Performance Analysis of Sidelink Data Communications in Autonomous Mode

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***Abstract*—Third Generation Partnership Project (3GPP) has defined a solution for direct-mode communications by introducing SideLink (SL) channels in LTE-Advanced Pro. First, we point out that in case of autonomous SL operation, half-duplexing constraints combined with the current SL Hybrid Automatic Repeat Query (HARQ) protocol can heavily affect the decoding performance. These degradations are taken into account for the derivation of an analytical model of the SL data channel successful MAC access probability. This model, which has been validated by simulation, is of particular interest for Public Safety (PS) applications and it avoids overestimation of the SL throughput at high spectral efficiencies. Finally, by using the proposed model, it is shown that if a minimum requirement on successful access probability is imposed e.g. by PS applications, then SL communications as defined in LTE-Advanced Pro can support only a small number of concurring transmitters. For instance, for a minimum successful access probability of the SL data channel equal to 90%, only up to 8 transmitters can be supported by the SL data channel using a typical SL configuration.**

I. Introduction

Long Term Evolution (LTE) has been identified by the main Public Safety (PS) actors as the reference technology for future broadband Private Mobile Radio (PMR) systems. 3GPP standards progressively added the features required for supporting PS services. For instance, Proximity Services (ProSe) were introduced in Release (Rel) 12, and extended in Rel 13-14, i.e. LTE-Advanced Pro (LTE-A Pro) [1]. These services are enabled by direct, or Device-to-Device (D2D), communication and discovery between User Equipments (UEs).

3GPP refers to D2D communication at Medium Access Control (MAC) and PHYsical (PHY) layer with the term "SideLink" (SL), which clearly distinguishes it from the traditional UpLink (UL) and DownLink (DL). Currently, LTE-A Pro supports D2D communication between UEs in coverage, in partial coverage and out of coverage. The last feature is essential for PS actors requiring connectivity in every situation, even in case of infrastructure failing or lacunar coverage. When the network coverage is no longer available, resource allocation for SL is done in Mode 2, i.e. autonomously by the UEs themselves.

A large amount of works is available in the open literature dealing with different flavors of D2D communications and their related allocation problems, often outside the 3GPP framework ([2] and references therein). However, the exact characterization of SL communication behavior as specified by 3GPP is important, e.g. for understanding how the standard can be used for supporting PS services. A simple model of the SL control and data channels was published in [3], but it fails to include the impact of Half-Duplexing (HD) constraints as pointed out in [4], where Griffith *et al.* provided an accurate model of the SL control channel. Authors in [5] modeled the SL discovery channel behavior.

In this paper, for the first time an accurate model of the behavior of the SL data channel in autonomous operation is presented. Moreover, we take into account the degradations on Hybrid Automatic Repeat Query (HARQ) performance generated by half-duplexing constraints. Finally, by considering the access probabilities of both SL control and data channels, a weighted achievable throughput is defined, which is useful to characterize SL performance. Sect. II introduces an overview of SL communications operation in Mode 2 as specified by LTE-A Pro. Sect. III points out issues related to HARQ, while Sect. IV provides the model of the successful access probability at MAC layer. Sect. V contains some initial indications about the overall performance of SL communications, and further, conclusions are drawn in Sect. VII.

II. Overview of SL Communications in LTE-A Pro

At PHY and MAC layer, D2D communications in LTE-A Pro are organized inside one (or multiple) set of resources called Resource Pool (RP). In the frequency domain, a RP is defined by N_{RB} Resource Blocks (RB) divided in two sub-bands of equal width. A RP is temporally described by a Sidelink Control (SC) period of configurable length in subframes, ranging from 40 ms to 320 ms [6]. RPs are pre-configured inside the UE for out-of-coverage operation and Frequency Hopping (FH) can be used. The SC period is divided into a first part dedicated to the transmission of the SL Control Information (SCI) on the Physical Sidelink Control CHannel (PSCCH) and a second part for data transmission on the Physical Sidelink Shared CHannel (PSSCH) (see Fig. 1). A UE needs to decode SCI information in order to be able to demodulate the PSSCH. The SC period is repeated thus providing a periodic structure, a new radio frame designed for SL communications.

A. Transmission procedure in PSSCH

In autonomous mode, the transmission procedure is divided into two steps. First, the UE independently chooses where to

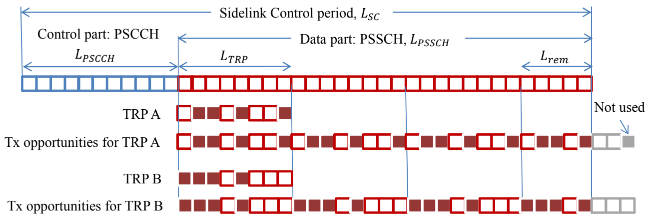

Fig. 1. SC period example with two Time Resource Pattern (TRPs) of weight 4: shaded squares indicate subframes scheduled for transmission.

send the SCI over the PSCCH (control part). The RB choice is done in a uniform random way, according to predefined rules (see [4] for more details). Then, for data transmission in the PSSCH, the UE randomly selects the allocation (i.e. a set of contiguous RBs and a set of subframes in the time domain), which is encoded in the SCI, valid for one SC period.

In Mode 2, PSSCH uses a fixed pre-configured Modulation and Coding Scheme (MCS), which determines the modulation and the code rate used by the LTE turbo encoder. The MCS is unique for all users in a RP. When a packet is ready for transmission, it is always transmitted four times without waiting for feedback. In detail, the packet is coded and four Redundancy Versions (RV) are created. Then, a fixed RV sequence, namely RV 0, 2, 3, 1, is sent in consecutive scheduled subframes [7]. Once the first packet is sent, if the UE buffer is not empty, another packet is processed and sent in the next set of four consecutive scheduled subframes, according to the same allocation information, and so on until the end the SC period is reached.

This procedure has been designed to provide a robust and redundant communication mode, since, due to the completely random choice of the allocation resources, a packet loss may happen because of: 1) collisions at the receiver side, if two or more transmitters choose the same resources; 2) HD constraints, i.e. a UE acting as a transmitter, when scheduled for SL transmission, cannot activate its receiver for listening to other transmitting UEs. Another case is when a UE is busy in the transmission/reception of a channel with priority higher than the SL data channel. In this paper, we deal only with HD constraints for SL data transmission.

B. *Time and frequency resource allocations in PSSCH*

LTE-A Pro uses Time Resource Pattern (TRP) of Transmission which is a short bitmap used for indicating scheduled subframes in the data part of the SC period (see filled squares in Fig. 1). TRP has length L_{TRP} equal to 6, 7, or 8 bits, depending on the LTE-A Pro FDD/TDD frame configuration used for SL, e.g. for FDD $L_{TRP} = 8$ [8]. The positions of TRP bits equal to 1 indicate the position of the scheduled subframes inside the PSSCH part of the SC period. The PSSCH length L_{PSSCH} can be much longer than L_{TRP}, hence TRP is repeated periodically up to the end of the RP. The TRP weight w, i.e. the number of TRP bits equal to 1, may take values in the range $1, \dots, L_{TRP}$ and represents the number of subframes scheduled for transmission in one TRP. All possible TRPs with a given weight are included in LTE-A Pro. It is possibile to restrict the set of available TRPs to the ones having only one or more selected weights [8].

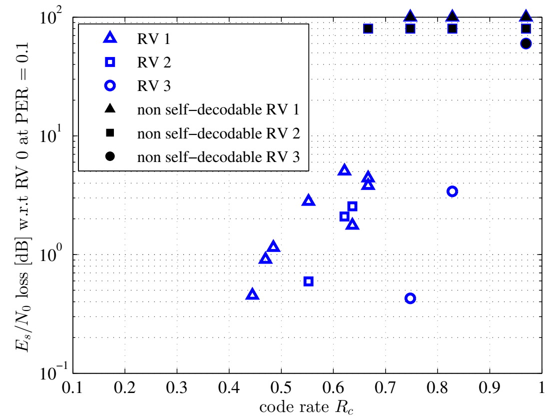

Fig. 2. E_s/N_0 loss in dB of RV 1, 2, 3 with respect to RV 0 at a target PER of 0.1 for some MCS; filled markers represent non self-decodable RVs.

Concerning allocation in the frequency domain, SCI gives only one RB allocation per SC period. Frequency hopping can be used, otherwise the initial fixed RB allocation is kept. FH type 1 is an explicitly signalled hopping pattern however, due to SL bandwidth and signalling limitations, the FH pattern is completely determined by the first allocation and hence it is deterministic. FH type 2 is a pseudo-random FH pattern hopping in $N_{sb} = 1, 2, 4$ separated sub-bands of equal size. There are 505 different seeds, but only one is associated to a given RP, and used for all communications therein. It comes that FH type 2 is useful only to reduce collisions among RPs, but not inside the same RP. In both cases, only inter-subframe FH is allowed. The previous analysis shows that for all FH types, inside one RP, FH patterns are deterministic, once the RB allocation in the SCI is decided, and do not depend on user identity. If two users select the same RB allocation, then, their FH patterns will be the same over the whole data part of the SC period. Only if the selected TRPs are different, the non-collided subframes will allow discriminating the signals.

III. HARQ BEHAVIOUR IN PSSCH

In order to understand the impact of HD constraints on PHY layer performance, it is important to briefly describe how HARQ RVs are generated by the rate matching algorithm, whose aim is to match the number of coded bits to the resources available for transmission on the air (a detailed tutorial can be found in [9]). The coded bits at the output of the LTE turbo code of rate 1/3 are separated in systematic bits (equal to information bits), parity 1 and parity 2 bits. These three groups of bits are separately interleaved and then multiplexed in a so-called Virtual Circular Buffer (VCB), which can be visualized as a table with a fixed number of columns (namely 96) and with a variable number of rows depending on the input packet size. Systematic bits occupy the first third of the columns, while multiplexed parity 1 and parity 2 bits occupy the remaining columns. The rate matching algorithm generates RV i by starting to read the VCB column-wise at a predetermined column c_i. If the end of the virtual circular buffer is reached, the rate matching continues to read starting from the beginning, until the number of bits required to fill the resources allocated for the transmission is reached. Since systematic and parity bits are not mixed together in the VCB, their distribution inside a RV is not homogeneous and depends on the offset c_i. Following LTE-A Pro specifications, for code rates $R_c > 1/2$, RV 0 contains most of systematic bits. Then, the percentage of systematic bits decreases for RV 3, 1 and 2. Now, besides a sufficiently high SNR, turbo decoding needs also a minimum amount of systematic bits for starting to converge towards the correct sent codeword [10]. Below a given percentage of systematic bits, it is impossible to decode the packet even in absence of noise. This effect is shown in Fig. 2, where we plot the E_s/N_0 loss in dB of RV 1, 2, 3 with respect to RV 0 at a target Packet Error Rate (PER) of 0.1, in an additive white Gaussian noise channel. This is done for a subset of LTE MCSs with different R_c, modulations and packet lengths. Losses increase with weaker codes, i.e. increasing code rate R_c of RV 0. Filled markers at the right top of the figure represent RVs which are not self-decodable (their y-axis values are just conventional values used for visualization). Starting from $R_c \approx 0.67$ RV 2 is no longer self-decodable, then from $R_c \approx 0.75$ RV 1 as well is not self-decodable and finally RV 3 at very high R_c.

Many MAC models consider that packet reception is successful if at least one of its (re)transmissions (i.e. RVs) is not lost or collided. However, if losses are due to half-duplexing constrains, soft bits cannot be accumulated by the UE (since it is in transmit state). In case of a unique received RV, successful decoding even at very high SNR happens only when the RV is self-decodable. Hence, it is important to include this effect in the evaluation of the SL MAC access probability.

IV. PSSCH SUCCESSFUL ACCESS PROBABILITY

In this section the probability of successful access to the PSSCH is calculated. FH Type 2 will be assumed for simplicity of presentation, but the derivation can be applied to FH Type 1 or no FH, by setting $N_{sb} = 2$ or 1.

A. Analytical model

Let us focus on the probability $P[\mathcal{R}_k^K]$ of the event $\mathcal{R}_k^K$ that k users among the K transmitters correctly receive the packet of one transmitter, under no capture effect, with $k = 0, \dots, K-1$. We adapt to PSSCH the approach used for PSCCH in [4]. Briefly, if $\mathcal{C}$ is the event that at least one collision happens in the access phase, then

$$P[\mathcal{R}_k^K] = P[\mathcal{R}_k^K|\mathcal{C}]P[\mathcal{C}] + P[\mathcal{R}_k^K|\overline{\mathcal{C}}]P[\overline{\mathcal{C}}] \quad (1)$$

$$= [1-(1-P[\mathcal{X}])^{K-1}]\delta(k) + (1-P[\mathcal{X}])^{K-1}P[\mathcal{R}_k^K|\overline{\mathcal{C}}] \quad (2)$$

where $\delta(k)$ is the discrete Kronecker function. $P[\mathcal{X}]$ is the collision probability between two transmitters, defined as the probability that a receiver cannot correctly decode the packet of one transmitter due to the interference generated by the other or to bad decoding configurations, i.e. that the received interference-free RVs are not self-decodable. The $\delta(k)$ function illustrates the fact that in case of collision no user in the group can correctly receive the packet. The probability $P[\mathcal{R}_k^K|\overline{\mathcal{C}}]$ of event $\mathcal{R}_k^K$ conditioned on the fact that no collision happened, is determined by HD constraints. In the case of PSSCH, $\{\mathcal{R}_k^K|\overline{\mathcal{C}}\}$ can be modeled as a set of independent trials (because of independent user resource allocations), conditioned on the absence of collisions, like for PSCCH [4]. For PSSCH, the failure probability is $P[\mathcal{O}_2|\overline{\mathcal{X}}] = P[\mathcal{O}_2 \cap \overline{\mathcal{X}}]/P[\overline{\mathcal{X}}]$, where $\mathcal{O}_2$ is the event of HD constraint. Notice that $P[\mathcal{O}_2 \cap \overline{\mathcal{X}}] = P[\mathcal{O}_2] - P[\mathcal{X}]$, since $\mathcal{X} \subseteq \mathcal{O}_2$.

The success probability is $P[\overline{\mathcal{O}}_2|\overline{\mathcal{X}}] = P[\overline{\mathcal{O}}_2 \cap \overline{\mathcal{X}}]/P[\overline{\mathcal{X}}] = P[\overline{\mathcal{O}}_2]/P[\overline{\mathcal{X}}] = (1-P[\mathcal{O}_2])/P[\overline{\mathcal{X}}]$. Putting together the previous probability in a binomial distribution we obtain

$$P[\mathcal{R}_k^K|\overline{\mathcal{C}}] = \binom{K-1}{k} \frac{(1-P[\mathcal{O}_2])^k (P[\mathcal{O}_2]-P[\mathcal{X}])^{K-k-1}}{(1-P[\mathcal{X}])^{K-1}}. \quad (3)$$

To obtain a close form expression for (1) we need to calculate $P[\mathcal{O}_2]$ and $P[\mathcal{X}]$ for the PSSCH.

1) Derivation of $P[\mathcal{O}_2]$: Differently from PSCCH, in PSSCH when all RVs are self-decodable, HD constraints happen only when two users choose the same TRP. We assume SCI settings such that only TRP having the same weight w are used[1]. Then, the number of different TRP with length L_{TRP} and weight w is $N_{TRP} = \binom{L_{TRP}}{w}$ and the probability that two transmitters choose the same TRP is $1/N_{TRP}$. Moreover, in presence of non self-decodable RVs, additional packet losses are possible. As an example, consider nodes A and B using a MCS with one non self-decodable RV, say RV 2. The transmission position of RV 2 by user A corresponds to the position of the second value of 1 inside its selected TRP bitmap. Then, if $L_{TRP} = 8$ and $w = 4$, it is possible to see by inspection that there are 4 TRP choices of user B for which RV 2 *only* is not collided. But RV 2 cannot be decoded alone, and user B loses the packet in this example. In general, conditioned on user A TRP choice, the number of user B TRP choices which do no collide with z subframes of user A and collide with the remaining $w-z$ subframes is $\binom{L_{TRP}-w}{w-z}$. This formula corresponds to LTE-A Pro TRP design, which is a synchronous fixed retransmission scheme. A different formula would apply if other TRP designs were used, like orthogonal optical codes [11]. Hence, supposing that there are N_{nd} non self-decodable RVs, the number N_{bad} of bad configurations for reception, including perfect collision, is

$$N_{bad} = \begin{cases} 1 & , w = 1, 2, \\ 1 + N_{nd}\binom{L_{TRP}-w}{w-1} & , w = 4. \end{cases} \quad (4)$$

Equation (4) holds true, for SL using LTE-A Pro frame configuration for FDD systems [8]. Similar expressions can

[1]LTE-A Pro allows the use of TRP with different weights in the same PSSCH. But TRPs with different weights have different collision probabilities, leading to variable and random protection level on the sent packets. This choice does not seem optimal and therefore it is not investigated here.

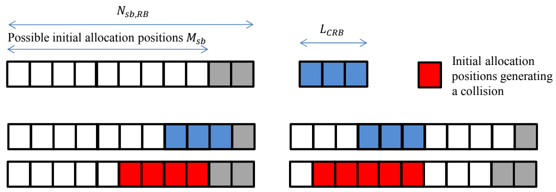

Fig. 3. Partial collisions when the number L_{CRB} of contiguous allocated RBs is greater than 1.

be found for TDD frame configurations. In LTE-A Pro design, N_{bad} is independent of the TRP choice of the first transmitter, hence we can write $P[\mathcal{O}_2] = N_{bad}/N_{TRP}$.

2) Derivation of $P[\mathcal{X}]$: In PSSCH, unlike PSCCH, frequency and time allocations are independent. As a consequence, $P[\mathcal{X}] = P[\mathcal{C}_{RB}]P[\mathcal{O}_2]$, with $P[\mathcal{C}_{RB}]$ the probability of making identical choices for RBs, and $P[\mathcal{O}_2]$ the probability of either choosing identical TRPs or choosing two different TRPs where all interference-free RVs are non-self decodable.

Concerning $P[\mathcal{C}_{RB}]$, considering FH Type 2, the RB choice can be split in two independent phases: the choice of one sub-band among N_{sb} (the probability that two transmitters choose the same sub-band is $1/N_{sb}$), and the choice of the RB position inside the chosen sub-band. The number M_{sb} of possible allocation positions inside a sub-band with $N_{sb,RB}$ RBs depends on the number L_{CRB} of contiguous RBs occupied by the sent packet, $M_{sb} = N_{sb,RB} - L_{CRB} + 1$ (see Fig. 3 for an example with $N_{sb,RB} = 11$ and $L_{CRB} = 3$). We suppose here that all the users occupy the same number L_{CRB} of RBs, which makes sense for certain services like voice or small alerts. In this case, in fact, the collision probability is the same for all couples of users and equation (3) holds true. The number $c(m)$ of allocation positions leading to a collision (red squares in Fig. 3) depends on the allocation choice m of the first transmitter (blue squares in Fig. 3):

$$c(m) = \begin{cases} \min\{L_{CRB} + m, M_{sb}\} & m \in I_0, \\ 2L_{CRB} - 1 & m \in I_1, \\ \min\{L_{CRB} + M_{sb} - 1 - m, M_{sb}\} & m \in I_2. \end{cases} \quad (5)$$

Intervals $I_0 = [0, \min\{L_{CRB} - 2, \lceil M_{sb}/2 \rceil - 1\}]$, $I_1 = [L_{CRB} - 1, M_{sb} - L_{CRB}]$ and $I_2 = [M_{sb} - 1 - \min\{L_{CRB} - 2, \lceil M_{sb}/2 \rceil - 1\}, M_{sb} - 1]$ are applied to equations (5) when they are valid. For each possible combination of allocation choices $m, m' = 0, \ldots, M_{sb}-1$, the number of collided RBs is $\max\{L_{CRB} - |m - m'|, 0\}$. Making the pessimistic assumption that any partial collision generates a loss of the packet, and putting together the probabilities of collision inside one sub-band and among different sub-bands, we can write

$$P[\mathcal{C}_{RB}] = \frac{1}{N_{sb} M_{sb}^2} \sum_{m=0}^{M_{sb}-1} c(m). \quad (6)$$

Finally, the collision probability between two transmitters is

$$P[\mathcal{X}] = P[\mathcal{C}_{RB}]P[\mathcal{O}_2] = \frac{N_{bad}}{N_{TRP}} \frac{1}{N_{sb} M_{sb}^2} \sum_{m=0}^{M_{sb}-1} c(m). \quad (7)$$

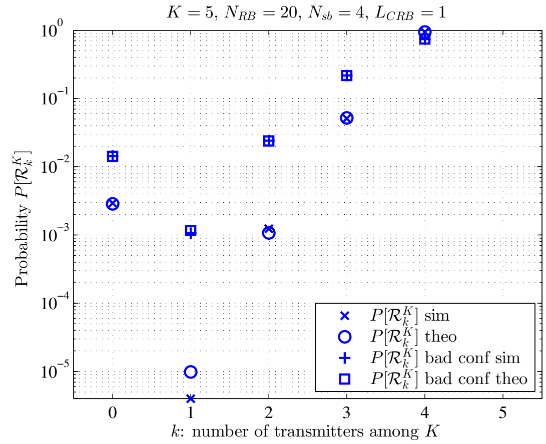

Fig. 4. $P[\mathcal{R}_k^K]$ with and without half-duplexing constraint, for $K = 5$, $N_{sb} = 4$ sub-bands, $N_{RB} = 20$ RBs and $L_{CRB} = 1$.

If $N_{nd} = 0$ (all RVs are self-decodable), expression (7) yields the familiar $P[\mathcal{X}] = 1/(N_{TRP} N_{RB})$ when $L_{CRB} = 1$. When $L_{CRB} = N_{sb,RB}$, i.e. the packet occupies the whole sub-band, then $P[\mathcal{X}] = 1/(N_{TRP} N_{sb})$.

By using (2), (3) and the previous findings, the probability of correctly receiving k nodes among K transmitters is

$$P[\mathcal{R}_k^K] = [1 - (1 - P[\mathcal{X}])^{K-1}]\delta(k) + \binom{K-1}{k} \left(1 - \frac{N_{bad}}{N_{TRP}}\right)^k \left(\frac{N_{bad}}{N_{TRP}} - P[\mathcal{X}]\right)^{K-k-1} \quad (8)$$

with $P[\mathcal{X}]$ as in (7). As a consequence, the probability that, given a transmitter, all the other $K-1$ users correctly receive its packet is $P[\mathcal{R}_{K-1}^K] = (1 - N_{bad}/N_{TRP})^{K-1}$ and it is independent of the number of RBs N_{RB} of the RP. This is due to the 3GPP design choice for PSSCH. A closer look to equation (8) reveals that $P[\mathcal{R}_k^K]$ is weakly dependent on the number of RBs available for SL communications, for all k.

B. Numerical examples

Fig. 4 presents the comparison between theoretical formulas and simulation for the probability $P[\mathcal{R}_k^K]$ with $K = 5$ transmitters, with packets occupying 1 RB ($L_{CRB} = 1$). The PSSCH configuration is: $N_{RB} = 20$ RBs, $N_{sb} = 4$ sub-bands, $L_{TRP} = 8$ and $w = 4$. The "bad conf" legend refers to a case with $N_{nd} = 1$ non self-decodable RV, i.e. from (4) $N_{bad} = 5$ in this scenario. At least 10^5 PSSCH random accesses have been simulated according to the standardized procedure. The figure shows a perfect match between simulation and theory in the limit of numerical precision.

Fig. 5 is derived with the same simulator and PSSCH configuration of Fig. 4, by simulating at least $2 \cdot 10^4$ accesses for each set of K transmitters. It shows the dependence of the successful access probability $P[\mathcal{R}_{K-1}^K]$ with respect to K. Curves without HD constraints apply only to additional users in the network which are only interested in reception and never transmit. The important impact of HD constraints, even without bad decoding configurations, can be appreciated. An even steeper decrease of the success probability is produced

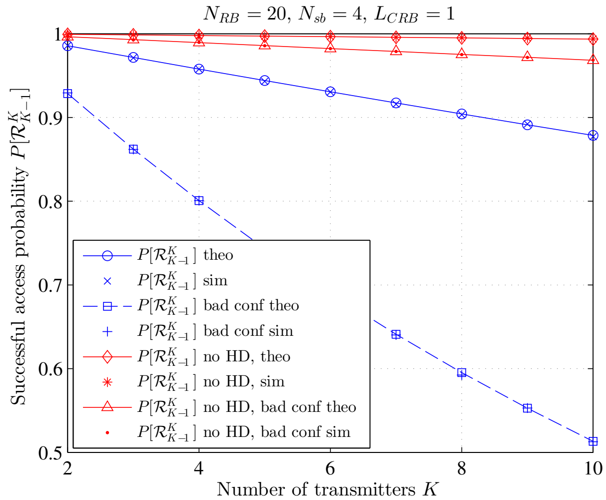

Fig. 5. Probability $P[\mathcal{R}_{K-1}^{K}]$ for a variable number of users accessing PSSCH with 20 RBs divided in 4 sub-bands, with packets of 1 RBs.

when just one non self-decodable RV is present in the MCS used by the system. Our results show that the current PSSCH design is targeted to very few concurrent transmitting users, unless a low probability of success is acceptable.

V. Global metrics for SL behavior

The aim of this section is to define a weighted achievable throughput which takes into consideration: 1) a requirement on the reliability of the overall SL communication $P_{s,target}^{SL}$; 2) the structural constraints of the SL channels in LTE-A Pro; 3) the throughput of the chosen MCS.

By joining our results with the ones in [4], it is possible to derive a SL successful access probability P_s^{SL} for the overall system. Since all K transmitters have to successfully decode the control channel, its successful access probability is $P_s^{(c)} = P^{PSCCH}[\mathcal{R}_{K-1}^{K}]$ (from [4]). For the data channel $P_s^{(d)} = P^{PSSCH}[\mathcal{R}_{K-1}^{K}]$, because we want to model multiple parallel one-to-many communications in the same group, e.g. multiple group calls for PS users. Then, $P_s^{SL} = P_s^{(c)} P_s^{(d)}$ since the allocation decisions on the two channels are independent.

Further, it is interesting to evaluate the maximum number of transmitters $\hat{K}$ such that a minimum requirement on SL communication reliability $P_{s,target}^{SL}$ for all users is satisfied

$$\hat{K} = \max K : P_s^{SL} > P_{s,target}^{SL} \tag{9}$$

where P_s^{SL} is a function of K and of the parameters of both PSCCH and PSSCH, such as the number of frames dedicated to PSCCH L_{PSCCH} and to PSSCH L_{PSSCH}, $N_{RB}, N_{TRP}, L_{CRB}, N_{sb}, N_{bad}$, etc.. The number of RBs N_{RB} for the data and control part are the same.

We now discuss the structural constraints of SL channels. Let L_{SC} be the number of subframes allocated to SL in a SC period, then $L_{PSSCH} = L_{SC} - L_{PSCCH}$. Once a TRP is randomly selected, the transmitter can compute the number of scheduled subframes. Since four transmissions per packet are always used, when the scheduled subframes are not a multiple of four, the last remaining subframes are not used. This procedure is schematically represented in Fig. 1, where filled non-shaded squares represent subframes which can effectively be used for transmission in PSSCH. As an example, if TRP A is chosen, 15 subframes are scheduled in the SC period, but only $\lfloor 15/4 \rfloor = 3$ packets can be sent. In general, let us define $N_{TRP,SC} = \lfloor L_{PSSCH}/L_{TRP} \rfloor$ the number of TRP intervals in the PSSCH and $L_{rem} = L_{PSSCH} - N_{TRP,SC} L_{TRP}$ the number of remaining subframes (see Fig. 1). Now, the number of scheduled subframes w_{rem} among the last L_{rem} subframes is a random variable with a probability mass distribution depending on the TRP design of LTE, and equal to

$$P[w_{rem} = r] = \frac{\binom{L_{rem}}{r}\binom{L_{TRP}-L_{rem}}{w-r}}{\binom{L_{TRP}}{w}}, \tag{10}$$

with $r \in [\max\{0, w - L_{TRP} + L_{rem}\}, \dots, \min\{w, L_{rem}\}]$. The number of packets sent in the PSSCH is a random variable $N_p(w_{rem}) = \lfloor (N_{TRP,SC} w + w_{rem})/4 \rfloor$, with average $N_{p,av} = E_{w_r}[N_p(w_{rem})]$ over all the possible TRPs.

Finally, we define the weighted achievable throughput η_1 for one user, for a given MCS conveying b_{MCS} information bits and occupying L_{CRB} RBs, such as

$$\eta_1 = N_{p,av} b_{MCS} P_s^{SL} / L_{SC}, \tag{11}$$

which takes into account the successful access probability P_s^{SL}, the MCS and the number $N_{p,av}$ of data packets that can be sent in a SC period. The total weighted achievable throughput $\eta_K = K\eta_1$ includes the contribution of K users, and corresponds to the maximum aggregated throughput of the SL channel. The expression of η_K holds true because in LTE-A Pro all the users must use the same MCS configuration in one given RP, and further the same traffic type is supposed for all UEs, which can be enforced by the association of logical channel identities to different RPs.

VI. Numerical evaluation

Thin curves in Fig. 6 represent η_K as a function of the length of control part L_{PSCCH}, for $L_{SC} = 40$ and different K. PSSCH configuration is the same of Fig. 4. The size of packets is $L_{CRB} = 1$ RB, which fits well to PS voice application. As an example, two MCSs are considered for evaluation: MCS 1 carries $b_1 = 224$ information bits with $R_c = 0.47$ and has no bad decoding configuration; MCS 2 carries $b_2 = 328$ bits with $R_c = 0.67$ but RV 2 is not self-decodable ($N_{bad} = 5$).

The thin dashed and solid curves correspond to η_K respectively for MCS 1 and MCS 2; different colors represent different K. When $K = 1$, no collision is present, hence the optimal length of the control part is 2 subframes (i.e. its minimum value in LTE-A Pro). In this case MCS 2 trivially provides higher achievable throughput. When $K > 1$, collisions and HD issues are present. If the control part is too short, the throughput falls due to low $P_s^{(c)}$. Then a maximum is achieved and the curves start decreasing, since a too long control part penalizes the number of packets that can be sent in

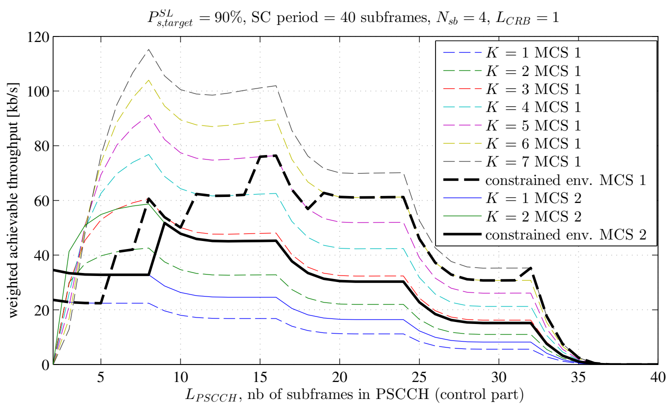

Fig. 6. Total weighted achievable throughputs for different K and two MCSs, under a constraint on minimum successful access probability of 90%; points below or on the thick curves satisfy the constraint.

the whole SC period. For fixed K, curves of MCS 2 are always higher than the corresponding curves of MCS 1. Moreover, one would say that the optimal choice is to select a high K and the PSCCH length that yields the maximum throughput. However, these thin curves are drawn without setting a constraint on the successful access probability.

If the system has a constraint on SL communication reliability, then previous conclusions change. The new results are represented by the thick curves (dashed for MCS 1 and solid for MCS 2) in Fig. 6. All the throughput points on the thick curves or below them satisfy the requirement on reliability set to $P^{SL}_{s,target} = 90\%$ in this example. The maximal number of transmitters satisfying the requirement changes with the control part length. Moreover, MCS 2 has a bad decoding configuration, therefore matching the reliability constraint is much harder (see also Fig. 5). For MCS 2, only curves for $K = 1, 2$ are drawn in the figure because for $K \geq 3$, $P^{SL}_{s,target} = 90\%$ is never satisfied. In summary, MCS 1 provides a much larger set of configurations than MCS 2 satisfying the required minimum successful access probability. Hence, choosing MCS 2 becomes suboptimal if we want to maximize η_K for medium values of L_{PSCCH}, or if $K \geq 3$. However, MCS 2 can be the right choice if the number of concurrent transmitters K is always very limited.

VII. Conclusion

In this paper, after briefly presenting SL communications in LTE-A Pro, consequences of half-duplexing constraints on SL error coding performance are investigated. MCSs with high code rate typically have one or more RVs which cannot be decoded if received alone. This fact has been taken into account in the evaluation of the successful access probability of the SL data channel, in presence of concurrent transmitters.

Then, analytical formulas are derived of the probability that any subset of the transmitters correctly receives the transmission of one given user. Finally, by using results for the control channel in [4], the successful access probability for the overall SL system is computed. A weighted achievable throughput has been proposed taking into account the access probability and structural constraints of the SL data channel in LTE-A Pro. The analysis of the model results shows that LTE-A Pro SL communications are suited to a very small number of concurring transmitters, if a high reliability is imposed by the applications. For instance, in typical SL settings, for PS voice communications (e.g. small packets) and under a minimum successful access probability of 90% for the overall system, user throughput is expected to be around 18 kb/s for at maximum 5 concurrent transmitters, with a robust MCS. Using a less robust MCS, user throughput can be increased to 24 kb/s, but only two concurrent transmitters can be supported with the same target reliability. These facts must be carefully considered when using SL communications for PS services.

Another added value of our analysis is that hints are given about possible improvements in LTE-A Pro SL communications. Simple ideas for future investigations range from i) parameter tuning, e.g. by increasing the TRP length for decreasing losses due to HD constraints or by defining FH per user, up to ii) PHY and/or MAC modifications, e.g. by defining a better rate matching algorithm for SL or by proposing new access procedures.

Acknowledgment

This work has been carried out in the framework of the H2020 project ICT-671639 COHERENT, which is funded by the European Union.

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