Implementation and Validation of an LTE D2D Model for ns-3

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ABSTRACT

The ability to perform device-to-device (D2D) communication in Long Term Evolution (LTE)-based cellular networks became possible with the introduction of Proximity Services (ProSe) functionalities in the 3rd Generation Partnership Program (3GPP) specifications. In this paper, we provide a description of the ProSe implementation that extends the LTE model already available in ns-3. Our model contains key features defined in LTE Release 12 and further enhanced in LTE Release 13 related to synchronization, discovery, and communication. We also provide validation of each feature by comparing simulation results with analytical models developed as part of our work on D2D communication.

CCS CONCEPTS

• **Networks → Network performance evaluation**; **Network simulations**; **Mobile networks**;

KEYWORDS

3GPP, Long Term Evolution, Device-to-Device Communication, Network Modeling, ns-3

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1 INTRODUCTION

Direct communication between user devices is prominent in unlicensed-band technologies such as Wi-Fi and Bluetooth. Multiple network simulation platforms, including ns-3, have implementations to support the simulation and performance evaluation of such networks.

Recently, the 3rd Generation Partnership Program (3GPP) introduced Proximity Services (ProSe) [7] into Long Term Evolution (LTE), enabling direct communication between nearby User Equipment (UEs). ProSe allows for operation in both licensed (LTE uplink spectrum) and unlicensed bands. It also supports autonomous operations for out-of-coverage public safety users. The UEs transmit and receive information without going through the evolved Node B (eNodeB) in order to synchronize, discover, and communicate with each other. Various applications and services will be enhanced by the use of device-to-device (D2D) communication. Commercially, it will be used for advertising, social networking, and gaming [1] . For public safety, D2D features will help first responders overcome service degradation due to limited resources and network failures [2]. Furthermore, D2D communication enables network operators to offload certain traffic from eNodeBs and to mitigate network congestion [12].

Analytical studies have shown that LTE D2D can provide lower delays and more energy savings compared to other short-range communication technologies such as Wi-Fi [13]. D2D communication can achieve better performance in terms of capacity, throughput, power efficiency, and spectral utilization compared to the LTE infrastructure operations [2] [18] [15]. Moreover, D2D can extend coverage when an in-coverage UE acts as a relay for other out-of-coverage UEs [1]. Given its novelty and relevance, D2D communication has been recognized as one of the key components for the fifth generation (5G) mobile networks, attracting interest from both researchers and manufacturers [8].

Currently, ns-3 offers an implementation of the LTE network, which was developed by Piro et al. [14]. We extended that implementation to support LTE D2D. In [16], we introduced our model including preliminary results on D2D communication. In this paper we provide a description of the implemented functionalities including synchronization and discovery, made available on-line[1]. Furthermore, we present validation results against mathematical models for D2D discovery and communication modules.

The rest of this paper is structured as follows. In Section 2, we provide a background on LTE D2D, outlining each of its functionalities (direct communication, direct discovery, and synchronization). In Section 3, we describe the modifications made to the ns-3 LTE module to support D2D capabilities. Section 4 presents the evaluation and validation of the model. Finally, Section 5 concludes the paper.

2 BACKGROUND

In order to support LTE D2D ProSe, 3GPP defined the PC5 interface, a new direct link between UEs called "Sidelink" at the access stratum layers. ProSe-enabled UEs can use Sidelink to exchange information when they are in close proximity. Three LTE D2D functionalities are defined under ProSe: direct communication, direct discovery, and synchronization. The direct communication functionality allows the UEs to establish a communication link between them without the need of routing the data via the eNodeBs. The direct discovery functionality allows to advertise and detect useful information provided by the UEs in proximity without the need of establishing a communication link. Finally, the synchronization functionality provides the mechanisms needed by the UEs in proximity to agree

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[1] National Institute of Standards and Technology (NIST) GitHub: https://github.com/usnistgov

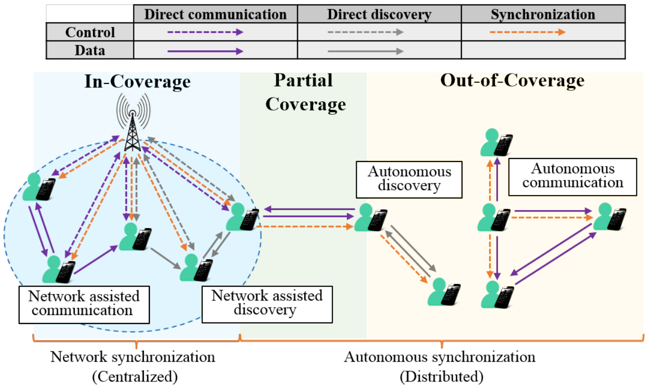

Figure 1: Overview of the LTE D2D functionalities and scenarios of operation.

on common system information and to be able to decode Sidelink transmissions.

To control the access to the D2D communication and discovery functionalities, a ProSe Function was added to the LTE core network. It is also responsible for allocating and storing discovery application identifiers (ProSe Application Code), and the processing and handling of UEs request through a new PC3 interface.

The LTE D2D functionalities can operate regardless of the network status of the UEs. Thus, three scenarios were identified by 3GPP: in-coverage, partial coverage, and out-of-coverage, as illustrated in Figure 1. When the UEs are in-coverage, the functionalities are network assisted, i.e., the UEs use the configuration and control information provided dynamically by the network, as well as preconfigured parameters. When the UEs are out-of-coverage, they rely on preconfigured parameters, enabling autonomous operations. Partial coverage, is a hybrid between the other two scenarios, in where UEs within network coverage can provide system information to out-of-coverage UEs. The following sections describe each of the LTE D2D functionalities.

2.1 Direct Communication

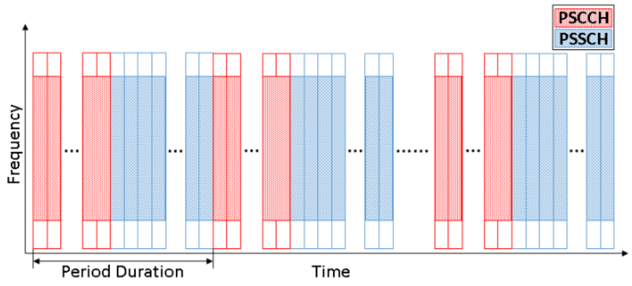

Figure 2: Sidelink communication period.

D2D communication over Sidelink is performed over periodically repeating periods in the time domain [5]. Each Sidelink period is composed of two channels spaced out in time, the Physical Sidelink Control Channel (PSCCH) and the Physical Sidelink Shared Channel (PSSCH), as depicted in Figure 2. Each channel is defined by a resource pool, i.e., a combination of certain Resource Blocks (RBs) in the frequency domain, and certain subframes in the time domain [5]. A detailed resource pool analysis for the PSCCH and its resource scheduling procedures can be found in [11].

The PSCCH is used by ProSe-enabled UEs to send a Sidelink control information (SCI) message, to indicate to who this message is addressed, how and where the data will be transmitted, i.e., the group destination ID, the modulation and coding scheme (MCS), and the PSSCH resource assignment in time and frequency, among other parameters. Each UE can be associated with one or more group IDs, and must scan through the control channel time duration to detect if another UE is going to transmit something addressed to their group. Upon successful reception of a SCI message, pertaining UEs can then proceed to tune to the corresponding resources in the PSSCH.

Transmissions in the PSSCH follow a Time Resource Pattern (TRP), which is a subframe indication bitmap of a fixed length N_{TRP} (e.g., 8 subframes) repeated through the length of PSSCH, to identify which subframes are used by a transmitting UE. Each TRP is identified by an index I_{TRP} corresponding to the predefined subframe indication bitmap established in [5]. In order to mitigate throughput degradation due to medium interference, every transmission on the PSSCH is performed with four (4) hybrid automatic repeat request (HARQ) processes without feedback. Hence, every transport block transmission on the PSSCH requires 4 subframes to be carried.

LTE Release 12 introduced two resource allocation modes, Mode 1 and Mode 2, for D2D communication. The eNodeB configures in-coverage UEs to operate on either mode, however, out-of-coverage UEs can operate only in Mode 2. In Mode 1, D2D communications are assisted by the eNodeB, i.e., resource scheduling is performed dynamically by the eNodeB. In Mode 2, UEs manage resource scheduling autonomously relying on preconfigured settings, and both, PSCCH and PSSCH, resources are selected at random from their respective resource pools.

2.2 Direct Discovery

D2D discovery, as stated in 3GPP, is a functionality that allows the detection of services and applications (e.g., gaming, social networking, advertising, etc.) offered by other UEs in close proximity [1]. It is carried independently from direct communication, as one is not required to precede the other.

D2D discovery allows discovery-enabled UEs to directly identify other neighboring discovery-enabled UEs. It can be either open or restricted depending on whether the UE needs a permission from the other discovered-to-be UE. Moreover, two models of discovery have been defined. Model A is based on an open announcement procedure where UEs broadcast information, while Model B is a request/response process used when a UE wants to ask for a certain information.

Initially, in Release 12, D2D Discovery was only supported for in-coverage scenarios for both public safety and commercial usages. However, in Release 13, 3GPP extended discovery to support out-of-coverage for public safety.

Before starting the discovery process, UEs should go through a Service Authorization and Provisioning procedure. The UE initiates the request, and the ProSe Function determines whether the UE is authorized to use ProSe direct discovery announcing (sending discovery messages), ProSe direct discovery monitoring (receiving discovery messages), or both. In the out-of-coverage case, such information is preconfigured and stored in advance in the device. Once authorized, the UEs can exchange discovery messages, called announcements [4].

The Medium Access Control (MAC) layer uses the Sidelink Discovery Channel (SL-DCH) to map the discovery message to the Physical Sidelink Discovery Channel (PSDCH). The most important component of the discovery message is the ProSe Application Code. It is allocated per announcing UE and application [3]. Another significant part related to direct discovery is the System Information Block (SIB) 19 which is transmitted by the eNodeB and provides the information about the radio resource pool where a device is allowed to announce and to monitor discovery messages [6]. ProSe enabled UEs must rely on preconfigured system information upon the absence of SIB 19.

The discovery resource pool determines the discovery period that could be up to 1024 radio frames (10.24 seconds) long. A discovery offset is defined to delay the discovery process with respect to the beginning of the period. The resource pool includes a bitmap that indicates which subframes (noted SF) could be used for discovery, and the number of times this bitmap must be reused within the discovery period. In Figure 3, SF_j represents one subframe (i.e. time slot) allocated to discovery and N_t defines the total number of such subframes.

A resource configuration for the frequency domain is also provided. It defines the total number of RBs dedicated to discovery (N_f) and the associated start and end numbers (RB_{start} and RB_{end} respectively). This allows the organization of the discovery bandwidth in clusters as shown in Figure 3 and computed in [5]. We also note that the discovery message can be retransmitted several times, with the number of retransmissions being configurable between 0 and 3 [6].

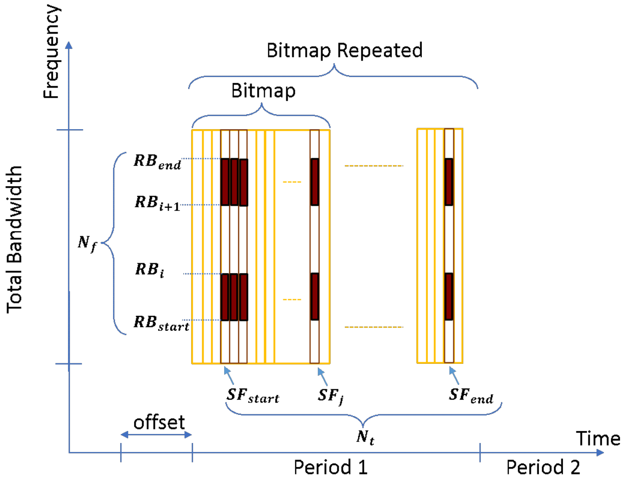

Figure 3: Resource pool configuration for discovery.

Two discovery resource allocation types are defined, Type 1 and Type 2B. In Type 1, (i.e., "UE-Selected"), UEs select independently and arbitrarily the discovery resources to transmit discovery messages. Type 2B (i.e., "Scheduled") represents a UE-dedicated resource allocation provided by the eNodeB [2].

2.3 Synchronization

In order to establish effective direct communication and discovery, UEs need to be aligned in time and frequency, and they need to agree on the same system information used in the communication procedures (e.g., bandwidth, subframe indication, etc.). Thus, two UEs attempting to communicate need to follow the same Synchronization Reference (SyncRef). If the UEs are in-coverage, their SyncRef is provided by the eNodeB and the synchronization configuration can be found inside the SIB18 and SIB19 messages for communication and discovery respectively. When the UEs are out-of-coverage, preconfigured parameters are used to initiate the synchronization process and to agree on a common SyncRef, giving priority to those originating from in-coverage UEs (e.g., partial coverage scenario), if available.

The Sidelink synchronization information transmission procedure defines when a UE should be a SyncRef and announce the synchronization information [6]. When in-coverage, the UE becomes a SyncRef if the eNodeB explicitly instructs it, or if the perceived eNodeB signal strength is below a given threshold and the UE is transmitting in the Sidelink. An out-of-coverage UE becomes a SyncRef if it is transmitting in the Sidelink and either it does not have a selected SyncRef, or the signal strength of the selected SyncRef is below a given threshold. Otherwise, the UE will cease to be a SyncRef or will not become one.

When the UE becomes a SyncRef, it periodically transmits Sidelink Synchronization Signals (SLSS) for announcing its synchronization information. An SLSS is transmitted in one subframe in the time domain and uses the central 6 RBs in the frequency domain. The periodicity of the SLSS is 40 ms, and the exact time slot is indicated by a relative subframe offset present in the synchronization configuration.

An SLSS is composed of four elements: The Primary Sidelink Synchronization Signal (PSSS), the Secondary Sidelink Synchronization Signal (SSSS), the Demodulation Reference Signals (DMRS), and the Physical Sidelink Broadcast Channel (PSBCH). The PSSS and SSSS are used for time and frequency reference; together they encode the SLSS identifier (SLSSID), which identifies the SyncRef. There is a subset of SLSSIDs reserved for identifying SyncRefs in-coverage (configured by the network) and another subset reserved for out-of-coverage use. The PSBCH carries the MasterInformationBlock-SL (MIB-SL), which contains the system level information needed for the configuration of the synchronizing UE. The DMRSs are used as a reference for channel estimation, demodulation of the PSBCH, and measurement of Sidelink Reference Signal Received Power (S-RSRP) in the receiving UE. The S-RSRP is the indicator of the SyncRef signal strength.

The UEs search for available SyncRefs, measure the S-RSRP of the detected ones if any, and synchronize to the most adequate one according to the Sidelink synchronization reference procedure. A SyncRef is considered detected if the UE has obtained its SyncRef

SLSSID and has decoded its MIB-SL. After the measurement and filtering process, a SyncRef is considered valid if its S-RSRP exceeds a predefined minimum required threshold by a given hysteresis value. The UE ranks the valid detected SyncRefs by their priority group and their S-RSRP values. The priority group is determined by their SLSSID and their network condition (in-coverage or out-of-coverage, indicated inside the MIB-SL). In-coverage SyncRefs have the highest priority, followed by out-of-coverage SyncRefs with SLSSID from in-coverage (i.e., the SyncRef is using in-coverage synchronization information even if it is out-of-coverage), and the lowest priority is for pure out-of-coverage SyncRefs.

When the UE does not have a valid selected SyncRef, it will synchronize to the SyncRef with highest priority group and strongest S-RSRP. If the UE already has a valid selected SyncRef, the UE compares it with the candidate SyncRef with the strongest S-RSRP. The UE selects the candidate SyncRef if it belongs to a higher priority group than the currently selected SyncRef, or if it belongs to the same priority group, but its S-RSRP exceeds the one of the selected SyncRef by a given threshold. Otherwise, the UE keeps the selected SyncRef. In out-of-coverage scenarios, the convergence to a unique SyncRef within a group of UEs is challenging, as it is a distributed process influenced by different parameters. The synchronization framework in our model was used in previous work to evaluate the out-of-coverage synchronization performance [9].

3 IMPLEMENTATION

In this section we describe the additions and modifications made to the ns-3 LTE module (version 3.22) to support the D2D functionalities. An overview of the changes is shown in Table 1 and detailed descriptions for each module are provided in the following subsections.

3.1 Non Access Stratum (NAS)

The functionalities of the NAS layer include Evolved Packet System (EPS) mobility management and session management by exchanging messages between the UE and the core network. Since ns-3 supports only one core, the mobility management functions are not implemented in the EpcUeNas class. Existing functionalities include the activation of EPS bearers, filtering of UL data packets, and the transmission/reception of data packets. A bearer is associated with one or several Traffic Flow Templates (TFTs) used to define the rules mapping IP packets to the right bearer based on IP addresses, ports, and type of service parameters.

For D2D communication, there is no EPS bearer setup. Thus, the model includes new functions to activate Sidelink bearers. A new type of TFT, called SlTft, maps IP packets to the Sidelink bearers based only on the IP destination address of the packets. The Send function has also been modified to allow the transmission of packets even when the state of the NAS layer is OFF to support out-of-coverage scenarios.

3.2 Radio Resource Control (RRC) Protocol

The RRC layer provides signaling between the eNodeB and the UE to perform attachment and setup radio bearers. Regarding D2D, it also contains the resource pools' configurations used for communication, discovery, and synchronization. Modifications were made to both the eNodeB side, via the LteEnbRrc class, and the UE side, via the LteUeRrc class.

On the eNodeB side, SIBs 18 and 19 were added to broadcast Sidelink resource pool configurations for communication and discovery respectively. The configuration of the resource pools is done using functions added to the LteHelper. The eNodeB is also now capable of processing SidelinkUeInformation messages sent by the UE. This type of message contains information associated with the demand and management of resources for communication and discovery, such as the identity of the destination(s) and the number of resources requested (for the "Scheduled" mode). The response is sent by the eNodeB using the RrcConnectionReconfiguration message.

Regarding the UE RRC layer, new functions were added to support the creation of Sidelink bearers and the modification (creation/removal) of discovery applications, regardless of the UE network state (in-coverage or out-of-coverage). UEs filter the received discovery messages based on the applications that they are interested in monitoring.

The extended model is also capable of processing the new SIB18 and SIB19 messages defined in the LteRrcSap class, and the dedicated Sidelink configuration received in RrcConnectionReconfiguration messages.

The synchronization protocol logic described in Section 2.3 was mainly implemented in the LteUeRrc class. The most relevant functionalities of the developed model are: the activation and deactivation of the SLSS transmission according to the Sidelink synchronization information transmission procedure, the configuration of the SLSS to be transmitted by the physical layer protocol, the reception of the SyncRefs measurement report, the selection of the SyncRef according to the Sidelink synchronization reference procedure, and the instruction to change SyncRef to the other layers.

3.3 Packet Data Convergence Protocol (PDCP)

The PDCP layer available in ns-3 already supports the Unacknowledged Mode (UM) transmission used by the Sidelink bearers. However, a logical channel within a UE can no longer be identified uniquely by its logical channel identifier (LCID). With D2D communication, UEs create new logical channels for each destination to which they are transmitting (i.e. Layer 2 group ID), assigning LCIDs independently. It is possible that multiple UEs select the same LCID for the same group so receiving UEs must identify the remote UE for which it receives packets. Therefore, the identifiers for the logical channels have been extended to include the source Layer 2 ID and destination Layer 2 ID that identify the transmitter UE and the group to which the packets must be delivered.

3.4 Radio Link Control (RLC) Protocol

The modifications made to the RLC layer, namely class LteRlc, are identical to the PDCP layer, where new identifiers were added to support Sidelink bearer identification.

3.5 Medium Access Control (MAC) Protocol

The MAC protocol is responsible for allocating radio resources. To support the scheduled mode where the eNodeB allocates resources

Table 1: Overview of the main changes and extensions introduced with the LTE D2D model implementation

ns-3 class	Direct communication	Direct Discovery	Synchronization
EpcUeNas	- Management of sidelink bearers - Transmission of packets when out-of-coverage		
LteEnbRrc	- Transmission of *SIB18* message	-Transmission of *SIB19* message	
	- Transmission of *RrcConnectionReconfigurationmessage* - Processing of *SidelinkUeInformation* message		
LteUeRrc	- Creation of sidelink bearers - Reception and processing of *SIB18* message - Transmission of *SidelinkUeInformation* message	- Creation and removal of discovery applications - Reception and processing of *SIB19* message - Filtering of discovery messages - Tracing of discovered applications	- UE synchronization status tracking - Execution of the sidelink synchronization information transmission procedure - Execution of the SyncRef selection procedure
	- Reception and processing of *RrcConnectionReconfiguration* message		
LtePdcp	- Extension of the logical channel identifiers		
LteRlc	- Extension of the bearer identifiers		
LteEnbMac	- Reception and processing of *BSR* messages (Mode 1) - Generation and transmission of traffic scheduling allocation (Mode 1)		
LteUeMac	- Generation of traffic scheduling allocation (Mode 2) - Coordination of the sidelink transmissions (Mode 1 and 2)	- Creation and scheduling of discovery messages	- Timing information updating upon synchronization
LteUePhy	- Reception of transmissions in the uplink channel - Implementation of half-duplex mode		
	- Monitoring, reception, and transmission of *SCI* messages - Coordination of the PSSCH reception according to announcement in the *SCI* messages	- Monitoring, reception, and transmission of discovery messages	- Monitoring, reception, and transmission of SLSSs - Control S-RSRP measurement and report process - Timing information updating upon synchronization
LteSpectrumPhy	- Advanced interference calculation for sidelink transmissions		
LteHarqPhy	- Integration of sidelink physical layer error models		

for the UEs transmitting on the Sidelink, the implementation modifies both the eNodeB (LteEnbMac) and the UE (LteUeMac) classes. The changes include the handling of Sidelink Buffer Status Requests (BSRs) that indicate how much D2D traffic needs to be transmitted, and the schedulers to handle the Sidelink resource allocations (i.e. Mode 1). The interface between the RRC and MAC layers has also been modified to allow the RRC layer to manage the resource pools that can be used to schedule resources. A sample scheduler based on the existing Round Robin implementation is provided in class RrSlFfMacScheduler.

To perform D2D functionalities out-of-coverage or when in-coverage but the allocation mode is UE selected (i.e. Mode 2), UEs have to handle their own resource scheduling decisions. The current implementation adds attributes to the LteUeMac to configure the number of resource blocks, subframes, and MCS to be used in each Sidelink period where a Sidelink transmission occurs. The UE MAC also receives notification from the RRC layer about changes in SyncRef. When this occurs, the MAC updates the timing information (frame and subframe references) accordingly.

The discovery messages are created in the LteUeMac using information (i.e., ProSe Application Code) configured by the LteHelper. Discovery resources are assigned via the “UE-Selected” mode based on the resource pool defined in the scenario. “Scheduled” mode is not implemented yet.

3.6 Physical Layer (PHY) Protocol

The UE physical layer has been significantly modified to support the Sidelink features. To address the need for UEs to receive transmission in the uplink channel, since the Sidelink is using the uplink frequency, the LteUePhy includes an additional instance of LteSpectrumPhy that connects to the uplink channel. Since it is difficult for a UE to send and receive at the same time on the same frequency due to self-interference, the model uses half-duplex mode on the Sidelink by default. This constraint can be removed by changing the value of the FullDuplexEnabled attribute. Information about the Sidelink and discovery resource pools have also been added to the physical layer in order to compute the boundaries of both the communication and discovery periods, to appropriately monitor the resources associated with the PSCCH, PSSCH and PSDCH, as well to perform Layer 1 filtering. The physical layer processes the SCI messages received on the PSCCH to determine when data may arrive on the PSSCH and provide the information to the LteSpectrumPhy class. Discovery and synchronization have been implemented as broadcast processes where monitoring UEs receive all messages sent of the relevant types, and pass them to the upper layers, that will perform the appropriate filtering.

The LteUePhy class was extended to handle the transmission and reception of SLSSs, the S-RSRP measurement and report, and the change of timing due to SyncRef (re)selection. In our model, the whole SLSS is represented inside the MIB-SL, which is modeled as a control message comprising all the MIB-SL fields defined in [6] plus two metadata fields: the SLSSID of the SyncRef, and a reception timestamp to emulate the time acquisition that real systems do upon detection of the PSSS and SSSS. Regarding the calculation of the S-RSRP, we use the same approach to the one already implemented in ns-3 for the downlink RSRP measurement. In case that a change of SyncRef is instructed by the RRC, the PHY updates the timing information (frame and subframe references) accordingly.

The introduction of additional physical channels for Sidelink lead to the development of physical layer error models. The LTE toolbox in Matlab was extended and the results were integrated in ns-3. A complete description of the methodology and resulting models are available in [17]. To handle the new error models, the LteHarqPhy class was also modified to store the Signal-to-Interference Noise Ratio (SINR) value of each transmission that is used as part of the soft combining process during retransmissions. Another key enhancement is the handling of collisions/interference. The LTE interference model available in ns-3 computes the SINR for each incoming transmission. Its design assumes that there is no frequency overlap between the transmissions coming from/to an eNodeB within a subframe because the eNodeB does all the scheduling. Transmissions from other eNodeB/UEs are simply considered interference. With ProSe, out-of-coverage UEs or those in "UE-selected" mode can select the same (or overlapping) resources because the allocation is uncoordinated. In order to determine which packet will be successfully decoded, the new implementation keeps track of the SINR values for each Sidelink transmission.

3.7 Channel Models

To more accurately model the propagation loss that occurs in a D2D transmission, several D2D propagation models have been implemented as specified by 3GPP [2]. They capture outdoor to outdoor (3gppOutdoorPropagationLossModel), outdoor to indoor (3gppHybridPropagationLossModel), and indoor to indoor (3gppIndoorPropagationLossModel) environments. While each model can be used individually in a scenario, another propagation model, 3gppPropagationLossModel, has also been created as a wrapper that evaluates the conditions between the transmitter and receiver (i.e. are they indoor or outdoor), and calls the appropriate model, thus supporting heterogeneous deployments.

3.8 Helpers

The LteHelper class is used to facilitate the creation of scenarios involving LTE nodes. The helper class has been updated to support all the changes presented previously, mainly regarding the creation of UE devices for which the internal structure has changed. It installs the Sidelink configuration containing the D2D resource pools and the discovery applications after being defined in the scenario. It also allows to configure the initial time references (SLSSID, and frame and subframe numbers) of a group of UEs.

4 VALIDATION

4.1 Direct Communication

4.1.1 PSCCH.

The selection of resources to transmit a SCI message over the PSCCH is performed randomly without any feedback or collision avoidance mechanism when operating in Mode 2. Given a PSCCH resource pool size (N_{PSCCH}), and the number of UEs (n_{UE}) contending to transmit, we can compute the likelihood of a collision to occur among UEs' resource selection as:

$$P_{Collision} = 1 - \binom{N_{PSCCH}}{n_{UE}} \times \frac{n_{UE}!}{{N_{PSCCH}}^{n_{UE}}} \tag{1}$$

The selection of a resource by two or more UEs operating in the same Sidelink period is considered as a collision. To validate our PSCCH model, two PSCCH pool configurations yielding 176 and 880 transmission resources, respectively, were simulated. For each configuration multiple scenarios were simulated with a fixed number of deployed UEs contending for D2D transmission, lasting 1000 Sidelink periods. The collision rate for PSCCH resource selection was evaluated against the theoretical values for each scenario. Figure 4 shows the average collision rate from the simulations, including 95 % confidence intervals, to lineup with the theoretical values. As expected, the probability of a PSCCH collision increases as the number UEs contending for pool resources increases.

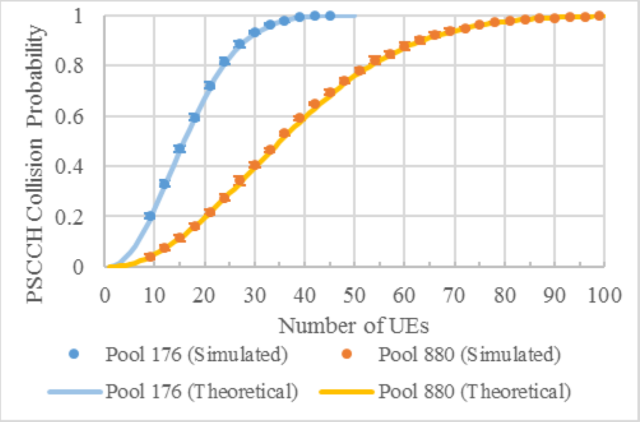

Figure 4: PSCCH resource collision validation.

4.1.2 PSSCH.

We validate the implementation of the shared channel by comparing the theoretical data rates to the ones obtained in simulations. We compute the theoretical data rate, in bit/s, for a given MCS and RB allocation as follow:

$$rate = \frac{tbSize \times \left\lfloor \frac{(period - PSCCH) \times KTRP}{8 \times N_{HARQ}} \right\rfloor}{period} \tag{2}$$

Where the tbSize is the transport block size defined in [5] (in bits), period is the duration of the Sidelink (in ms), PSCCH is the size of the control channel (in ms), KTRP is the number of active subframes in the repetition pattern, and $N_{HARQ} = 4$. In the simulation scenario, we place a transmitter and a receiver such that there is no packet loss due to the channel conditions. Three configurations, shown in Table 2, are used to validate that the model takes into account the Sidelink configurations. Figure 5 shows that the data rates obtained in simulation are perfectly matching the theoretical values for all configurations.

Table 2: Simulation parameters for PSSCH validation

Configuration	SL period (ms)	PSCCH duration (ms)	KTRP	MCS
1	40	8	2	10
2	80	8	4	12
3	320	40	8	15

4.2 Direct Discovery

In this Section, we validate the D2D direct discovery's implementation in UE-Selected mode. We compare the simulation results to the

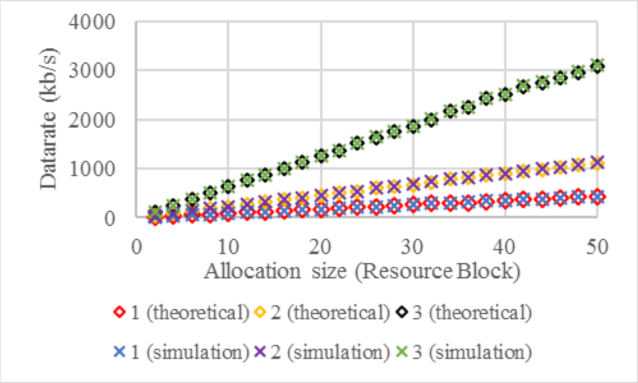

Figure 5: PSSCH data rate validation.

analytical model elaborated by Griffith et al. [10]. The mathematical study considered a group of UEs interested in both announcing their own application and monitoring everyone else's application. The exchange of discovery messages occurs using a simplistic propagation environment: all the UEs were able to detect each other and all colliding announcements (using same discovery resources) were discarded. The model also took into account the half duplex limitation where a UE could not receive any discovery message from another UE if both UEs happened to transmit announcements in the same time slot (i.e., a subframe). Under those assumptions, the time needed for a random UE to discover all other UEs in its group is computed.

In our simulations, we considered a resource pool consisting of 5 subframes and 10 pairs of resource blocks. We deployed 10 UEs, distributed randomly within an area of 100 m x 100 m. For this scenario, we performed 10 runs, with 500 trials per run. We computed the number of periods needed for one random UE to discover everyone else in the group. The average of the results collected from all the runs was used to generate the Cumulative Distribution Function (CDF) of the number of periods needed for one UE of the discovery group to discover all other UEs.

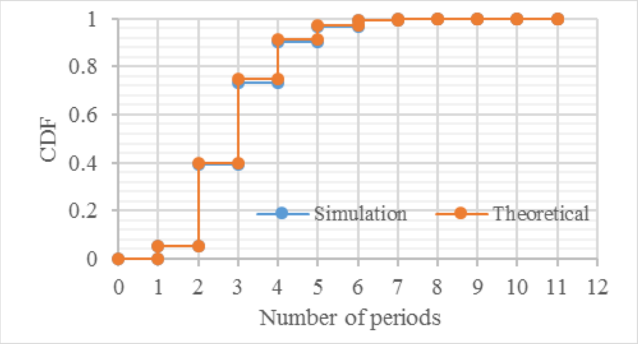

Figure 6: Number of periods needed for one random UE to discover all other UEs in the group: 50 resources and 10 UEs.

The ns-3 simulation results agree with the theoretical results as shown in Figure 6. Further resource pool configurations and group sizes had been tested in [10] and the corresponding results matched as well.

4.3 Synchronization

We tested different values of the synchronization protocol parameters in order to evaluate if the implementation follows the expected behavior. We used the outdoor uniform two ring topology described in [2] with 63 transmitter UEs, and we repeated each experiment 50 times with different random seeds. We consider all UEs out-of-coverage and unsynchronized at the beginning of the simulation. We considered two scenarios depending on the transmitter application: always-on, where the UE is sending full buffer traffic all the time; and on-off, where the transmitter is active intermittently, following the pattern for voice traffic specified in [2].

Figure 7 shows the number of SyncRef UEs in the system, along with 95 % confidence intervals, for various values of the parameter syncTxThreshOoC. This parameter is the threshold that out-of-coverage UEs use to determine if they have to become a SyncRef and transmit SLSSs. We observe that the larger the value of syncTxThreshOoC, the larger the number of UEs acting as SyncRefs. This is the expected behavior, as the range of selected SyncRef S-RSRP values causing that the UE acts a SyncRef is larger when the threshold value is larger. Given the uniform distribution of the UEs, the larger the range the more UEs detect their SyncRef within that range and act as SyncRefs.

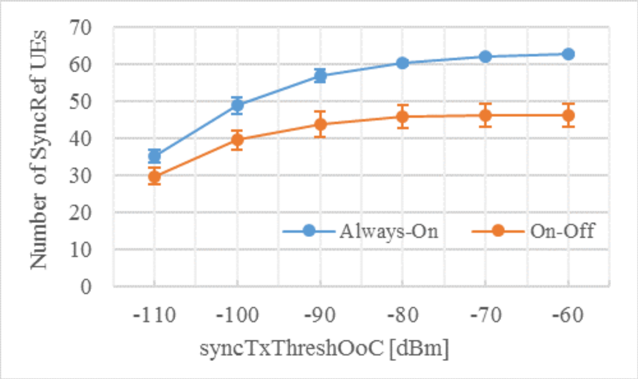

Figure 7: Number of SyncRef UEs in the scenario after 450 SyncRef selection cycles for different values of the parameter syncTxThreshOoC.

5 CONCLUSION AND FUTURE WORK

In this paper, we presented the extensions made to the ns-3 LTE implementation to support D2D synchronization, discovery, and communication as defined by ProSe. The behavior of the model has been verified using multiple scenarios, and D2D discovery and communication were validated using mathematical models. This model is being developed as part of an ongoing research in Public Safety Communications and 5G technologies. While we continue the work carried out so far, our goal in releasing the model on the NIST GitHub, is to accelerate its development, and to include new features such as relays, priority queueing, and additional transmission modes used for vehicular-to-anything (V2X).

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