P_s depends on the number N users within intererence range, *i.e.* on the number of potential interferers which might blindly choose to transit in the same slot, thereby causing a collision. If N grows too large, the probability of success P_s may drop below an acceptable threshold.

When UEs detect that too many collisions are taking place, by receiving undecodable power, they can locally decide to reduce the rate of transmissions from 10 Hz to, for instance, 5 Hz or 2 Hz. This means transmitting respectively once every two frames or once every five frames. This decision, likely applied locally by most of the UEs within range, will reduce the channel load, increasing the probability of successful reception at the price of a controllably reduced frequency of transmissions.

In the mathematical expressions of Ps for RSC (equation 4) and for OOC (equations 6 and 7) this is modeled with the probability μ_p. Specifically, a transmission rate of 5 Hz corresponds to $\mu_p = 0.5$, a rate of 2 Hz corresponds to $\mu_p = 0.2$ and so on.

In figure 8 are illustrated the channel accesses of two users adopting the Random Slot Choice mechanism. The first UE, labeled with a dotted arrow, transmits in one slot per frame, every frame ($\mu_p = 1$). The second UE, labeled with a crossed arrow, only transmits in one slot every two frames ($\mu_p = 0.5$).

In figure 9, channel accesses are illustrated for two UEs adopting the Optical Orthogonal Code access scheme with $w = 2$. The first UE, labeled with a dotted arrow, transmits in $w = 2$ slots per frame, every frame ($\mu_p = 1$). The second UE, labeled with a crossed arrow, transmits in $w = 2$ slots per frame as well, but only once every two frames ($\mu_p = 0.5$).

In the first frame of figure 9, the occurrence of a collision is showed: both UEs, in fact, independently decide to access the 4^{th} slot, resulting in the loss of both messages. In this specific situation, the advantage of OOC is evident: since both

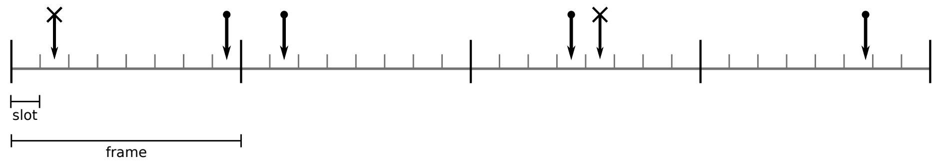

Figure 8: Transmission rate adopting RSC - $\mu_p = 1$ (dotted arrow) vs. $\mu_p = 0.5$ (crossed arrow)

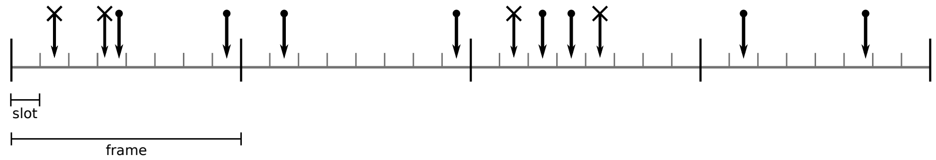

Figure 9: Transmission rate adopting RSC - $\mu_p = 1$ (dotted arrow) vs. $\mu_p = 0.5$ (crossed arrow). Note: a collision takes place in the 4^{th} slot of the 1^{st} frame.

UEs perform a second retransmission in the frame, there is an higher probability of successfully delivering the message (as shown in the figure). The cost of this advantage is a more aggresive use of the shared resources, which causes a faster degradation of the system performances when the number of users N increases.

3.4.2 Transmission power

Transmission power is also a crucial design parameter, which can be tuned to control the transmission range. UEs can react to variations of network density by modifying the transmission power. In sparse networks, higher power can be used to increase the range, while in dense urban environment power can be dimmed down to only reach the closest neighbors, the most important ones in a safety-critical scenario.

3.4.3 Choice of optical orthogonal codewords

In this work, in which we considered an isolated network of N nodes, we assume that every UE randomly chooses one OOC codeword with fixed values of L, w and λ. If the length of the codewords is sufficiently larger than the number of retransmission per frame (*i.e.* the condition $w \ll L$ holds), then we can consider, for a reasonable choice of λ, the cardinality N_c of the code to be sufficiently large so that $N_c \gg N$.

Under these conditions, we can safely assume that no one of the N users will choose the same codeword as any of the other $N-1$. In a realistic dynamic environment however, like a vehicular network, it is very likely that two users associated to the same codeword will sooner or later meet, making all of theirs transmissions collide. To prevent the occurrence of such scenario, UEs could randomly switch codeword at every frame.

More sophisticated codeword assignment techniques as proposed in [8] are out of the scope of this work. Furthermore, in the same document, the authors suggest the use of codewords with different Hamming weight to different UEs to perform QoS differentiation. Users with higher QoS will in this case be assigned codewords with larger weight, increasing the number of retransmissions per frame and thus the probability of reception of their packets.

4 Discussion and outcomes

In this document we presented a mechanism for the broadcast of periodic vehicular safety communications over LTE-Direct. The objective was to allow LTE-enabled terminals to perform periodic broadcast transmissions on a set of orthogonal resources underlaying the cellular network, while minimizing the network involvement. To do so, we proposed a mechanism divided in two phases, a) *resource allocation* and b) *distributed resource access scheduling*, of which only the former requires the intervention of the network.

The *resource allocation* procedure, inspired by eMBMS, allows the definition of a shared *quasi-static* set of resources on a wide area over multiple eNBs. UEs can retrieve the time-frequency coordinates of the shared resource pool without setting up a connection with the eNB. Moreover, no further network-side mobility management is required. The quasi-static nature of the dedicated resources provides resilience against eNB failure, as their exploitation can continue also in case of temporary loss of network coverage. On its side, the network has the flexibility to modify, according to its needs, the characteristics (namely the time distribution) of the allocated spectrum.

The *distributed resource access scheduling* is a set of techniques that allow each UE to locally organize the network allocated resources into a common structure of *slots* and *frames*, and use it as reference to access the resource pool according to a distributed *TDMA-like* scheme, still in phase of investigation. Three classes of techniques are compared, showing promising results which qualify LTE-direct as a valid technology to complement DSRC for broadcasting periodic vehicular safety messages. Moreover, we showed how the performances of the system can be optimized applying the same *Decentralized Congestion Control* scheme defined for DSRC.

The performances of the multiple access schemes discussed in this document are in all cases limited by collisions, as UEs *blindly* decide how to access the channel. We envision that a significant performance improvement could be achieved by applying more sophisticated access mechanisms. Self-organizing TDMA (S-TDMA) for instance, which exploits UEs positions information to regulate the channel access, appears particularly suitable for the characteristic of the considered system: its application will thus be object of future research.

Other than suiting the vehicular networking scenario, the flexibility of the proposed method also makes it a valuable solution for all the applications that require broadcast of messages over a custom area, possibly being covered by several eNBs. Applications such as local advertisement or social proximity services could then take advantage of the envisioned LTE-direct broadcast method.

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