Adaptive Synchronization Reference Selection for Out-Of-Coverage Proximity Services

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***Abstract*—The introduction of Proximity services (ProSe) in Long Term Evolution Advanced (LTE-A) allows User Equipments (UEs) to communicate directly without routing the data through the LTE access network. This is a major step towards supporting mission-critical communication for first responders who need the ability to communicate ubiquitously. To properly receive data, the UEs must be synchronized. Thus, reducing the synchronization delays is important to avoid service disruption. When operating outside of the network coverage, UEs cannot rely on the synchronization information provided by the base station. In such cases, a distributed protocol is required to announce and detect the synchronization information within devices in proximity. In this paper, we present an adaptive algorithm that reduces the out-of-coverage synchronization delays while meeting the requirements specified in the LTE-A standard. The algorithm takes into account the UE traffic and synchronization conditions to achieve these goals. We evaluate the algorithm performance using our ns-3 ProSe implementation and show that fast convergence time to a synchronized state can be achieved using the proposed algorithm while satisfying the standard performance constraints.**

I. Introduction

Proximity Services (ProSe) is a Long Term Evolution Advanced (LTE-A) function that was introduced in release 12. ProSe allows LTE-A User Equipments (UEs) to perform device-to-device (D2D) communication [1]. The UEs use a direct link called sidelink to transfer information between them without the need of using traditional links through a base station (downlink/uplink). ProSe is defined to work in-coverage with or without network assistance, and out-of-coverage in an autonomous way. The ability to work out-of-coverage is crucial for public safety mission-critical use cases, as it allows first responders to communicate regardless of the location of the incident or the network status [2].

UEs need to be synchronized to be able to decode the information transmitted over the sidelink. Thus, the UEs need to follow the same Synchronization Reference (SyncRef), which indicates the common timing, frequency, and system configuration to use. In-coverage UEs follow the SyncRef indicated by the network, while out-of-coverage UEs follow the SyncRef of other UEs.

Achieving fast convergence to a synchronized state within a group of out-of-coverage UEs is challenging, as the synchronization protocol is a distributed process. In this paper, we assess how the frequency of triggering the SyncRef selection algorithm impacts the convergence time. Intuitively, the more often the UEs execute the SyncRef selection algorithm, the faster the convergence is. However, there are several limiting factors.

First, the sidelink is half-duplex since it uses the same frequency for transmission and reception. The operations needed for the SyncRef selection algorithm (i.e., detection and signal strength measurement of SyncRefs in proximity) require the UE to be in reception mode. Data transmissions scheduled during these periods are preempted, as synchronization operations have priority over other ProSe functions [3]. As a result, the ProSe standard defines a maximum transmission drop rate due to SyncRef selection of 2 %, which limits the algorithm triggering frequency [4].

Second, the receiver circuitry is active during SyncRef selection. Thus, the synchronization process consumes power even when no data is transmitted. This is an important factor to consider in the implementation of the synchronization process, especially for first responder UEs used during mission-critical tasks.

The simplest synchronization scheme is to execute the SyncRef selection algorithm periodically, as is done in the LTE downlink [5]. However, we have shown that a periodic SyncRef selection scheme can lead to problems when two SyncRefs are transmitting simultaneously and continuously over time [6], although we did not address the period selection procedure nor did we consider traffic patterns other than the case of saturated UEs that transmit continuously.

In this paper, we analyze the period selection procedure considering the above mentioned constraints, which are traffic and scenario dependent. We consider on-off traffic patterns with different activity factors, and we show that a synchronization period chosen for a given activity factor may not satisfy the constraints if the traffic varies. Moreover, a period chosen for a worst-case scenario could lead to infrequent synchronization and large convergence times, which is undesirable for public safety mission-critical scenarios. To address these

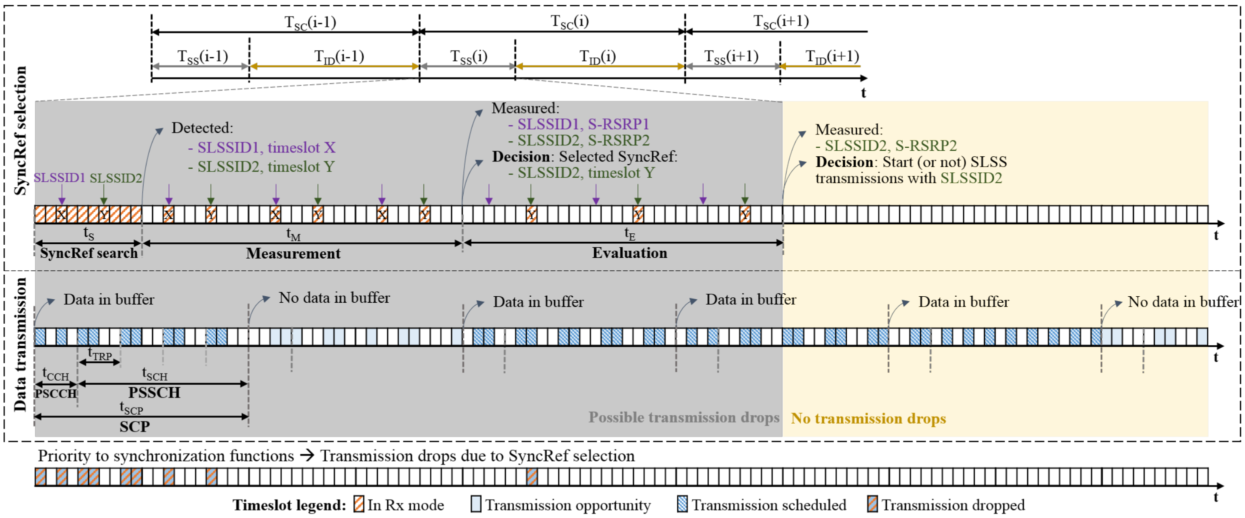

Fig. 1. System model scheme. Timeline of a UE performing SyncRef selection and sidelink communication data transmissions concurrently.

limitations, we propose an algorithm that triggers the SyncRef selection dynamically, based on the local traffic condition and configuration of each UE.

Given the novelty of ProSe, the literature related to out-of-coverage ProSe synchronization protocol is scarce. Most of the existing studies focused either on SyncRef detection procedures [7], or on the decision process required to select the adequate SyncRef after detection of multiple ones (see [6] and references therein). These studies led to the standard design and procedures explained in this paper. To the best of our knowledge, our work is the first one to focus on the SyncRef selection triggering function, which is one of the topics left to implementation by the LTE-A standardization body.

The rest of the paper is organized as follows. In Section II, we characterize the system model and in Section III, we define the problem in study. In Section IV, we describe the proposed algorithm and detail the results of the performance evaluation in Section V. Finally, we conclude the paper in Section VI.

II. System model

ProSe UEs partition time in blocks of 1 ms, called subframes (SFs). Thus, we will use the terms timeslot, SF, and ms interchangeably in this paper. We assume that during a given SF, the UE can be either in reception (Rx) mode or in transmission (Tx) mode. We assume UEs switch between modes instantaneously. We consider the evaluation period of N SFs in which the UE is performing sidelink communication and synchronization functions concurrently. We assume the UE is out-of-coverage. The notation used throughout the paper is listed in Table I.

A. Sidelink synchronization

This function comprises two concurrent processes [8]:

1) The transmission of synchronization information: where the UE advertises its synchronization information by transmitting several signals and a message [9]. From now on, we will refer to that set of elements as the Sidelink Synchronization Signal (SLSS). An SLSS has a duration of one SF and is transmitted periodically every 40 ms. The SLSS encodes an ID (SLSSID) which identifies the synchronization information being transmitted. UEs transmitting SLSSs are called SyncRef UEs and the conditions for becoming a SyncRef are dependent on the synchronization status of the UE.

2) The selection of synchronization reference: where the UE acquires the synchronization information transmitted by nearby SyncRefs and selects and synchronizes to the most suitable SyncRef. We model this process as a chain of three sub-processes. First, the UE performs a SyncRef search in which it is continuously in Rx mode during t_{S} SFs . Second, the UE measures the Sidelink Reference Signal Received Power (S-RSRP) of the SLSSs transmitted by the n_{SR} detected SyncRefs. The UE takes l samples of each SyncRef within a given period of time (t_{M}). As the SLSSs are transmitted with fixed periodicity, the UE only needs to be in Rx mode for the known corresponding SFs, as depicted in Figure 1. The UE uses the information contained in the SLSS and the S-RSRP measurements to select the most suitable SyncRef and synchronize to it. Third, the UE evaluates the selected SyncRef if any, measuring its S-RSRP for a given period of time (t_{E}). This information supports the decision process used to determine if the UE itself needs to become a SyncRef.

We denote the duration of the ith SyncRef selection process as $T_{\mathrm{SS}}(i)$, which is variable, as each sub-process is conditionally executed depending on the result of the previous sub-process. An idle period of length $T_{\mathrm{ID}}(i)$ follows the ith SyncRef selection process, in which no

TABLE I
LIST OF SYMBOLS

Symbol	Definition
t_{S}	Duration of the SyncRef search sub-process
t_{M}	Duration of the S-RSRP measurement sub-process
l	Number of S-RSRP measurement samples
t_{E}	Duration of the SyncRef evaluation sub-process
$T_{\text{SS}}(i)$	Duration of the SyncRef selection process i
$T_{\text{ID}}(i)$	Duration of the idle period after the SyncRef selection process i
$T_{\text{SC}}(i)$	Duration of the synchronization cycle i
$n_{\text{SR}}(i)$	Number of detected SyncRefs during the SyncRef selection process i
$n_{\text{RX}}(i)$	Number of SFs in Rx mode during the synchronization cycle i
Δ_{RX}^{X}	Ratio of time the UE spent in Rx mode during a given period of duration X SFs
t_{SCP}	Duration of the SCP
t_{CCH}	Duration of the PSCCH
t_{SCH}	Duration of the PSSCH
t_{TRP}	Duration on the TRP
n_{TRP}	Number of repetitions of the TRP within the PSSCH
k_{TRP}	Number of SFs available for transmission in each TRP
$n_{\text{TO}}(i)$	Number of SFs with transmission opportunities during the synchronization cycle i
$n_{\text{TS}}(i)$	Number of SFs with scheduled transmissions during the synchronization cycle i
$\beta_{\text{TX}}(i)$	Ratio of transmission opportunities with scheduled transmissions during the synchronization cycle i
$n_{\text{DR}}(i)$	Number of SFs with dropped transmission during the synchronization cycle i
$\beta_{\text{DR}}(i)$	Ratio of SFs with dropped transmissions during the synchronization cycle i
Δ_{DR}^{X}	Transmission drop rate for a given period of duration X SFs
γ	Maximum ratio of time the UE is allowed to be in Rx mode due to the synchronization function
δ	Maximum allowed transmission drop rate
T	Length of the synchronization cycles when using periodic SyncRef selection triggering algorithm
T_{RX}	Feasible T satisfying the constraint in the time in Rx mode
T_{DR}	Feasible T satisfying the transmission drop rate constraint
E_i	Duration of the estimation period for the adaptive SyncRef selection triggering algorithm
C_i	Duration of the calculation period for the adaptive SyncRef selection triggering algorithm
$n_{\text{TS}}^{\text{ID}}(i)$	Number of SFs with scheduled transmissions during the idle period of the synchronization cycle i
$n_{\text{TS}}^{\text{SS}}(i)$	Number of SFs with scheduled transmissions during the SyncRef selection i

synchronization operations requiring the UE to be in Rx mode are performed. The ith synchronization cycle, of duration $T_{\text{SC}}(i)$, is the period comprising the SyncRef selection i and the corresponding idle period.

During the ith synchronization cycle, the UE spends $n_{\text{RX}}(i)$ SFs in Rx mode. We assume one SF per S-RSRP measurement sample for the measurement and evaluation sub-processes. Thus, $n_{\text{RX}}(i)$ is given by:

$$n_{\text{RX}}(i) = t_{\text{S}} + n_{\text{SR}}(i) \times l + l. \tag{1}$$

For a given evaluation period of N SFs in which m synchronization cycles occurred, the fraction of time the UE spent in Rx mode (Δ_{RX}^{N}) is

$$\Delta_{\text{RX}}^{N} = \frac{1}{N} \sum_{i=1}^{m} n_{\text{RX}}(i). \tag{2}$$

The LTE-A standard defines some parameters and constraints related to the SyncRef selection process [4]. First, the UE should be able to identify newly detectable SyncRef UEs within 20 s, thus, the SyncRef selection process should be executed at least once every 20 s. Second, it provides the values for the measurement and evaluation period length, i.e., t_{M} = 400 ms and t_{E} = 800 ms. Third, the UE should be able to measure up to six (6) SyncRef in each SyncRef selection process. Last, the UE can drop a maximum of 2 % of its sidelink communication transmissions at the physical layer for the purpose of SyncRef UE selection within a 20 s period.

B. Sidelink communication

The sidelink communication function is performed over periodically repeating Sidelink Communication Periods (SCPs) of duration t_{SCP} [10]. Each SCP is composed of two channels: the Physical Sidelink Control Channel (PSCCH) of duration t_{CCH} and the Physical Sidelink Shared Channel (PSSCH) of duration t_{SCH}. When the UE has data to transmit, it uses the PSCCH to send the Sidelink Control Information (SCI) message, and the PSSCH to send the data. The SCI contains the information needed by receiving UEs to decode the data in the PSSCH if it is intended for them: the data destination, the modulation and coding scheme (MCS), and the PSSCH resource assignment in time and frequency, among other parameters.

The SCI message is sent twice in the PSCCH and the resource assignment is done randomly, i.e., the used SFs and Resource Blocks (RBs) vary from one SCP to another. The data is allocated in the PSSCH following a Time Resource Pattern (TRP), which is a SF indication bitmap of fixed length t_{TRP}, and that is repeated n_{TRP} times during the PSSCH, where $n_{\text{TRP}} = \lfloor \frac{t_{\text{SCH}}}{t_{\text{TRP}}} \rfloor$. Each TRP has k_{TRP} SFs available for transmission, and the set of TRPs to be used is defined in [10]. For each SCP, the UE randomly selects the TRP to use as well as the RBs within each SF of the TRP [11].

We denote as $n_{\text{TO}}(i)$ the number of SFs with transmission opportunities the UE has during the synchronization cycle i. The parameter $n_{\text{TO}}(i)$ is calculated using Eq. (3), given that two transmissions are needed for the PSCCH and that the k_{TRP} transmissions are repeated n_{TRP} times in the PSSCH.

$$n_{\text{TO}}(i) = \frac{T_{\text{SC}}(i)}{t_{\text{SCP}}} (2 + n_{\text{TRP}}\, k_{\text{TRP}}). \tag{3}$$

We assume the UE will use all the transmission opportunities within a SCP if it has data to transmit. However, if the UE does not have data to transmit at the beginning of a given SCP, the transmission opportunities within that SCP are not used, and these timeslots are free to be used to perform other operations. We denote as $n_{\text{TS}}(i)$ the number of timeslots in which the UE scheduled a transmission during the synchronization cycle i. Thus, $n_{\text{TS}}(i)$ is given by Eq. (4), where $\beta_{\text{TX}}(i)$ is the ratio of transmission opportunities the UE intended to use to perform transmissions within the synchronization cycle i. The parameter $\beta_{\text{TX}}(i)$ characterizes the traffic pattern of the transmitting UE, as it is an indication of the ratio of time the UE has data to transmit.

$$n_{\text{TS}}(i) = \beta_{\text{TX}}(i)\, n_{\text{TO}}(i). \tag{4}$$

C. Transmission drops due to SyncRef selection

We denote as $n_{\text{DR}}(i)$ the number of timeslots in which the UE drops a transmission during the ith synchronization cycle. This implies that transmissions were scheduled for these SFs, but the UE was in Rx mode performing operations associated to the SyncRef selection. Nevertheless, the UE does not drop transmissions every time it is in Rx mode for synchronization purposes, as can be seen in Figure 1. The specific SFs in which the UE is in Rx mode during a SyncRef selection process depend on external factors to the UE, e.g., number of SyncRefs in proximity and their timing. The specific SFs where the UE schedules its communication transmissions depend on random processes, e.g., selection of TRP and PSCCH timeslots. We define $\beta_{\text{DR}}(i)$ to be the fraction of SFs during the ith SyncRef selection in which the UE was in Rx mode and a transmission drop occurred. Thus,

$$n_{\text{DR}}(i) = \beta_{\text{DR}}(i)\, n_{\text{RX}}(i). \tag{5}$$

Furthermore, the transmission drop rate for the evaluation period of N SFs (Δ^{N}_{DR}) in which m synchronization cycles occurred is

$$\Delta^{N}_{\text{DR}} = \frac{\sum_{i=1}^{m} n_{\text{DR}}(i)}{\sum_{i=1}^{m} n_{\text{TS}}(i)}. \tag{6}$$

D. System constraints

The length of the synchronization cycles occurring during the evaluation period of N SFs should be chosen to guarantee Eq. (7) and Eq. (8) for that period. The parameter γ is the maximum fraction of time the UE is allowed to be in Rx mode due to the synchronization function, and δ is the maximum allowed transmission drop rate.

$$\Delta^{N}_{\text{RX}} \le \gamma. \tag{7}$$

$$\Delta^{N}_{\text{DR}} \le \delta. \tag{8}$$

For the rest of the paper we will use δ = 0.02 and $N = 20\,000$ ms (20 s) in order to align with the LTE-A standard requirements mentioned in Section II-A2. The fraction of time spent in Rx mode, γ, is an indicator of the maximum power that the UE can allot to the SyncRef selection process, since the UE must expend power to actively listen for SyncRef signals and to do the computations to determine which SyncRef to follow.

TABLE II
EVALUATION PARAMETERS

	Param.	Value		Param.	Value
Eval. period	N (ms)	20000	**Sidelink comm.**	t_{SCP} (ms)	40
SyncRef selection	t_{S} (ms)	40		t_{CCH} (ms)	8
	t_{M} (ms)	400		t_{SCH} (ms)	32
	t_{E} (ms)	800		t_{TRP} (ms)	8
	l	4		k_{TRP}	2

At present, the standard does not give a value for γ, so we consider several values in this paper.

III. PROBLEM FORMULATION

When using a periodic algorithm to trigger the SyncRef selection process, all the synchronization cycles have the same length T, namely, $T_{\text{SC}}(1) = T_{\text{SC}}(2) = ... = T_{\text{SC}}(m) = T$. The selection of T is critical in order to satisfy Eq. (7) and Eq. (8) because it determines the number of SyncRef selection processes to be executed within an evaluation period. This selection is challenging as the values of Δ^{N}_{RX} and Δ^{N}_{DR} are dependent on multiple variable factors. However, it is possible to estimate a set of possible values for T that satisfy the constraints in worst case conditions.

For a fixed period T, the number of synchronization cycles within an evaluation period of N SFs is given by $m = \frac{N}{T}$. By grouping Equations (1) – (8), and assuming that all the synchronization cycles in the evaluation period are identical and that the UE detects the maximum allowed number of SyncRefs each time ($n_{\text{SR}} = 6$), we find expressions for:

- The values of T satisfying Eq. (7):

$$T_{\text{RX}} \ge \frac{(t_{\text{S}} + 6\,l + l)}{\gamma}. \tag{9}$$

- The values of T satisfying Eq. (8):

$$T_{\text{DR}} \ge \frac{\beta_{\text{DR}}\,(t_{\text{S}} + 6\,l + l)\, t_{\text{SCP}}}{\beta_{\text{TX}}\,(2 + n_{\text{TRP}}\, k_{\text{TRP}})\,\delta}. \tag{10}$$

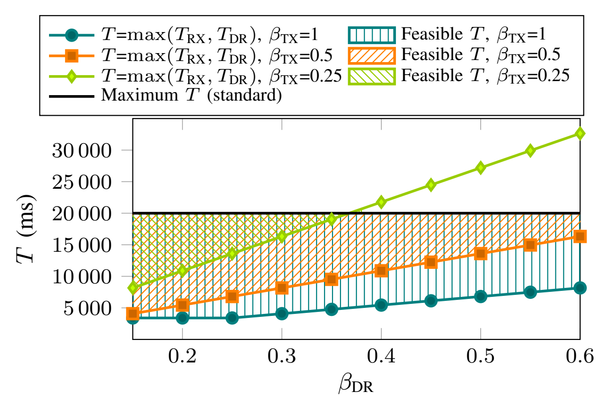

Fig. 2. Feasible values of the synchronization cycle length for the periodic SyncRef selection triggering, considering different traffic intensities (β_{TX}) and ratio of transmission drops (β_{DR}). Constraints: δ = 0.02 and γ = 0.02.

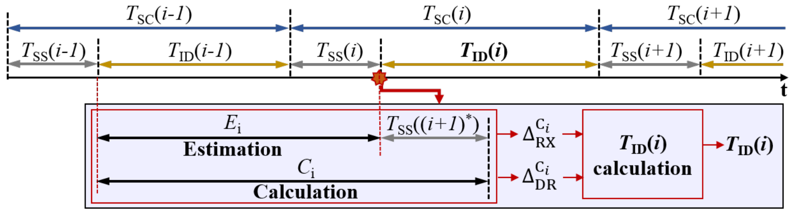

Fig. 3. Proposed adaptive SyncRef selection triggering algorithm.

Thus, one should choose T to satisfy Eq. (11), which considers both constraints and $T < 20$ s (Section II-A2).

$$\max(T_{\text{RX}}, T_{\text{DR}}) \leq T \leq 20\,000 \text{ ms}. \tag{11}$$

Figure 2 shows feasible values for the period T for different values of activity factors β_{TX} and transmission drops β_{DR} using the parameters in Table II. We display only the possible values for β_{DR} given that configuration. We see that the set of feasible values for T decreases with β_{TX}, but most importantly, we can see that there is no feasible T for $\beta_{\text{TX}} = 0.25$ when $\beta_{\text{DR}} > 0.37$. This implies that a single fixed value of T is not able to guarantee that the SyncRef selection algorithm will satisfy the required performance constraints for all situations.

To achieve fast convergence in the distributed out-of-coverage synchronization algorithm, T should be as small as possible to increase the frequency of SyncRef selection. Choosing T following a worst case scenario for a given value of β_{TX} is inefficient for larger values of β_{TX}, as T is unnecessarily large. For example, in the worst case ($\beta_{\text{DR}} = 0.6$), the minimum feasible value is $T = 16\,320$ ms for $\beta_{\text{TX}} = 0.5$, which is double the needed T for $\beta_{\text{TX}} = 1$ ($T = 8\,160$ ms). Moreover, the values of n_{SR}, β_{TX}, and β_{DR} vary from one SyncRef selection to another, making a worst case T selection even more inefficient. To overcome those limitations, we propose an algorithm that makes the value of T variable, adjusting it depending on the conditions experienced by the UE.

IV. Proposed proactive algorithm

We developed an adaptive SyncRef selection triggering algorithm, whose objective is to reduce the convergence time by triggering the selection process as soon as possible. This is done while respecting the constraints of time allowed in receiving state (Eq. (7)) and maximum packet drop rate (Eq. (8)) for every evaluation period. Thus, the length of the synchronization cycles (T_{SC}) varies depending on the UE conditions. A schematic representation of the proposed algorithm is presented in Figure 3 and described in this section.

The proposed algorithm estimates the suitable duration for the synchronization cycle in progress ($T_{\text{SC}}(i)$). To do so, it calculates the value of $T_{\text{ID}}(i)$ at the end of the current SyncRef selection process as can be seen in Figure 3.

The UE uses two sets of information:

- The data collected for the proactive *estimation period* of duration $E_i = T_{\text{ID}}(i-1) + T_{\text{SS}}(i)$, which comprises the idle period of the previous synchronization cycle, and the current SyncRef selection. The data includes the amount of time spent in Rx mode and the number of transmission drops.
- A prediction of the information for the next SyncRef selection, denoted as $(i+1)^*$, with a duration $T_{\text{SS}}((i+1)^*)$. We consider two predictions: a strict (S) prediction that assumes the worst case scenario for the next SyncRef selection (e.g., $n_{\text{SR}} = 6$, selection of a SyncRef and $\beta_{\text{DR}} = 1$); and a historical (H) prediction that assumes the next process will be similar to the one that occurred during the estimation period.

Using this information, the UE calculates the fraction of time in Rx mode and the transmission drop rate for the proactive *calculation period* of duration $C_i = E_i + T_{\text{SS}}((i+1)^*)$, namely $\Delta_{\text{RX}}^{\text{C}_i}$ and $\Delta_{\text{DR}}^{\text{C}_i}$, using Eq. (12) and Eq. (13) respectively.

$$\Delta_{\text{RX}}^{\text{C}_i} = \frac{n_{\text{RX}}(i) + n_{\text{RX}}((i+1)^*)}{C_i}. \tag{12}$$

$$\Delta_{\text{DR}}^{\text{C}_i} = \frac{n_{\text{DR}}(i) + n_{\text{DR}}((i+1)^*)}{n_{\text{TS}}^{\text{ID}}(i-1) + n_{\text{TS}}^{\text{SS}}(i) + n_{\text{TS}}^{\text{SS}}((i+1)^*)}. \tag{13}$$

The denominator of Eq. (13) is composed of the scheduled transmissions during the calculation period, i.e., during the previous idle period ($n_{\text{TS}}^{\text{ID}}(i-1)$) and SyncRef selection ($n_{\text{TS}}^{\text{SS}}(i)$), and the prediction for the next SynRef selection ($n_{\text{TS}}^{\text{SS}}((i+1)^*)$).

Next, the UE estimates $T_{\text{ID}}(i)$ relative to the previous idle period using Eq. (14). Thus, $T_{\text{ID}}(i)$ increases compared to $T_{\text{ID}}(i-1)$ if any of the constraints are not met during the calculation period, and is reduced otherwise.

$$T_{\text{ID}}(i) = \max\left(\frac{\Delta_{\text{RX}}^{\text{C}_i}}{\gamma} T_{\text{ID}}(i-1), \frac{\Delta_{\text{DR}}^{\text{C}_i}}{\delta} T_{\text{ID}}(i-1)\right). \tag{14}$$

Finally, the UE sets a timer $T_{\text{ID}}(i)$ and performs the $(i+1)$st SyncRef selection upon its expiration.

V. Evaluation

In previous work, we extended the LTE module of the ns-3 simulation platform [12] to consider ProSe functionalities [13]. The following evaluation was performed using this implementation.

A. Configuration

We considered 24 out-of-coverage UEs in proximity in a broadcast scenario. Half of the UEs transmit data to the group, and the other half is silent but receives the transmitted data. Each UE was configured with a different random SLSSID, frame, and subframe number at the beginning of each simulation, creating an initially non-synchronized environment. The convergence time is defined as the time required for all UEs to acquire the same synchronization parameters. We used the parameters in Table II for the configuration of the sidelink communication and SyncRef selection.

The transmitter UEs followed an on-off traffic pattern with On and Off periods exponentially distributed with mean μ_{ON} and μ_{OFF} respectively. We set $\mu_{\text{ON}} = 2.5\,\text{s}$, and we varied μ_{OFF} to evaluate scenarios with different TAF[1]. The periodic algorithms were worst-case configured ($\beta_{\text{DR}} = 0.6$ and $\beta_{\text{TX}} = \text{TAF}$). The adaptive algorithm was configured with $\delta = 0.02$. Both types of prediction, strict (S) and historical (H), were tested for the proposed proactive (Pro) algorithm. The simulation time was 1000 s and each configuration was simulated 150 times using different random seeds.

For all evaluations, we monitored the fraction of time in Rx mode ($\Delta^{20\text{s}}_{\text{RX}}(i,t)$) and the transmission drop rate ($\Delta^{20\text{s}}_{\text{DR}}(i,t)$) for each UE i and for each monitoring period of 20 s in the simulation. To this purpose, we use a monitoring sliding window of 20 s length, advancing every 1 ms.

B. Results

The results presented in this section correspond to the scenario with TAF = 50 %, unless otherwise stated. Similar trends were observed for the other scenarios, and figures are omitted due to lack of space.

We observe that the adaptive algorithm is able to reduce the convergence time of the scenarios while satisfying the system constraints in most of the monitoring periods, as shown in Table III and Figure 4. Table III shows the percentage of monitoring period instances in the whole evaluation that do not satisfy the transmission drop rate constraint. These cases are observed because a monitoring window containing part of a SyncRef selection process with transmission drops, and sliding from a period with successful transmissions to a period without any transmission, will exhibit an increased transmission drop rate for that monitoring

[1]The Traffic Activity Factor (TAF) denotes the average fraction of time the UE is transmitting, and it is calculated as $\text{TAF} = \frac{\mu_{\text{ON}}}{\mu_{\text{ON}}+\mu_{\text{OFF}}}$.

TABLE III

Percentage of monitoring periods where $\Delta^{20\text{s}}_{\text{DR}}(i,t) > \delta$, considering all transmitters in all simulations

			Scenario	
			TAF = 75 %	TAF = 50 %
Algorithm	Fix		0	0.0033
	γ = 0.02	Pro S	0	0.0019
		Pro H	0.0004	0.0390
	γ = 0.12	Pro S	0	0.0025
		Pro H	0.0063	0.4573
	γ = 0.24	Pro S	0	0.0016
		Pro H	0.0068	0.4536
	γ = 1.00	Pro S	0	0.0010
		Pro H	0.0550	0.4538

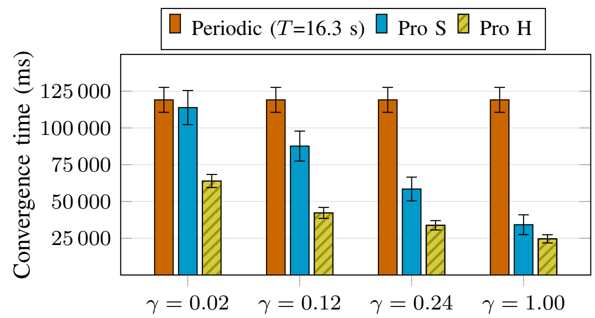

Fig. 4. Convergence time. Average with 95% confidence interval are shown.

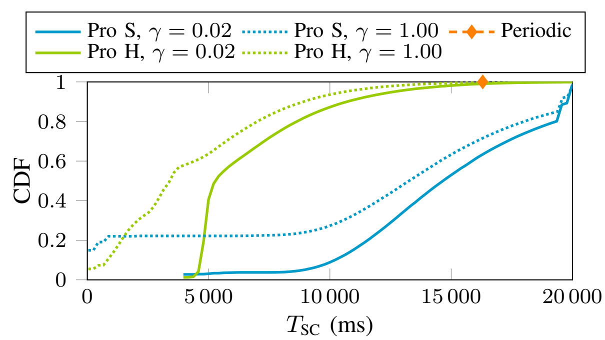

Fig. 5. Cumulative distribution function of the length of the synchronization cycles (T_{SC}) for the transmitter UEs.

period. This is confirmed by the increase of such cases when the transmitters have larger off periods, i.e., with smaller TAF. However, we see that all the values in Table III are below 1 %, which represents very good performance considering the granularity of the monitoring.

For all the scenarios and configurations considered, $\Delta^{20\text{s}}_{\text{RX}}(i,t) < \gamma$ for all UEs. The length of the synchronization cycles is mostly influenced by the constraint in the transmission drop rate for the transmitters, which is stricter. For the receivers, there is no large variation in the time spent in Rx mode between consecutive synchronization cycles, which indicates that the proactive algorithm can easily adapt to respect the constraint.

A larger γ allows us to perform the SyncRef selection more often in periods of low transmission drop rate or

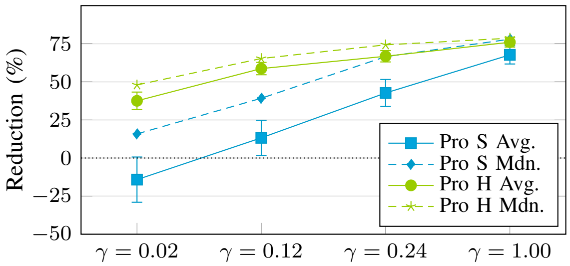

Fig. 6. Percentage of reduction in the convergence time regarding the periodic algorithm. Average with 95% confidence interval and median are shown.

when transmitters are in off periods. This is reflected in Figure 5, where we observe larger proportion of smaller synchronization cycles with $\gamma = 1.00$ than with $\gamma = 0.02$. Thus, the transmitters synchronize faster and the receivers react faster to these SyncRef changes when the algorithms are configured with larger γ, which reduces the convergence time as can be seen in Figure 4.

As expected, the strict prediction handles sudden increases in the transmission drop rate better than its historical counterpart. This is reflected by fewer cases in which $\Delta_{\text{DR}}^{20\text{s}}(i,t) > \delta$ for the strict algorithm (Table III). However, the strict criterion provides less flexibility and the reductions in convergence time are smaller than when using historical prediction. The performance gap decreases when γ increases, as larger γ increases performance by acting in the off or low transmission drop periods, balancing the transmission drops in the predictions as shown in Figure 4.

Although the adaptive algorithm reduces the average convergence time, it did not produce an improvement in all cases. Figure 6 depicts the percentage of convergence time reduction of the proactive algorithm compared to the periodic algorithm. It is calculated per simulation, i.e., it compares the algorithms under the same initial conditions. From Figure 6, we observe that the average value is below the median value for all of the cases, which reflects the influence of few cases with small reductions or even increases (negative reductions) in the convergence time. A good example can be seen for the algorithm with strict prediction and $\gamma = 0.02$. However, the central tendency is better represented by the median in this case, and, since it is positive, it highlights the overall performance gain achieved by the adaptive algorithm.

A configuration with $\gamma = 1.00$ allows UEs to be in Rx mode all the time, yet this was never the case in our evaluation. UEs were always able to detect SyncRefs and were in Rx mode during only a fraction of the measurement and evaluation periods for performing the S-RSRP sampling. The maximum value for the fraction of time in Rx mode attained by the UEs in our evaluation was 14.7 %. This value will be greater if the UEs cannot detect any SyncRef and are constantly performing the SyncRef search. Thus, adapting the value of γ depending on the UE conditions is crucial to control power consumption, e.g., $\gamma = 1.00$ when detecting multiple SyncRefs to ensure fast convergence, and reducing its value when convergence is achieved or when no SyncRef is detected in order to preserve battery charge.

VI. Conclusion

In this paper, we studied the synchronization protocol used by out-of-coverage ProSe-enabled UEs, such as those that will be used by first responders. We showed that choosing a fixed period for triggering the synchronization reference selection can be challenging and inefficient if constraints in the transmission drop rate and the time in reception mode are considered. We proposed an algorithm that reduces the synchronization delays by adapting the time to trigger the process depending on the local conditions of each UE. We evaluated the efficiency of the algorithms using system level simulations and we pointed out the trade-offs that should be considered to achieve a given level of performance and satisfy the LTE-A standard requirements.

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