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Performance Evaluation of LTE Device-to-Device Out-of-Coverage Communication with Frequency Hopping Resource Scheduling

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Fernando J. Cintrón
Wireless Networks Division
Communications Technology Laboratory

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Walter Copan, NIST Director and Undersecretary of Commerce for Standards and Technology

Abstract

This document presents a performance evaluation of Long Term Evolution (LTE) Device-to-device (D2D) communication when enabling frequency hopping resource scheduling. Moreover, as secondary objective, this document serves as a compendium for frequency hopping related procedures over D2D communications as defined by The 3rd Generation Partnership Project (3GPP) for the LTE standard. D2D communication is modeled and simulated using discrete event network simulator (ns-3). Simulated scenarios are designed to capture communication conditions occurring outside network infrastructure coverage, alike those experienced by authorized network users, such as public safety first responders, during network outages.

Key words

Device-to-Device (D2D) Communication; Frequency Hopping; Long Term Evolution (LTE); Resource Scheduling.

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1. Introduction

The 3^{rd} Generation Partnership Project (3GPP) introduced Device-to-Device (D2D) Proximity Services (ProSe) to Long Term Evolution (LTE) in release 12 [1]. Direct communication is one of the key functionalities defined to serve devices being in proximity, enabling them to communicate directly without the need to route communications through LTE's air interface Evolved Node B (eNodeB). Direct communication is envisioned to support public safety users within proximity to communicate directly in the event of network failure due to disaster or in areas lacking cellular coverage, such as remote locations or inside buildings.

ProSe defines the operation mode for ProSe-enabled user equipment (UE) based on the type of coverage scenarios, i.e., within network coverage (including single and multiple cells), partial coverage where some UEs are within network coverage but not all, and outside network coverage. When UEs are within network coverage, ProSe functionalities are assisted by LTE's Evolved Packet Core (EPC) and the air interface. The eNodeB orchestrates the available network resources, such as timing and bandwidth allocation. Furthermore, ProSe defines two modes of operation for the scheduling of resources: scheduled (mode 1), the eNodeB performs the resource scheduling for all UEs engaged in direct communication, as it does with LTE downlink and uplink scheduling; UE-selected (mode 2), where the eNodeB intervention is limited to the resource allocation, and each UE is responsible of their resource scheduling within the allocated D2D bandwidth.

Although direct communication in mode 2 can operate while in-network coverage, it also enables authorized UEs to communicate when they fall outside network coverage, i.e., where there is no LTE air interface support and coordination of communication resources. Direct communication in out-of-coverage relies on preconfigured communication parameters that are set before deployment on every ProSe-enabled UE by network operators. The communication parameters include the communication resource pool to indicate the group of resources in time and frequency available to UEs, among other settings defined by 3GPP's standard in [2]. Due to the lack of coordination on the communication resources when the air interface is absent, direct communication can suffer from interference created by resource contending UEs. Griffith et al. [3] and [4], modeled and evaluated the performance of direct communication's control and data channel, respectively, in mode 2 out-of-coverage, disclosing potential resource interference and channel inherited half duplex constrains.

Direct communication without LTE's air interface support remains an open research topic. It has gained the attention of the public safety sector, for whom having a functional and reliable means of communication becomes crucial in their line of work. This work evaluates the performance of out-of-coverage direct communication with LTE's frequency hopping schemes, using and extending the implementation of the network simulator[1] ns-3

[1]Certain commercial products are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the commercial products identified are necessarily the best available for the purpose.

module for D2D, introduced in [5]. Section 2 provides an overview of direct communication resource pools and 3GPP's standard definitions to manage the scheduling of D2D communication resources over LTE's Frequency Division Duplexing (FDD) implementation. Section 3 presents a series of direct communication evaluations under different modeled scenarios using frequency hopping resource scheduling schemes. Section 4 concludes this work and provides the final remarks.

2. D2D Communication

D2D communication is carried through a direct link established between UEs in proximity, named sidelink (SL). Communication over sidelink is performed in a periodical manner in the time domain [6]. The length of the communication period is configurable from 40 ms to 320 ms, including a set of predefined values in between. Each sidelink period is composed of two channels, the Physical Sidelink Control Channel (PSCCH) and the Physical Sidelink Shared Channel (PSSCH), as depicted in Fig. 1.

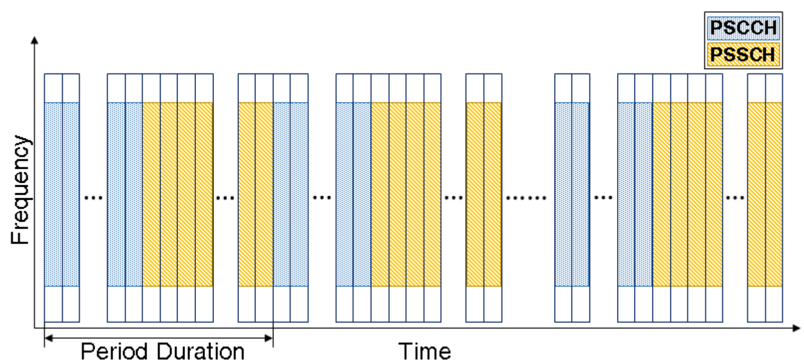

Fig. 1. Sidelink communication periods in frequency vs. time domain; PSCCH and PSSCH are depicted within each period.

2.1 Sidelink Communication Control

The PSCCH is used by ProSe-enabled UEs to send sidelink control information (SCI) messages, indicating how the data will be transmitted, and which resources will be used in the PSSCH. Each UE monitors the control channel to detect if another UE is transmitting in the current sidelink period. Upon successful reception of a control message, a UE can proceed to tune to the corresponding resources in the PSSCH.

Resource scheduling for the PSCCH is beyond the scope of this study. A performance evaluation for the resource scheduling procedures in the PSCCH is presented in [3]. The remainder of this section is dedicated to the resource scheduling in the PSSCH and the D2D supported frequency hopping schemes.

2.2 Sidelink Communication Data

Communication resources in the PSSCH are scheduled in both time and frequency domains. A Transmission Resource Pattern (TRP) of a fixed time length (measured in subframes) is used to schedule frequency resources over time. The TRP is repeatedly used for every N_{TRP} subframes in the PSSCH. A transmitting UE selects a TRP index (I_{TRP}) from a list of predetermined values established by 3GPP in [6]. Each TRP index is associated with a corresponding TRP bit mask to indicate which K_{TRP} subframes from the N_{TRP} bit mask length are enabled for transmission. Table 1 provides example TRP indexes and their corresponding bit masks for $N_{TRP} = 8$. For example, a TRP index $I_{TRP} = 36$, for bit masks with $N_{TRP} = 8$ length, enables the first four subframes out of every eight subframes for transmission in the PSSCH.

Table 1. Time resource pattern index mapping examples for bit masks with $N_{TRP} = 8$ length.

I_{TRP}	K_{TRP}	bit mask
0	1	(1,0,0,0,0,0,0,0)
8	2	(1,1,0,0,0,0,0,0)
36	4	(1,1,1,1,0,0,0,0)
106	8	(1,1,1,1,1,1,1,1)

The scheduling of PSSCH resources in the frequency domain is indicated with a Resource Indication Value[2] (RIV), representing a start Resource Block (RB) index and the number of RBs thereafter to be used. Before transmitting in the PSSCH, a UE must announce in the period's PSCCH: the RIV, TRP indexes, the Modulation and Coding Scheme (MCS), a D2D group destination ID, and whether resource assignment remains constant through the period or if a frequency hopping scheme will be employed.

Figure 2 depicts a single sidelink communication period 40 ms long, with a resource pool of 50 RBs. The PSCCH occupies the first 8 subframes of the period, and is shown in dark blue, the remaining 32 subframes, shown in yellow, make up the PSSCH. The SCI message is being transmitted in the PSCCH resource 0, and is shown as a pair of green RBs in the first and second subframes, at RB indexes 0 and 25 respectively. The 6 RBs colored turquoise (RB indexes 22 to 27) in the first subframe contain the primary and secondary sidelink synchronization signals (PSSS and SSSS) and the Physical Sidelink Broadcast Channel (PSBCH). The figure also shows the scheduled resources for a UE transmitting in the period, the RB index is chosen to be 0, the number of RBs for each transmission is 10, and the I_{TRP} index is 36. Moreover, frequency hopping is disabled, hence, the resource selection remains constant through the length of the PSSCH.

2.3 Sidelink Communication with Frequency Hopping

D2D frequency hopping on the PSSCH is built upon the existing LTE Uplink frequency hopping procedures described in [6]. It is supported in both schedule assignments, modes

[2] The computation for the RIV is defined in [6].

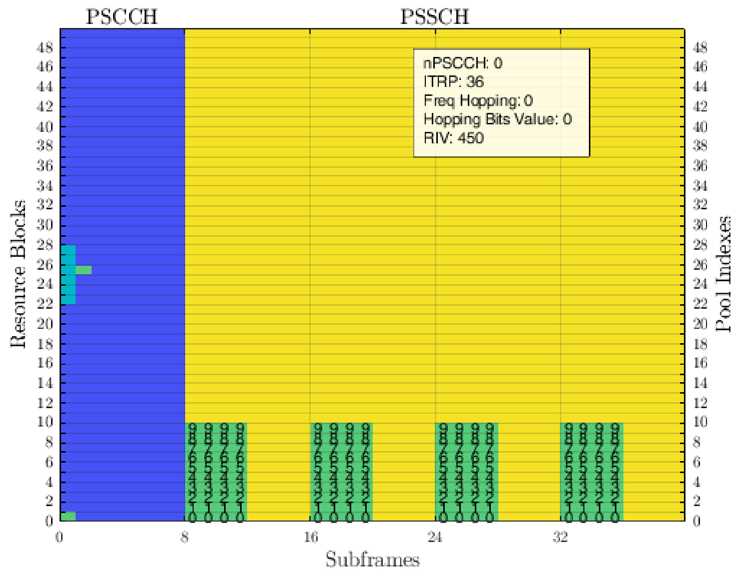

Fig. 2. Example sidelink communication resource scheduling for 10 RBs.

1 and 2, for D2D communications over the PSSCH. There are two types of frequency hopping: constant (Type 1) and pseudo-random (Type 2). Furthermore, LTE defines two modes to indicate when, in the time domain, frequency hopping takes place: in *inter-subframe* hopping, changes in transmission frequency occur on a subframe basis; in *intra and inter-subframe* hopping, changes in transmission frequency occur within subframe's slots and within subframes. *Inter-subframe* hopping is supported by both frequency hopping types, Type 1 and Type 2, but *intra and inter-subframe* hopping is only supported by Type 2 for D2D communications. For the purpose of this study, discussion and evaluations are focused on *inter-subframe* hopping.

2.3.1 Type 1 Frequency Hopping

The resource schedule assignment (SA) for Type 1 frequency hopping is performed as follows. The parity of the PSSCH subframe index where the transmission will occur determines the SA formula to use. Equation (1) is used to determine the starting resource block for transmissions occurring in odd subframe indexes, while Eq. (2) is used for transmissions occurring in even subframe indexes, given a starting RB index ($RB^{'}_{START}$) selected by the sidelink grant for the current period.

$$n^{SL0}_{PRB} = RB^{'}_{START} + \tilde{N}^{HO}_{RB}/2 \tag{1}$$

$$n^{SL1}_{PRB} = \tilde{n}_{PRB}(i) + \tilde{N}^{HO}_{RB}/2 \tag{2}$$

$\tilde{N}^{HO}_{RB} = N^{HO}_{RB} + 1$, if N^{HO}_{RB} is an odd number, otherwise, $\tilde{N}^{HO}_{RB} = N^{HO}_{RB}$. The variable N^{HO}_{RB} represents an offset expressed in number of RBs set at the Radio Resource Control (RRC) layer by the *rb-Offset-r12* parameter in the *SL-HoppingConfig* information element [6]. The value $\tilde{n}_{PRB}(i)$ depends on the hopping pattern selected by the hopping information field in the sidelink grant, introduced in Table 2.

Type 1 frequency hopping restricts the number of RBs available for the PSSCH (N_{RB}^{PSSCH}), as well as the maximum number of contiguous RBs (L'_{CRB}) per transmission, as shown in Eq. (3) and Eq. (4), respectively.

$$N_{RB}^{PSSCH} = M_{RB}^{PSSCH\_RP} - \tilde{N}_{RB}^{HO} - \left(M_{RB}^{PSSCH\_RP} mod 2\right) \tag{3}$$

$$\begin{aligned} L'_{CRB} &= \lfloor 2^y / M_{RB}^{PSSCH\_RP} \rfloor \\ y &= \lceil log_2 \left(M_{RB}^{PSSCH\_RP} \left(M_{RB}^{PSSCH\_RP} + 1\right) / 2\right) \rceil - N_{SL\_hop} \end{aligned} \tag{4}$$

The LTE standard allows for different variants of Type 1 hopping depending on the available system bandwidth. When hopping is enabled, the hopping information is encoded together with the RIV in the sidelink control message. N_{SL_hop} bits are used for hopping information and the remaining y bits (Eg. 4) are used for the RIV. The hopping information determines the hopping pattern to be employed, shown in Table 2. The ranges of values for the hopping information in decimal representation are [0, 1] for system bandwidth in the range (6 to 49) RBs; [0, 3] for system bandwidth in the range (50 to 110) RBs.

Table 2. LTE hopping information.

System BW N_{RB}^{SL}	Number of Hopping bits	Information in hopping bits	$\tilde{n}_{PRB}(i)$
6 to 49	1	0	$\left(\lfloor N_{RB}^{PSSCH}/2 \rfloor + RB'_{START}\right) mod\ N_{RB}^{PSSCH}$
		1	Type 2 PSSCH Hopping
50 to 110	2	00	$\left(\lfloor N_{RB}^{PSSCH}/4 \rfloor + RB'_{START}\right) mod\ N_{RB}^{PSSCH}$
		01	$\left(-\lfloor N_{RB}^{PSSCH}/4 \rfloor + RB'_{START}\right) mod\ N_{RB}^{PSSCH}$
		10	$\left(\lfloor N_{RB}^{PSSCH}/2 \rfloor + RB'_{START}\right) mod\ N_{RB}^{PSSCH}$
		11	Type 2 PSSCH Hopping

Figures 3, 4, and 5 depict the scheduling of 10 RBs in a 40 ms sidelink period with 50 RBs system bandwidth, using frequency hopping Type 1, with hopping information (decimal values) 0, 1, and 2, respectively. From the figures it is possible to identify the constant hopping pattern and the difference in hopping distance achieved from each Type 1 scheduled configuration for the same start RB index selection ($RB'_{START} = 0$). The example in Figure 3 uses the hopping information bits value set to 1, therefore $\tilde{n}_{PRB}(i) = (\lfloor 50/4 \rfloor + 0)\, mod\ 50 = 12$. Likewise, $\tilde{n}_{PRB}(i) = -12$ and $\tilde{n}_{PRB}(i) = 25$ in Fig. 4 and Fig. 5, respectively. Note that the negative value for $\tilde{n}_{PRB}(i)$ in Fig. 4 means that 12 RBs must be counted down from the highest RB index in the PSSCH pool.

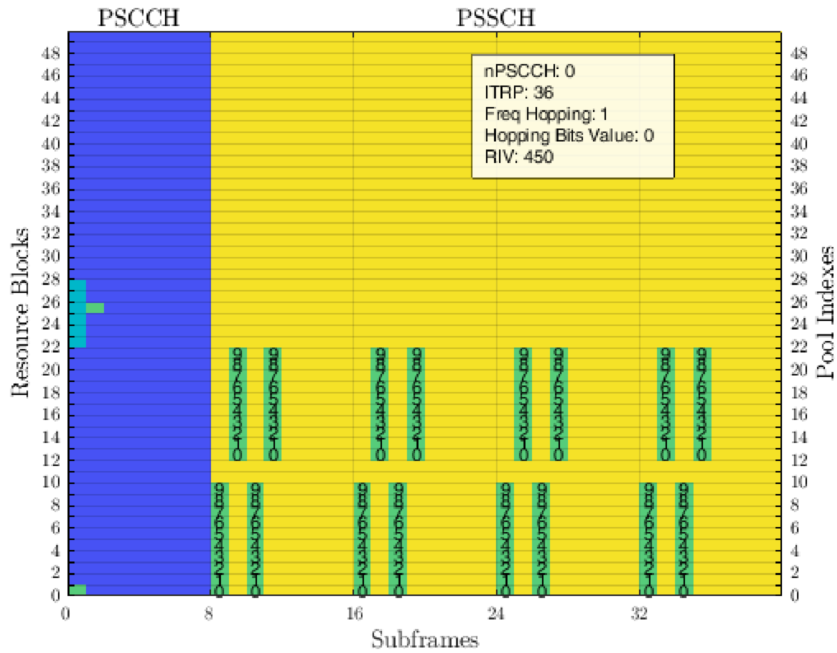

Fig. 3. Example sidelink communication resource scheduling for 10 RBs with frequency hopping Type 1, hopping information bits = 0 (decimal representation).

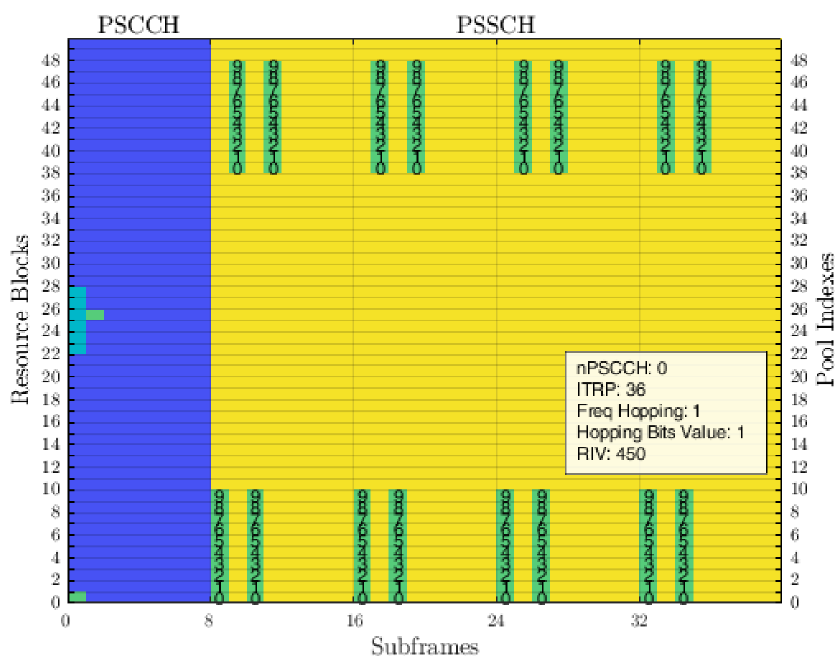

Fig. 4. Example sidelink communication resource scheduling for 10 RBs with frequency hopping Type 1, hopping information bits = 1 (decimal representation).

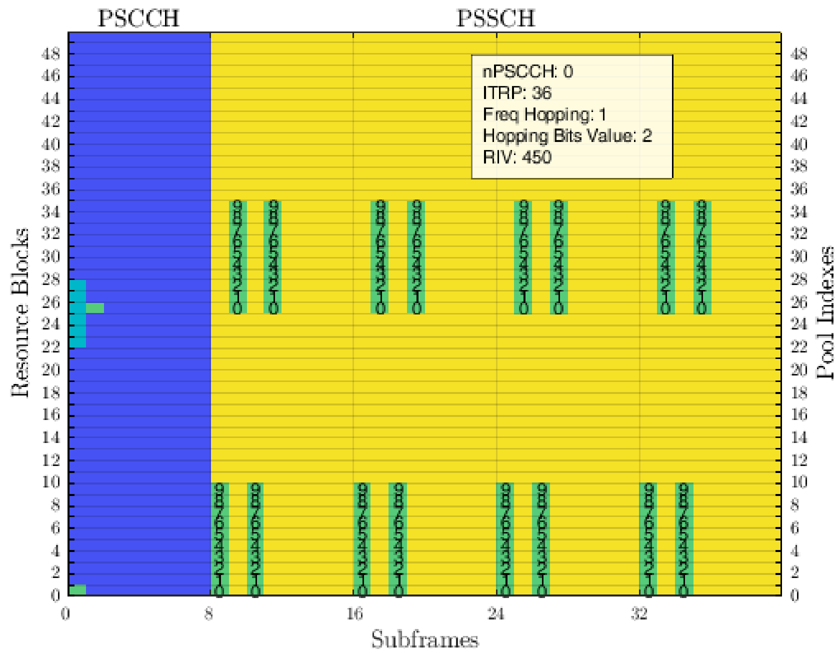

Fig. 5. Example sidelink communication resource scheduling for 10 RBs with frequency hopping Type 1, hopping information bits = 2 (decimal representation).

2.3.2 Type 2 Frequency Hopping

The resource schedule assignment for frequency hopping Type 2 is performed with a predefined hopping pattern computed from a pseudo-random generated binary sequence, controlled with a set of equations defined by LTE's 3GPP standard in [7]. The number of subbands (N_{sb}) where hopping takes place, and a seed value to initialize the pseudo-random sequence when in out-of-coverage (D2D communication mode 2), are two key configuration settings at the RRC's *SL-HoppingConfig* information element [6].

The number of RBs available for the PSSCH (N_{RB}^{PSSCH}), the number of contiguous RBs per transsmission (L'_{CRB}) and the size of the sub-bands (N_{RB}^{sb}) is regulated by Eq. (5), (6), and (7), respectively.

$$N_{RB}^{PSSCH} = \begin{cases} M_{RB}^{PSSCH\_RP} & N_{sb} = 1 \\ M_{RB}^{PSSCH\_RP} - \tilde{N}_{RB}^{HO} & N_{sb} > 1 \end{cases} \tag{5}$$

$$L'_{CRB} = min\left(\lfloor 2^{y}/M_{RB}^{PSSCH\_RP}\rfloor, \lfloor N_{RB}^{PSSCH}/N_{sb}\rfloor\right) \tag{6}$$

$$N_{RB}^{sb} = \begin{cases} M_{RB}^{PSSCH\_RP} & N_{sb} = 1 \\ \lfloor \left(M_{RB}^{PSSCH\_RP} - \tilde{N}_{RB}^{HO} - \tilde{N}_{RB}^{HO} mod 2\right)/N_{sb}\rfloor & N_{sb} > 1 \end{cases} \tag{7}$$

The SA for frequency hopping Type 2 is performed at each slot number (n_s) within a radio frame [7]. The RB index ($n_{PRB}(n_s)$) for the sidelink transmission occurring at subframe n_s is computed with Eq. (8), (9), and (11). Even though the slot number is used as time index, Eq. (9) uses the time index indicator i (Eq. (10)) to compute the subframe index when *inter-subframe* hopping is used instead.

$$n_{PRB}(n_s) = \begin{cases} \tilde{n}_{PRB}(n_s) & N_{sb} = 1 \\ \tilde{n}_{PRB}(n_s) + \lceil N_{RB}^{HO}/2 \rceil & N_{sb} > 1 \end{cases} \tag{8}$$

$$\begin{aligned} \tilde{n}_{PRB}(n_s) = \Big(&\tilde{n}_{VRB} + f_{hop}(i) \cdot N_{RB}^{sb} + \\ &\left(\left(N_{RB}^{sb} - 1\right) - 2\left(\tilde{n}_{VRB} \bmod N_{RB}^{sb}\right)\right) \cdot f_m(i) \\ &\Big) \bmod \left(N_{RB}^{sb} \cdot N_{sb}\right) \end{aligned} \tag{9}$$

$$i = \begin{cases} \lfloor n_s/2 \rfloor & \textit{inter-subframe} \text{ hopping} \\ n_s & \textit{intra and inter-subframe} \text{ hopping} \end{cases} \tag{10}$$

$$\tilde{n}_{VRB}(n_s) = \begin{cases} n_{VRB} & N_{sb} = 1 \\ n_{VRB} - \lceil N_{RB}^{HO}/2 \rceil & N_{sb} > 1 \end{cases} \tag{11}$$

The hopping distance, and the selection of whether the order of RBs in a transmission is mirrored within the sub-band or not, is computed from a hopping function $f_{hop}(i)$, and a mirroring function $f_m(i)$. Both functions utilize a pseudo-random sequence $c(i)$, generated with a length-31 Gold sequence defined by LTE's standard in [7].

Figures 6 and 7 depict the scheduling of 10 RBs in a 40 ms sidelink period with 50 RBs system bandwidth, using frequency hopping Type 2. The pseudo-random sequence used in the figures was initialized with the quantity $c_{init} = 504$. The figures differ in the number of sub-bands N_{sb} selected, two vs. four, depicted with the dashed lines. The starting n_{VRB} was selected to be at pool resource index 0, which is then translated into the starting RB index for each sub-band, unless the particular transmission is mirrored. Since the SA example presented in both figures share the same time scheduling settings, and $N_{sb} > 1$, mirrored transmissions can be observed at the same subframes indexes 10, 17, 27, and 32.

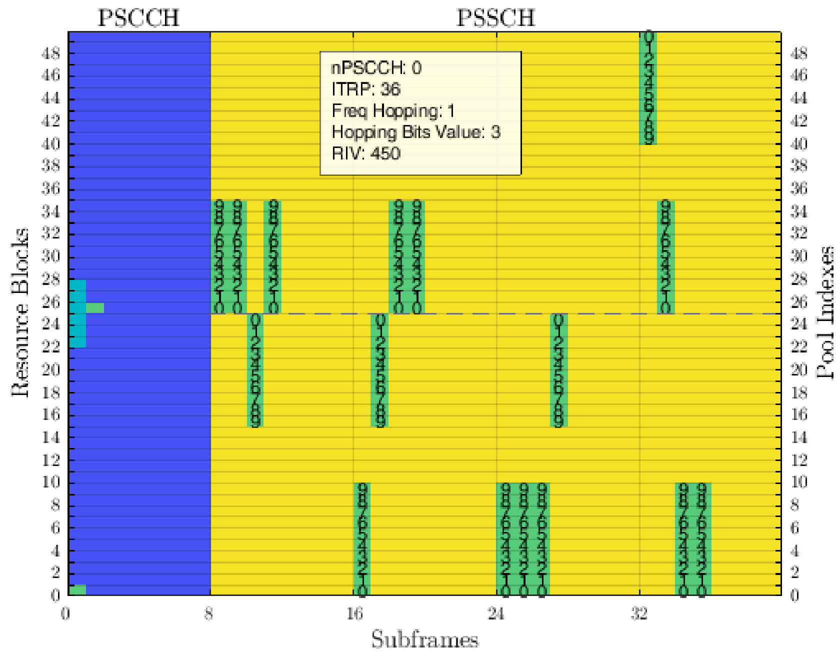

Fig. 6. Example sidelink communication resource scheduling for 10 RBs with frequency hopping type 2, and 2 sub-bands.

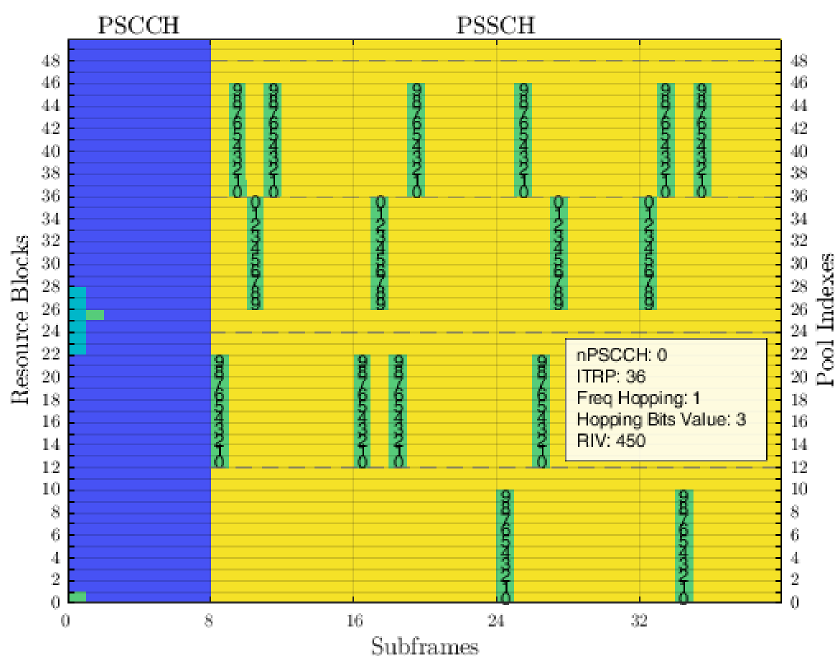

Fig. 7. Sidelink communication resource scheduling for 10 RBs with frequency hopping type 2, and 4 sub-bands.

3. Performance Evaluation

Two scenario settings were simulated to study the impact of frequency hopping over sidelink communication, single and group sidelink communication. For both scenarios, out-of-coverage sidelink communication (Mode 2) was assumed, i.e., there is no centralized scheduling of communication resources, and each transmitting UE selects the resources at random. Furthermore, fast fading was introduced to each simulation scenario, and COST231 propagation model was used [8].

3.1 Small Scale Fading Modeling

Fading traces were generated using Matlab Communications System Toolbox to create multipath fading environments in the simulated scenarios [9]. Extended Pedestrian A (EPA) and Extended Typical Urban (ETU) fading conditions were configured for LTE band 14, considering a 3 km/h speed for the UE. Since the experienced fading can vary among the receiving UEs, each receiving UE randomly selects a 500 ms window from the fading trace to be used for the length of the simulation.

Figures 8 and 9 display 100 ms samples on the X axis from the 20 s long, EPA and ETU fading trace configurations, respectively; the gain amplitude is plotted on the Z axis for each frequency resource block in a 10 MHz bandwidth (50 RBs) plotted on the Y axis. From the figures, it can be noticed that the changes in gain amplitude on the resource blocks in the frequency domain tend to be smoother for EPA configuration than for that obtained from ETU. Therefore, in order to evaluate the performance of frequency hopping under a more dynamic fading environment, focus is given to results obtained from scenarios subjected to ETU fading.

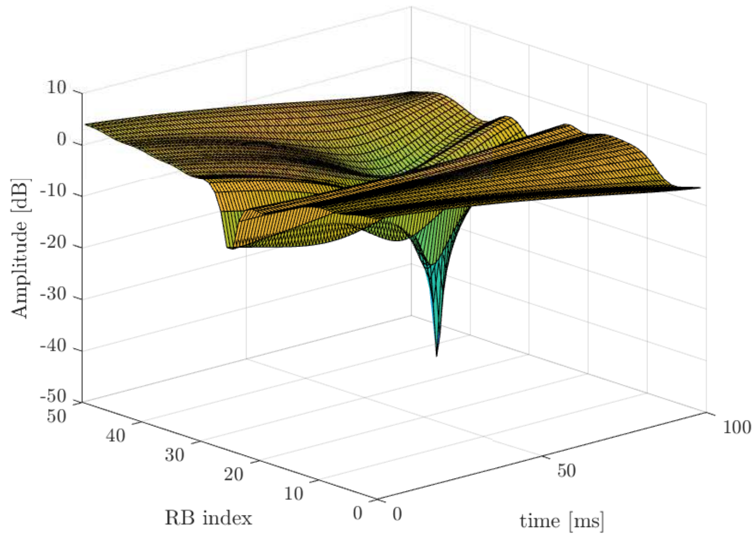

Fig. 8. Fading trace sample using Extended Pedestrian A model (EPA), LTE band 14, and 3 km/h speed.

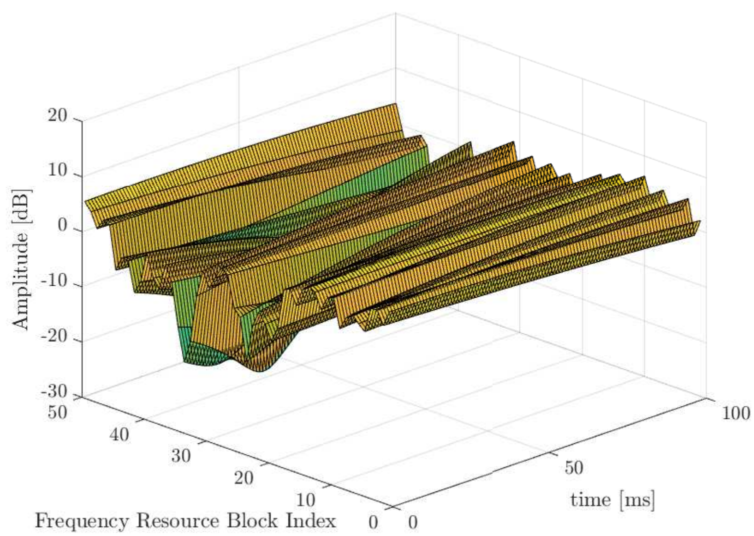

Fig. 9. Fading trace sample using Extended Typical Urban model (ETU), LTE band 14, and 3 km/h speed.

3.2 Communication Scenarios

All the communication scenarios shared the following settings. A sidelink period lasting 40 ms is used, of whose first 8 ms were dedicated for the PSCCH and the remaining 32 ms for the PSSCH. Each sidelink grant randomly allocates $L^{'}_{CRB} = 3$ RBs for each simulated communication period. The TRP selection is random from patterns with $N_{TRP} = 8$ and a fixed K_{TRP} through the scenario. The $\{$MCS, $K_{TRP}\}$ combination pairs $\{18, 1\}$, $\{10, 2\}$, and $\{6, 4\}$ were chosen to allow 1000 bits to be transmitted over the PSSCH in every sidelink period, averaging 25 kbit/s data rate[3]. For example, a single transmission using 3 RBs with MCS 6 yields a transport block size (TBS) of 256 bits. Using TRPs with $K_{TRP} = 4$ enables 16 out of 32 subframes for transmission in the PSSCH. Since D2D communication over sidelink utilizes 4 Hybrid Automatic Repeat reQuest (HARQ) processes without acknowledgment per transport block transmission, a total of 4 new transport blocks are transmitted over 16 transmissions per period.

Table 3 summarizes the different SL configurations evaluated in each scenario setting. Furthermore, for each SL configuration, five hopping patterns were evaluated independently (shown in Table 4); their performance was compared against the corresponding no-hopping SL configuration.

Table 3. Sidelink grant configurations.

SL Configuration	$L^{'}_{CRB}$	MCS	TBS	K_{TRP}	TBs per period	bits/period
1	3	18	1064	1	1	1064
2	3	10	504	2	2	1008
3	3	6	256	4	4	1024

Table 4. Simulated hopping patterns per SL configuration.

Hopping Type	Hopping Information	Number of Sub-bands (ns)	C_{init}
1	0	-	-
	1	-	-
	2	-	-
2	3	2	504
	3	4	504

Each scenarios setting assumes the transmitting UEs have full buffer, i.e., there is always data to be transmitted at any transmission opportunity.

3.2.1 Sidelink Single Link Evaluation

Sidelink communication between one transmitter UE and one receiver UE was simulated. The Euclidean distance between the two communicating UEs was the varying factor. The

[3] A 25 kbit/s data rate is chosen in order to model voice communication with Adaptive Multi-Rate Wideband (AMR-WB) codec, assuming the highest bit rate mode.

ratio of transport blocks successfully received by the receiver is used as the performance indicator. Each scenario was run ten times to compute the arithmetic mean of the performance metric and the 95 % confidence interval.

Figures 10, 11, and 12 present the transport block (TB) transmission success ratio obtained for each SL configuration. A clear trade-off is observed between higher (less robust) vs. lower (more robust) MCS values as the distance is increased, most notably at distances greater than 500 m. Results obtained with lower MCS values (MCS 6 and MCS 10) show to outperform those obtained with the higher MCS 18, at the cost of more transmission per period to sustain the desired bit rate. All frequency hopping variants performed better than the no-hopping case in each SL configuration. Moreover, the performance gain can be better appreciated when selecting a transmission success threshold to determine communication range. For example, assuming the intended communication could withstand a maximum TB transmission loss of 2 %, the communication range obtained by the frequency hopping variants for SL configuration 1 (Fig. 10) is around 400 m, in contrast to 300 m obtained when frequency hopping is disabled.

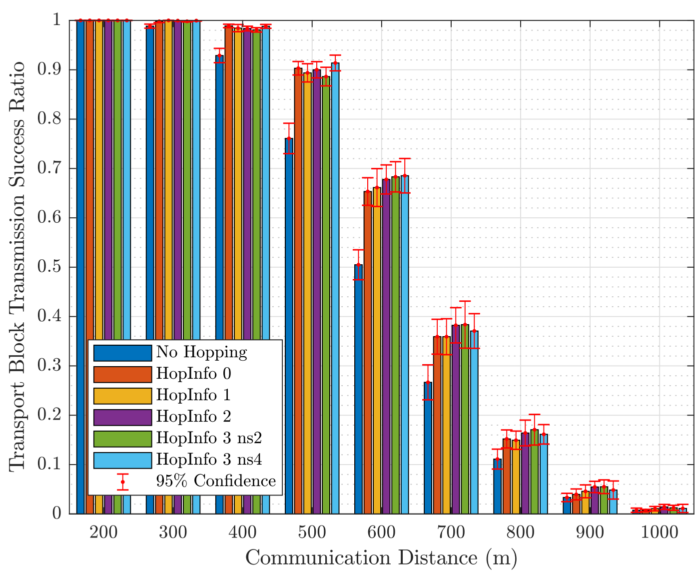

Fig. 10. Transport block success for single sidelink, MCS 18, $K_{TRP} = 1$, sidelink period 40 ms.

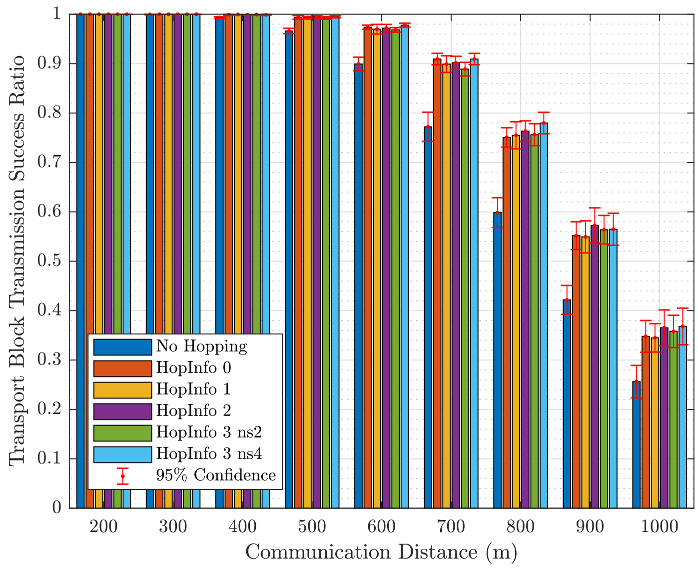

Fig. 11. Transport block success for single sidelink, MCS 10, $K_{TRP} = 2$, sidelink period 40 ms.

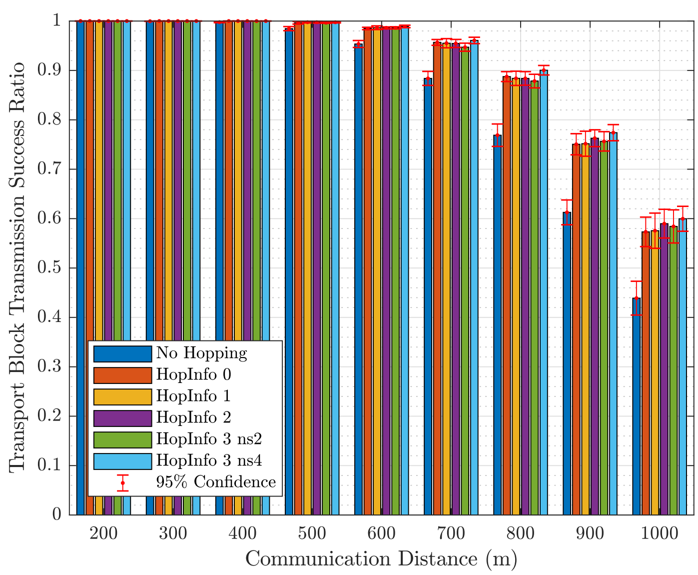

Fig. 12. Transport block success for single sidelink, MCS 6, $K_{TRP} = 4$, sidelink period 40 ms.

3.2.2 Sidelink Single Link with Random Interference Evaluation

Random interference was added to the SL single link communication scenarios to simulate potential interference created by nearby in-coverage UEs communicating with an eNB in the shared LTE uplink band. The interference bandwidth was fixed to occupy 10 contiguous RBs randomly selected from the 50 RB pool at every SL period. Results from the updated scenarios are presented in Figs. 13, 14, and 15. A significant drop in the TB transmission success ratio is observed (about 16.5 % reduction starting at 200 m and increasing thereafter) in all no-hopping configurations. On the other hand, the frequency hopping variants showed to be quite resilient to this type of interference; less than 2 % TB transmission loss is observed up to 300 m for MCS 18, between 400 m and 500 m for MCS 10, and 500 m for MCS 6.

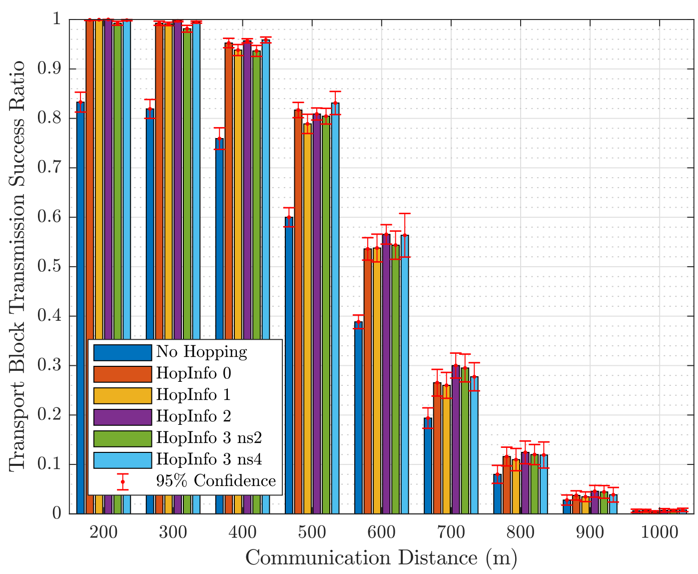

Fig. 13. Transport block success rate for single sidelink, MCS 18, K_{TRP} 1, sidelink period 40 ms, and 10 RBs interference.

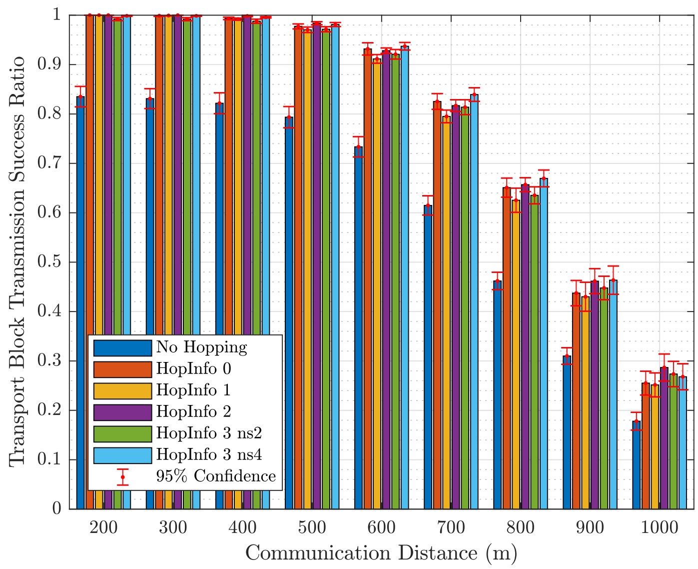

Fig. 14. Transport block success rate for single sidelink, MCS 10, K_{TRP} 2, sidelink period 40 ms, and 10 RBs interference.

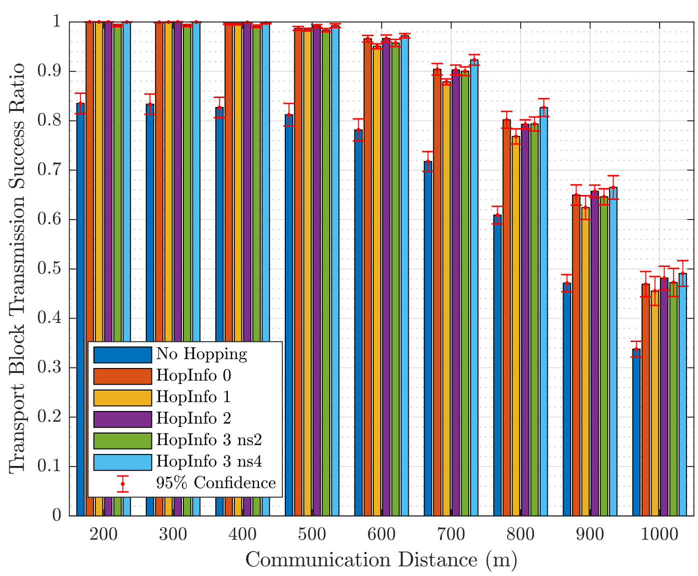

Fig. 15. Transport block success rate for single sidelink, MCS 6, K_{TRP} 4, sidelink period 40 ms, and 10 RBs interference.

3.2.3 Sidelink Group Communication Evaluation

Sidelink group communication in out-of-coverage (mode 2) was simulated in an area of 200 m × 200 m. All UEs were randomly deployed and contended for communication resources in every SL period. The number of UEs participating in the communication group was the varying factor. Two performance indicators were utilized, the aggregated number of TBs successfully received, and the TB loss spurts, i.e., the number of consecutive TB losses. The SL configurations presented in Table 3 and Table 4 are used. Each configuration was run five times to compute the arithmetic mean of the performance metrics and the corresponding 95 % confidence intervals.

Figures 16, 17, and 18 present the TB transmission success ratio obtained for each SL configuration when D2D group communication takes place. Interference from peer UEs contending for the same pool of resources is the principal factor affecting the D2D communication performance. This can be observed further as the communicating group size is increased. Frequency hopping shows to slightly improve the TB transmission success ratio, in particular Type 1 frequency hopping for MCS 18 and MCS 6 SL configurations, Figs. 16 and 18 respectively. Frequency hopping Type 2 with 2 sub-bands performed better than when configured with 4 sub-bands for all the SL configurations, this is partially due to the reduction of the total number of resources in the pool (from 50 RBs to 48 RBs), to create four equal sized sub-bands. Furthermore, as the number of sub-bands increases, the size of the sub-band is reduced, resulting in fewer options for the UEs to allocate their grant within any given sub-band.

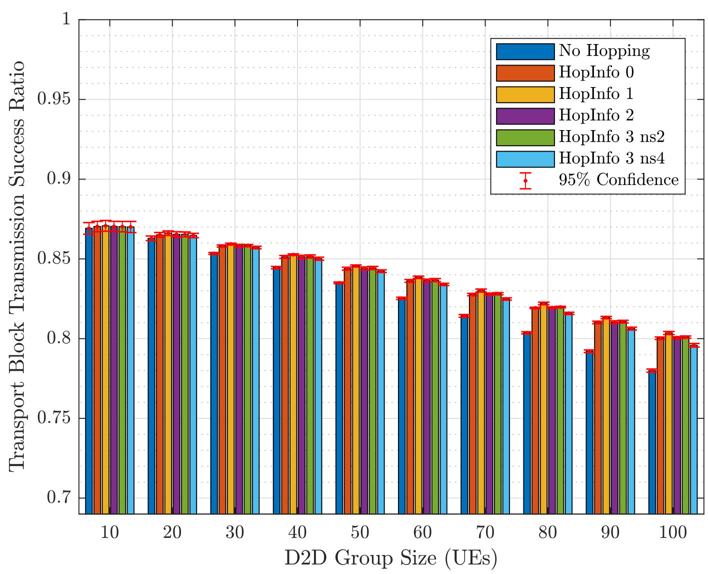

Fig. 16. Transport block success rate, MCS 18, $K_{TRP} = 1$, sidelink period 40 ms.

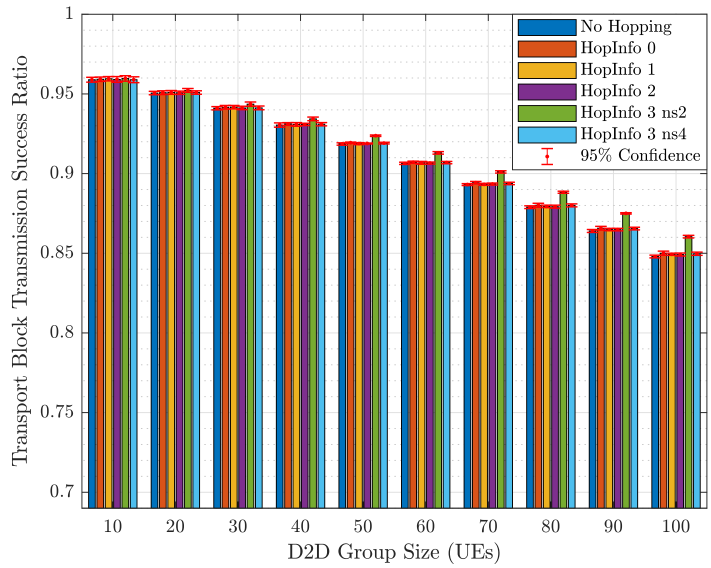

Fig. 17. Transport block success rate, MCS 10, $K_{TRP} = 2$, sidelink period 40 ms.

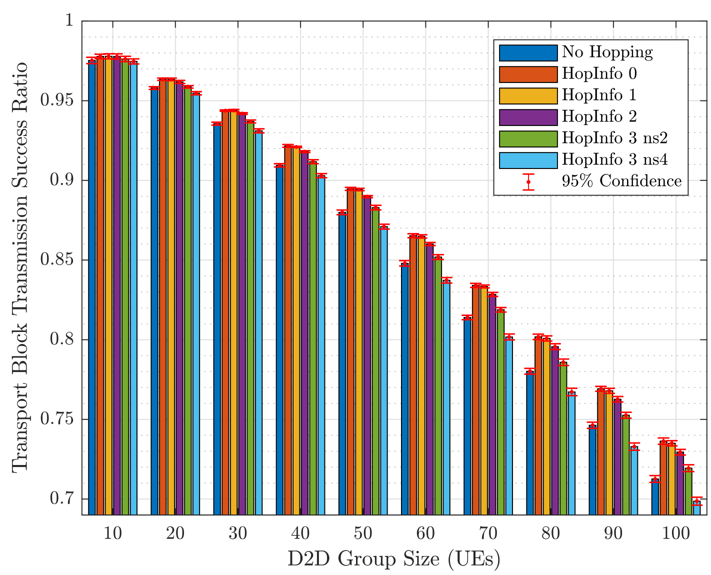

Fig. 18. Transport block success rate, MCS 6, $K_{TRP} = 4$, sidelink period 40 ms.

Another interesting observation from the TB success ratio results is how fast the performance is degraded with the increase of communicating devices. Even though a more robust MCS 6 is employed in SL configuration 1, a significant TB success ratio drop is observed in Fig. 18 for D2D group size 100, compared against the other two SL configuration results presented in Fig. 16 and 17.

To better evaluate the group communication results, consider the TB loss spurt performance on each SL configuration for D2D group size 100, presented in Figs. 19, 20, and 21. A TB loss spurt of zero corresponds to no TB loss; therefore, the values depicted in the figures correspond to the TB success ratio reported for group size 100 in the corresponding SL configuration. On the other hand, TB loss spurts greater than zero represent the number of consecutive TBs lost before a TB is successfully received. Every TB transmission-reception was considered to compute the probability mass function (PMF) of TB loss spurts. TB loss spurts with smaller occurrences than those presented in the figures are not shown for legibility purposes. From the figures, TB loss spurt values showing higher occurrences correspond to the number of TBs a SL configuration is able to transmit in a SL period, and multiples of it. In other words, consider the results obtained with SL configuration 3 (Table 3) where a $K_{TRP} = 4$ is used, resulting in 4 new TBs per period; Fig. 21 shows TB loss spurts instances are higher for values 4, 8, and 12, which are multiple of the number of TBs a single SL period is able to transmit for that SL configuration. Likewise higher TB loss spurts instances are seen in Figs. 19 and 20, corresponding to SL configurations 1 and 2, which allow 1 and 2 TBs per period, respectively.

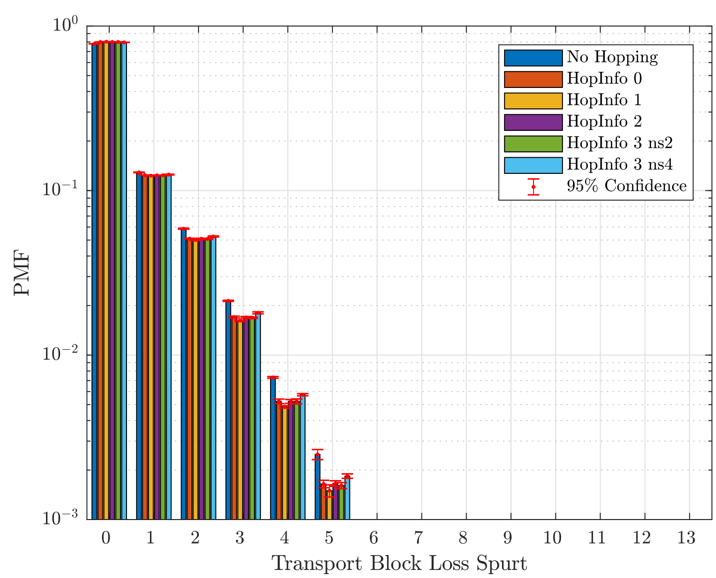

Fig. 19. Transport block loss spurt for D2D communication group size 100, MCS 18, $K_{TRP} = 1$.

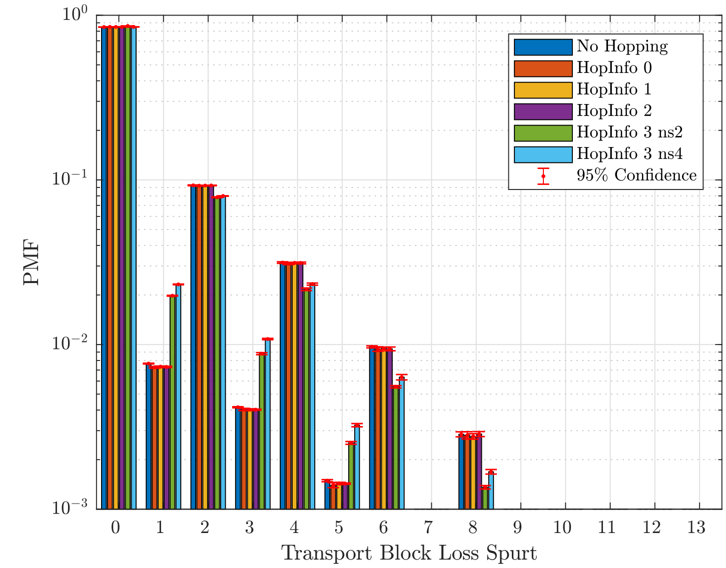

Fig. 20. Transport block loss spurt for D2D communication group size 100, MCS 10, $K_{TRP} = 2$.

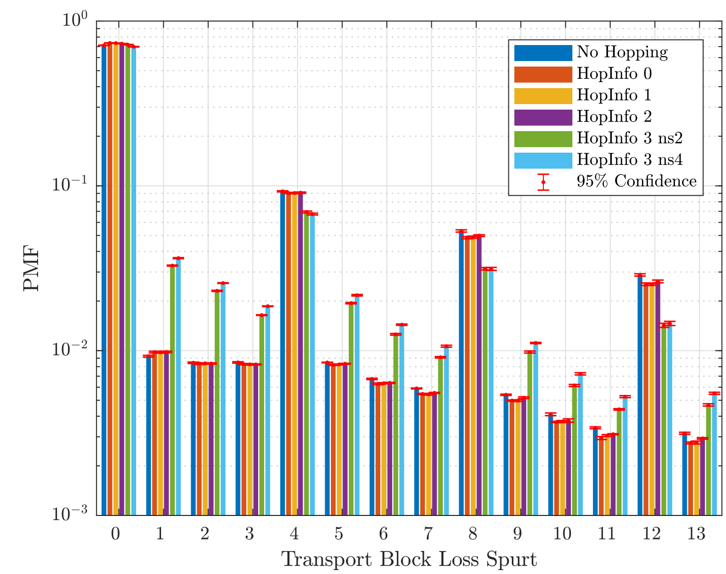

Fig. 21. Transport block loss spurt for D2D communication group size 100, MCS 6, $K_{TRP} = 4$.

These results indicate that because of the interference created from the uncoordinated nature of the resource allocation in D2D mode 2, receiving UEs can experience the loss of all the TB transmissions in a single SL period. In fact, about 10 % of the losses in all SL configurations for group size of 100 UEs correspond to the loss of all the TB transmissions in SL periods being lost. The negative impact of this is more evident in SL configuration 3, which has the highest number of TBs per period.

4. Conclusions and Final Remarks

The evaluations performed in this work showed that frequency hopping in D2D sidelink communications increases link reliability at larger communication range distances in both single link settings and in the presence of a single source random signal interferer. On the other hand, results obtained from sidelink group communication revealed a limited performance improvement when employing frequency hopping over the standard no-hopping sidelink schedule assignment. This is mainly due to sidelink mode 2 lack of resource scheduling coordination and the number of UEs simultaneously contending for communication resources. Overall, simple frequency hopping approaches, such as the constant hopping variants, proved to be beneficial for D2D communications without presenting a significant increase in computation complexity for the UEs. Constant hopping modes slightly outperformed pseudo-random hopping in most of the group communication scenarios settings, which are characterized by the high level of interference created among contending UEs. Pseudo-random hopping appears to be better fitted for the centralized resource scheduling mode of operation (mode 1) where interference is better mitigated and its computational complexity is carried by the eNBs.

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