Impact of timing on the Proximity Services (ProSe) synchronization function

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***Abstract*—Long Term Evolution Advanced (LTE-A) introduces a new feature called Proximity Services (ProSe) that enables device-to-device (D2D) communication between User Equipment (UE), including the capability to operate out-of-coverage. In order to establish a D2D communication link the UEs need to be synchronized. In out-of-coverage scenarios, the synchronization is performed in a distributed manner by the UEs. In this paper, we studied problems associated with the simultaneous execution of the synchronization procedure by LTE-A D2D-enabled UEs operating out-of-coverage. In particular, we focused on detection and convergence problems resulting from the half-duplex constraint and periodic scheduling. We showed that if two transmitter UEs are acting as synchronization references and they perform the procedure too close in time, convergence to a synchronized state is not possible. Moreover, the periodic triggering of the procedure will make the problematic condition persistent in time. We proposed an effective algorithm that prevent these problems, or resolve them in a reasonable time. We considered the protocol and requirements specified in the LTE-A standard, and we evaluated the performance of the proposed algorithm using system level simulations.**

I. INTRODUCTION

One new feature introduced by Long Term Evolution Advanced (LTE-A) is called Proximity Services (ProSe) [1]. ProSe enables device-to-device (D2D) communication between User Equipment (UE) via a direct link that has been given the term 'sidelink'. Additionally, the UEs can perform D2D communication in out-of-coverage conditions, i.e., without being attached to and controlled by an Evolved Node B (eNB). This is of vital importance for public safety uses [2], e.g., in emergencies or natural disasters causing network outage, or in mission critical interventions.

Most of the sidelink synchronization elements and procedures were derived from the LTE-A downlink design [3]. Each UE acting as a Synchronization Reference (SyncRef) transmits its synchronization information, which comprises several signals for frequency and time synchronization, and one information element containing system level information for further configuration.

Unlike an eNB, an out-of-coverage UE only acts as a SyncRef when transmitting on the sidelink [4]. Depending on the traffic pattern, a UE may transmit synchronization information only intermittently. Thus, a UE performing synchronization acquisition for a given period will only detect the SyncRef UEs that are actively transmitting during this period.

D2D-capable UEs use the same sidelink channel to transmit and receive. Given the half-duplex constraint, the UE has to switch between transmission and reception modes in order to avoid self-interference. This affects the synchronization process in the sense that a UE may not be able to perform the synchronization acquisition procedure and transmit data or its own synchronization signals at the same time. Thus, manufacturers need to design their synchronization procedures to be able to ensure a minimum level of synchronization performance while limiting the transmission drops.

A UE may perform downlink cell search for synchronization periodically, i.e., at regular intervals of time [5]. This is adequate, as the eNBs will persistently transmit the synchronization signals and information elements, and new cells will become available only due to UE mobility. In the D2D case, the UEs need to detect other UEs that are performing the same procedures in parallel. Moreover, UEs that are out-of-coverage rely only on preconfigured operational parameters, as there is no network coordination.

In this paper, we show that a periodic execution of the synchronization procedure in the out-of-coverage scenario can lead to SyncRef detection problems or a SyncRef ping-pong effect. The first issue occurs when two SyncRefs cannot detect each other because their synchronization procedures overlap in time, and the timely transmission and detection of each others synchronization signals is not possible. The second issue occurs when two SyncRefs are able to detect each other, but the synchronization executions are aligned in time such that each UE cannot perceive the change of condition of the other before making a synchronization decision. This will cause the SyncRefs to constantly synchronize to each other without converging to a single shared synchronization.

The rest of the paper is organized as follows. In Section II we provide a brief overview of the related literature. The sidelink synchronization procedure in out-of-coverage scenarios is described in Section III. In Section IV we define the system model and describe the identified problems. In Section V, we propose a strategy to cope with these problems, which is supported by the system level evaluation we present in Section VI. Section VII concludes the paper.

II. RELATED WORK

The LTE-A standard is specified by the 3rd Generation Partnership Project (3GPP). The sidelink synchronization signal design agreed by 3GPP is specified in [6], and Cannon et al. provide a comprehensive description in [3]. A UE should detect and successfully decode synchronization signals while

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satisfying the performance requirements defined by 3GPP. However, the receiver design is left to UE implementation, and much of the sidelink synchronization literature focuses on the design of optimal receivers that satisfy these 3GPP requirements, e.g., [7] and references therein.

After a UE has detected one or more synchronization signals and identified one or more SyncRefs, it should synchronize to the most convenient one. Prior to the standardization agreements, several criteria were proposed in the literature for deciding which SyncRef is the most convenient. For example, Fodor et al. [8] proposed to use a weighting function that combines the device characteristics such as transmit power, battery level, network coverage and mobility as the metric used for the SyncRef decisions. Abedini et al. [9] proposed two approaches. If in-network synchronization information is detected, the metric is the number of hops away from the in-network SyncRef, so that the UE selects the SyncRef that is closer to the operated network. In the out-of-coverage case, the proposed metric is the age of the synchronization acquisition, and the UE selects the oldest synchronization information.

Finally, the synchronization protocol agreed by 3GPP defines three priorities based on the network coverage condition of the SyncRef. The highest priority goes to in-network SyncRefs, followed by out-of-coverage SyncRef at one hop of the network, and the lowest priority corresponds to fully out-of-coverage SyncRefs. The perceived signal strength is used as a tie-breaker between SyncRefs having the same priority [4].

How often a UE should look for, detect, and select an adequate SyncRef is left to UE implementation. However, 3GPP defines some related performance requirements the UE should meet [10]. To the best of our knowledge, our work is the first one to focus on problems related to the scheduling of the sidelink synchronization protocol, while considering the 3GPP specifications and performance requirements, which we explain in the next section.

III. SIDELINK SYNCHRONIZATION IN OUT-OF-COVERAGE SCENARIO

The out-of-coverage synchronization procedure comprises two different but related operations that the UE needs to perform. The first operation is related to the transmission of synchronization information. The UE needs to verify whether it has to become a SyncRef or not, and if so, which information it should broadcast and when. This operation is explained in Section III-A. The second operation is related to the acquisition of synchronization information. The UE needs to search for available SyncRefs and in case multiple SyncRefs are available, the UE needs to select the best one and synchronize to it. This operation is explained in Section III-B.

A. Sidelink synchronization information transmission

The decision of becoming a SyncRef depends on whether the UE has a selected SyncRef, i.e., the UE is synchronized to another transmitting UE and receiving synchronization information from it. If the UE does not have a selected SyncRef, it will become one itself. If the UE has a selected SyncRef, the decision depends on the selected SyncRef signal strength. The evaluation performed by the UE for taking this decision will be explained in Section III-B4.

A SyncRef uses the Sidelink Synchronization Signal (SLSS) for announcing its synchronization information. The SLSS is transmitted in one subframe in the time domain (i.e., a 1 ms time slot) and uses the central 6 resource blocks in the frequency domain. An SLSS is composed of four elements:

- Primary Sidelink Synchronization Signal (PSSS)
- Secondary Sidelink Synchronization Signal (SSSS)
- Demodulation Reference Signal (DMRS)
- Physical Sidelink Broadcast Channel (PSBCH)

The PSSS and SSSS together encode the SLSS identifier (SLSSID), which identifies the transmitted synchronization information. The PSBCH carries the *MasterInformationBlock-SL* (MIB-SL), which contains system level information needed for the configuration of the synchronizing UE [4]. The DMRSs are used as a reference for channel estimation, demodulation of the PSBCH and measurement of the Sidelink Reference Signal Received Power (S-RSRP) in the receiving UE.

The SLSS is sent with a periodicity of 40 ms. The exact time position is indicated by a preconfigured relative subframe offset. There are two preconfigured offsets (*syncOffsetIndicator1* and *syncOffsetIndicator2*) and the UE will choose one or the other depending on its synchronization condition.

B. Sidelink synchronization reference (re)selection

The SyncRef (re)selection process is done in four steps which we describe bellow. First, the UE performs a SyncRef search in order to find all available SyncRefs. Next, the UE performs S-RSRP measurements for each detected SyncRef in order to estimate the channel. Finally, the UE uses all the information gathered in the previous steps to decide to which SyncRef it will synchronize. Afterwards, the UE evaluates the selected SyncRef to determine if the UE itself has to become a SyncRef. We discuss the implications of the scheduling of this process at the end of this section.

1) SyncRef search: In this process the UE performs a full search for detecting the available SyncRefs. As the periodicity of the SLSS is 40 ms, the UE should search for at least this amount time in order to be able to detect at least one SLSS of each available SyncRef.

A SyncRef is considered detected by the UE if the UE has obtained the SyncRef SLSSID and has decoded the corresponding MIB-SL. The UE analyzes the detected signals as follows. First, a correlation with all the possible PSSS values is done. If a peak is detected, the associated sequence corresponds to the PSSS sequence, and the peak time position provides the subframe timing. Next, the SSSS sequence is identified by performing a correlation with all the possible SSSS values in the time position of the SSSS (relative to the PSSS). The PSSS and SSSS sequences are combined to obtain the SLSSID, which the UE uses to demodulate the PSBCH and obtain the MIB-SL.

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2) S-RSRP measurement: In order to estimate the channel between the UE and a given SyncRef, the UE measures the corresponding S-RSRP, which is defined as the linear average over the power contributions (in Watts) of the resource elements that carry DMRSs in the SLSS [11]. The UE applies two levels of filtering before using the S-RSRP measurements in any decision process:

a) Layer 1 (L1) filtering: At the physical layer, the UE takes several S-RSRP samples of the same SyncRef over a given period of time called the measurement period. The measurement period is defined as 400 ms, and the UE is allowed to measure up to 6 detected SyncRefs [10]. However, the number of samples taken by the UE is left to implementation, as long as the UE meets the associated accuracy requirements. These samples are averaged for a better estimation. At the end of the measurement period, the physical layer reports the averaged L1 S-RSRP to upper layers.

b) Layer 3 (L3) filtering: This is an optional process that uses an infinite impulse response filter to determine the S-RSRP quantity to be used by the decision process, i.e., the L3 S-RSRP. The filter is controlled by a preconfigured forgetting factor. If the factor value is high, the L3 S-RSRP value will be close to the most recent L1 S-RSRP value (i.e., the instantaneous channel state). If the factor value is low, the L3 S-RSRP value will consider the older L1 S-RSRP measurements (i.e., the history of the channel state).

3) Decision process: In the out-of-coverage scenario, all the UEs have the same priority, hence the selection of a SyncRef only depends on the set of SyncRefs S-RSRP values. The decision process uses the gathered information from the detected candidate SyncRefs: SLSSID, MIB-SL and (L3) S-RSRP. A SyncRef is considered valid if its S-RSRP is higher than a predefined minimum required threshold, which is specified in [10].

If the UE already has a valid selected SyncRef, the UE needs to check whether this SyncRef is still suitable, or if the SyncRef needs to be discarded and the UE needs to select a new SyncRef. The UE compares the selected SyncRef S-RSRP with the strongest S-RSRP SyncRef candidate. If the candidate exceeds the selected SyncRef S-RSRP by a preconfigured hysteresis value (*syncRefDiffHyst*), the selected SyncRef is discarded, and the UE goes through the selection process as if it did not have a SyncRef at the beginning of the procedure.

If the UE does not have a valid selected SyncRef, it will choose the valid candidate with the strongest S-RSRP.

4) Selected SyncRef evaluation: After selecting a SyncRef, the UE should determine whether it has to become or cease to be a SyncRef. This process should be performed within 0.8 s [10]. The UE should measure the S-RSRP of the selected SyncRef UE and take the decision. The UE will become a SyncRef if the S-RSRP of the selected SyncRef is below the threshold *syncTxThreshOoC* and it is transmitting sidelink communication. If any of these two conditions is not met, the UE will cease to be a SyncRef or will not become one.

5) Scheduling: Given the highly dynamic nature of D2D communication in out-of-coverage scenarios, the SyncRef (re)selection process has to be repeated often enough to minimize the data lost due to unsynchronized transmitter-receiver pairs. However, several of the processes needed for the SyncRef (re)selection (e.g., SyncRef search and L1 S-RSRP measurement) require the UE to be in receiving mode. This reduces the amount of time the UE will be able to perform transmissions, due to the half-duplex constraint. Considering this, the standard limits the time a UE can spend in receiving mode for performing SyncRef (re)selection as follows: in a period of 20 s, an out-of-coverage UE is allowed to drop a maximum of 2 % of its sidelink transmissions at the physical layer for the purpose of SyncRef (re)selection [10].

The details of the SyncRef search and S-RSRP measurement processes are left to implementation. However, we can see the practical implications of this constraint with the following example. Lets consider that a UE spends a total of 80 ms in receiving mode while performing the SyncRef (re)selection process (e.g., 40 ms for SyncRef search + 40 ms for L1 S-RSRP measurements). If we consider the theoretical worst case scenario in which the UE always has data to send, the UE may be able to use the whole 20 s for transmitting. In this case, the UE can only spend 400 ms in receiving mode for performing the SyncRef (re)selection process (i.e., 2 % of 20 s). Thus, the UE can perform at maximum 5 SyncRef (re)selection processes within the 20 s [1].

One simple way to schedule the SyncRef (re)selection process, is to distribute them in time with a fixed period. This technique is already used by commercial UEs for network-based synchronization, i.e., for downlink cell search and measurement [5]. In our example, the periodic SyncRef (re)selection process may occur every 4 s (5 times in 20 s), where the UE performs an initial SyncRef (re)selection process when it finds itself out-of-coverage (e.g., the UE turns ON and no eNB is available or the UE moves out-of-coverage), and repeats the process every 4 s.

However, using a fixed period in device-based synchronization may come with the cost of inflexibility. If the SyncRef (re)selection processes of two different UEs are aligned in time in a way that will not allow their mutual synchronization, this problem may continue during the entire communication session. In the next section, we characterize these problems, and in Section V, we propose an algorithm to address them. In Section VI, we evaluate both approaches using system level simulations.

IV. SYSTEM MODEL AND PROBLEM DEFINITION

We consider an out-of-coverage scenario in which UEs arrive independently to the system according to a given arrival rate. A UE joining an out-of-coverage scenario can result from many different factors, e.g., the UE turned ON and no eNB was available, the UE moved to a zone without network coverage and lost network synchronization, the network suffered a blackout, or the in-network mode was simply

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[1] This is the theoretical worst case scenario. If the UE is not transmitting 100 % of the time, more SyncRef (re)selection process can be scheduled.

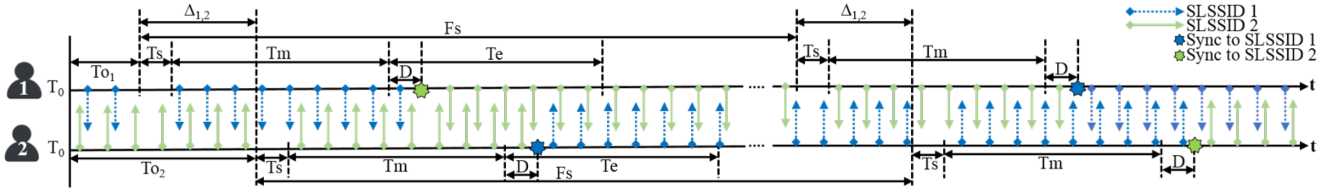

Fig. 1. Time alignment of the *periodic* SyncRef (re)selection process. SyncRef ping-pong effect example.

deactivated. When a UE arrives to the system, it performs an initial SyncRef (re)selection process. This process comprises a SyncRef search of duration T_s, a measurement period of duration T_m, and a decision process that we assume to be instantaneous. The effective change of timing and synchronization information occurs after a given delay, which is upper bounded by the parameter D. The UE evaluates the selected SyncRef during a period of duration T_e. Initially, we assume that the SyncRef (re)selection process will be repeated periodically after a given fixed time denoted as Fs.

In this scenario, we consider two transmitter UEs carrying different synchronization information. These UEs are mutually detectable at the time To, i.e., each UE is transmitting its own SLSSs and is receiving the SLSS of the other with a S-RSRP level above the minimum required after To. This can be the result of several cases. For example, the two UEs are already performing sidelink transmissions and they move into close proximity at time To; or the two UEs are already in proximity and they start their sidelink transmissions at To, or before To but after the last SyncRef (re)selection process of the other UE. Regardless of the case, the UEs do not detect each other before To but are mutually detectable after To.

The UEs will continue the sidelink transmissions for at least two SyncRef (re)selection periods. We denote as To_i the time relative to To in which UE i starts the next SyncRef (re)selection process. We define the parameter $\Delta_{i,j} = |To_i - To_j|$ to be the offset between the starting time of the SyncRef (re)selection processes of UE i and UE j. An example of the timeline of two UEs performing this periodical SyncRef (re)selection process is shown in Figure 1. We identified two possible synchronization problems in this scenario:

1) No detection: As both UEs are in proximity and advertising their synchronization information, they should be able to detect each other. However, due to the half-duplex constraint, if the UE is performing a SyncRef search, it cannot transmit SLSSs during that period. Thus, if the SyncRef search periods of the UEs are fully overlapped (i.e., $\Delta_{1,2} = 0$) the UEs will not be able to detect each other. Moreover, as Fs is fixed, this problem will persist. In the case that the SyncRef search periods of the UEs are partially overlapped (i.e., $0 < \Delta_{1,2} \leq T_s$), detection may be possible. This is the case if one of the UEs sends the SLSS before or after the SyncRef search period, and it is received in the non-overlapped part of the SyncRef search period of the other UE. Otherwise, the UEs will not be able to detect each other.

2) SyncRef ping-pong effect: If $\Delta_{1,2} > T_s$, the UEs will be able to detect each other. However, they may not be able to arrive to a common synchronization. For example, UE1 synchronizes to the information advertised by UE2 and UE2 synchronizes to the information advertised by UE1. In this case, as the period is fixed, this problem will be persistent as the UEs will change of synchronization information each time that the SyncRef (re)selection process is performed, without arriving to a synchronized state that allows them to communicate. We refer to this problem as the SyncRef ping-pong effect. It occurs when the synchronization events are aligned in a way that each UE cannot detect the change of synchronization information of the other UE, i.e., the SyncRef search of the UEs occurs before the decision process of the other UE finishes. In the described scenario, this happens when $0 < \Delta_{1,2} \leq T_s + T_m + D$, and Figure 1 depicts an example.

Table I shows a summary of the conditions and consequences explained above. We also include the condition in which the UEs will be able to converge to a synchronized state.

With this periodical algorithm, the value of $\Delta_{i,j}$ depends on the time in which the UEs arrive to the system, which is unknown by the other UEs. Thus, if a pair of UEs experiences any of the aforementioned problems, they will not have an exit condition provided directly by the synchronization protocol. An upper layer exit condition for the SyncRef ping-pong effect, can be that one of the UE stops to transmit, e.g., UE1, so that UE2 cannot detect UE1 anymore, and it keeps its

TABLE I
SUMMARY OF THE DIFFERENT POSSIBILITIES OF ALIGNMENT AND THE ASSOCIATED SYNCHRONIZATION CONDITIONS

Alignment	**Synchronization**	**Condition**	**Consequence**
$\Delta_{1,2} = 0$	No Convergence	No detection	The SyncRefs are not able to detect each other
$0 < \Delta_{1,2} \leq T_s + T_m + D$	Convergence Risk	No detection (Only if $0 < \Delta_{1,2} \leq T_s$)	The SyncRefs may not be able to detect each other
		SyncRef ping-pong effect	The SyncRefs may keep synchronizing to each other without converge to a synchronized state
$T_s + T_m + D < \Delta_{1,2} \leq F_s - (T_s + T_m + D)$	Convergence	None of the above	Convergence to a synchronized state

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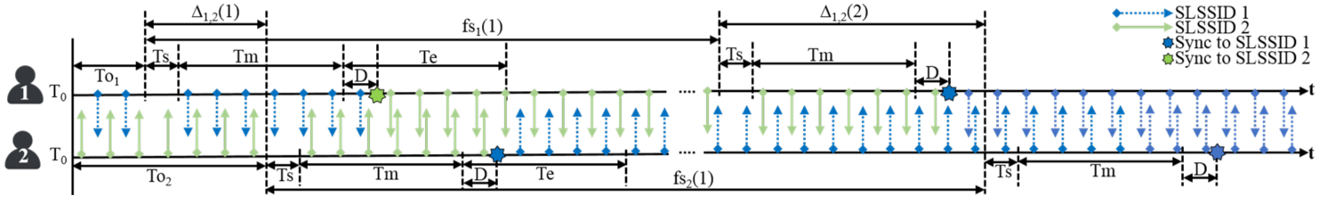


Fig. 2. Time alignment of the proposed *variable* SyncRef (re)selection process. SyncRef ping-pong effect resolution example.

own synchronization. Afterwards, UE1 will synchronize to the information of UE2 given that it is still transmitting. This will cause the convergence of both UEs to a synchronized state. However, this is not dependent on the synchronization protocol and it will not solve the detection problem.

V. PROPOSED ALGORITHM

In order to make the synchronization process resistant to the aforementioned problems, it should be decorrelated from the arrival of the UEs, and the persistent condition should be removed. To achieve these goals, we propose to trigger the SyncRef (re)selection process after a random backoff. Each time the process is performed, the UE schedules the next process to be triggered in a random time, i.e., the parameter Fs follows a random distribution.

We denote as $fs_i(k)$ the time between the k and $k+1$ SyncRef (re)selection process of UE i, i.e., $fs_i(k)$ is a realization of Fs and follows its distribution. Similarly, $\Delta_{i,j}$(m) denotes the time between the SyncRef (re)selection process of UE i and UE j at the m-th occurrence of the processes after To. Figure 2 shows an example of the timeline of two UEs using variable SyncRef (re)selection process triggering. The figure shows that $\Delta_{1,2}(1)$ and $\Delta_{1,2}(2)$ are different, which in this example removes the persistent ping-pong effect condition. This can be beneficial if any of the problems stated in Table I is encountered. For example, if $\Delta_{1,2}(1)$ satisfies any of the problematic conditions, it is less likely that $\Delta_{1,2}(2)$ falls under the same condition.

Moreover, the range of values for $fs_i(k)$ should be selected in order to maintain an adequate level of synchronization performance. The minimum value should be chosen to avoid that the UE performs the SyncRef (re)selection process too often, which may cause a percentage of transmission drops higher than the value established in the standard. The maximum value should be limited so that the UE performs the process often enough to react to synchronization changes. Finally, the length of the range should be large enough to ensure the variability needed for avoiding the synchronization problems.

VI. EVALUATION

In previous work [12], we extended the LTE module of the ns-3 network simulator [13] to consider standard-compliant sidelink communications. The evaluations described in this section were performed using this implementation.

A. Scenario

The scenario is composed of three out-of-coverage UEs in proximity, i.e., they can detect each other and establish a communication session using the sidelink. Two of the UEs are interested in transmitting data to the third UE, i.e., there are two transmitters and one receiver. At the beginning of the evaluation, the UEs are not synchronized. The receiver will be able to receive the data from the two transmitters only after the three UEs are synchronized. Thus, a relevant metric for the scenario is the convergence time to a synchronized state, i.e., the time taken by the three UEs to acquire and use the same synchronization information.

The relevant parameters of the evaluation are summarized in Table II. Each UE i arrives at time T_i, and performs the initial SyncRef (re)selection process of the simulation at this time. The parameter b represents how scattered these arrivals can be within a SyncRef (re)selection process period. For simplicity of the evaluation, we assume the two transmitters start their transmissions at the same time $To = 10$ s, and the communication session lasts for the remaining simulation time. The simulation time was 70 s and the simulations were repeated 1000 times using different random seeds. The UEs wait until the end of its scheduler allocation period to apply the change of timing once a SyncRef is selected. Thus, D is in the worst case equal to the preconfigured allocation period, which is 40 ms.

TABLE II

EVALUATION PARAMETERS

Parameter	**Value**
Scenario	
T_i (ms)	$Unif(0,b) \mid b \leq fs_{\min}$
Synchronization protocol	
syncTxThreshOoC (dBm)	-60
syncRefDiffHyst (dB)	0
syncOffsetIndicator[1,2]	7, 3
Layer 3 filtering	Deactivated
SyncRef (re)selection process parameters	
T_s (ms)	40
T_m (ms)	400
T_e (ms)	400
D (ms)	40
Maximum time in receiver mode	
For SyncRef search (ms)	40
For Measurement (ms)	36
For Evaluation (ms)	4
Time in Rx mode Total (ms)	80
SyncRef (re)selection process triggering	
Periodic: F_s (ms)	$fs_{\min}$
Variable: F_s (ms)	$Unif(fs_{\min}, fs_{\max})$
Evaluations performed	
$fs_{\min}$ (ms)	Evaluation A: 4000 Evaluation B: 2000 Evaluation C: 1000
$fs_{\max}$ (ms)	$(1+\alpha) * fs_{\min} \mid \alpha \in [0,1]$

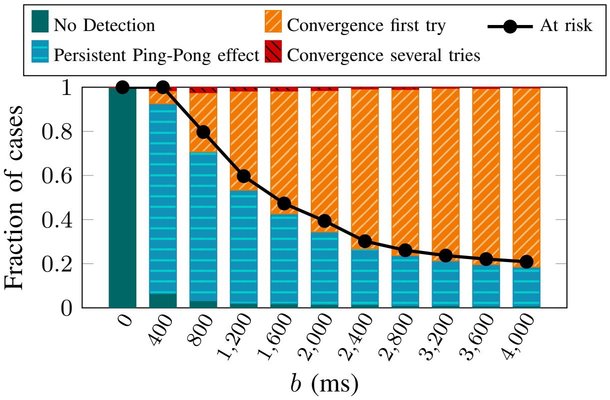


Fig. 3. Distribution of the synchronization conditions depending on the UE arrival distribution ($T_i \sim Unif(0, b)$) when using the *periodic* algorithm in the Evaluation A.

B. Algorithm configuration

The parameter fs_{min} is the minimum value Fs could take to satisfy the transmission drop rate constraint depending on the UE transmission conditions (Section III-B5). We performed three different evaluations (A, B and C) based on the values of fs_{min} (See Table II). The value fs_{min} = 4000 ms (Evaluation A) was obtained considering the theoretical worst case scenario (i.e., UE transmits 100 % of the time), and considering that the UE needs to spend 80 ms in reception mode for performing the SyncRef (re)selection process (Table II). The parameter fs_{min} can be adapted depending on the UE traffic conditions, the scheduling policies of both control and traffic channels, and the actual number of SyncRefs the UE detected.

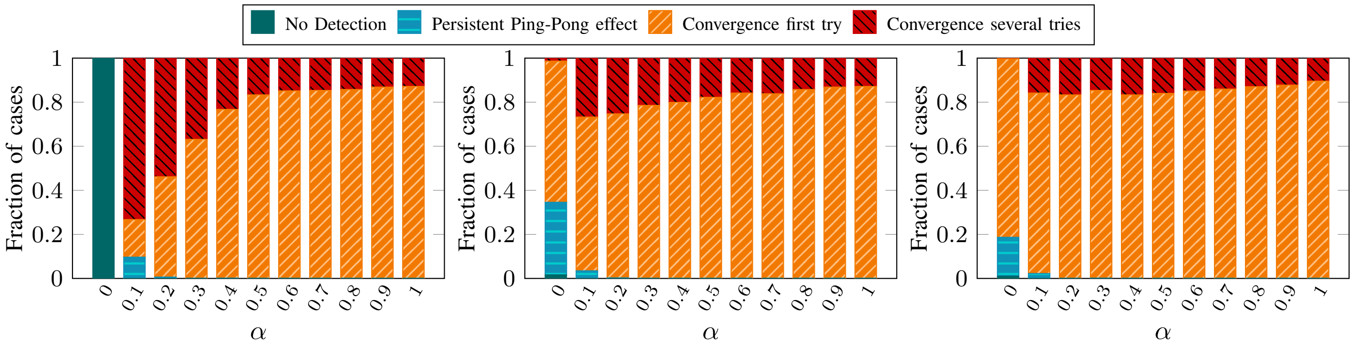
Each UE performs the SyncRef (re)selection process each fs_{min} ms when using the *periodic* algorithm. With the proposed *variable* algorithm, each UE schedules the next process in a time randomly chosen between fs_{min} and fs_{max}. We vary the value of fs_{max} using the parameter α (Table II) in order to explore the performance of the proposed algorithm.

C. Results

Figure 3 shows the distribution of the synchronization conditions for Evaluation A when the UEs are using the periodic algorithm. When b = 0 ms, all the UEs arrive at the same time. This implies that all UEs perform the initial process at the same time (T_1 = T_2 = T_3 = 0), and therefore they perform every process at the same time. This prevents the UEs from detecting each other, and synchronization convergence is not possible. The percentage of synchronization convergence increases with b, i.e., the more scattered the arrivals, the fewer synchronization problems are observed. However, in the best case (b = 4000 ms), we observe that 18 % of the cases still encountered a synchronization problem. The same trend is observed in Evaluation B and C.

The fraction of cases at risk in Figure 3 corresponds to the cases with a (re)selection process time alignment favorable for synchronization problems, i.e., the value of $\Delta_{1,2}$ was in one of the problematic alignment intervals in Table I. However, not all the cases that were at risk actually experienced a synchronization problem, or had one persistently. For example, with b = 400 ms, 8 % of the cases at risk converged to a synchronized state, while with b = 2000 ms 13 % of the cases at risk converged. Synchronization was achieved in these cases when the alignment of the (re)selection processes was favorable for convergence, either in the first synchronization attempt or after several ones. Initial convergence was due to partially overlapped SyncRef search periods, as explained in Section IV. Convergence after several tries was observed when the SyncRefs experienced the ping-pong effect, but the condition resolved. For example, after the SyncRefs synchronize to each other, each one changes its time reference, which also modifies the timeslot in which the SLSSs are sent. After one or several of these changes, the alignment can be favorable for convergence. However, Figure 3 shows that convergence after several tries happens rarely, as it depends on the alignment of multiple factors such as the choice of the offsets, the exact moment of transmission of SLSSs, how unsynchronized the UEs were upon arrival to the system, and the timing change history.

Figure 4 shows the results for Evaluation A when considering the proposed variable algorithm. The value $\alpha = 0$ corresponds to the periodic algorithm. The data show that with a value of $\alpha = 0.1$, the variable algorithm can considerably reduce synchronization problems, e.g., from 100 % to 10 % when b = 0 ms, from 35 % to 4 % with a b = 2000 ms, and from 18 % to 2 % when b = 4000 ms. Moreover, synchronization



(a) b = 0 ms (b) b = 2000 ms (c) b = 4000 ms

Fig. 4. Distribution of the synchronization conditions depending on α when using the *variable* algorithm in the Evaluation A. Three different values of b are considered and please note that the value $\alpha = 0$ corresponds to the *periodic* algorithm.

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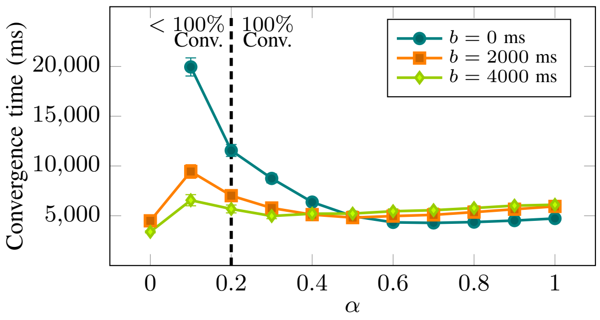

Fig. 5. Convergence time when using the *variable* algorithm in the Evaluation A. Only the cases where convergence was achieved are considered.

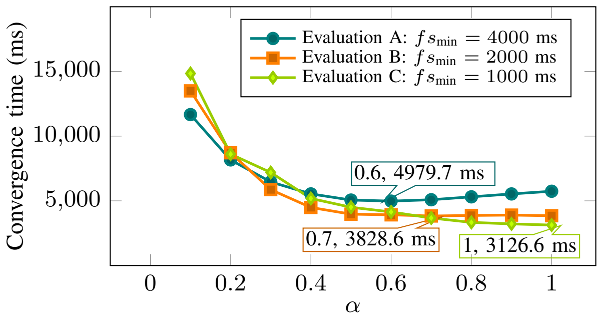

Fig. 6. Average convergence time when using the *variable* algorithm. The optimal values are highlighted with data labels for each evaluation.

problems can be completely avoided by choosing $\alpha \geq 0.2$ in most of the cases, which highlights the need for and benefits of using a variable algorithm.

Figure 5 shows the convergence time as a function of α. This figure shows the average and the 95 % confidence interval considering only the cases where convergence was achieved. Note that when b = 0 ms and $\alpha = 0$ there is no convergence, as shown in Figure 4a. Note also that the minimum value of convergence time for b = 2000 ms and b = 4000 ms corresponds to $\alpha = 0$, however, a non-negligible percentage of the evaluated cases did not converge in these scenarios: 35 % and 18 %, respectively (Figure 4). In the cases where 100 % of convergence was achieved, we observe that the convergence time has an upward concave shape as a function of α, reaching its minimum value in different α values depending on the parameter b, e.g., $\alpha = 0.7$ for b = 0 ms, $\alpha = 0.5$ for b = 2000 ms and $\alpha = 0.4$ for b = 4000 ms (Figure 5). However, the UEs do not have prior knowledge of the value of b, and the parameter α should be selected in order to provide the overall best performance considering all values of b.

Figure 6 shows the average convergence time, which is calculated considering all simulated values of b. This figure shows the results for the different evaluations (i.e., different values of fs_{min}). Note that the smaller the value of fs_{min}, the more often in average the UE will perform the SyncRef (re)selection process. However, the average convergence time is not necessarily smaller when fs_{min} decreases, as shown in Figure 6 for Evaluation C and $\alpha < 0.7$. The reason is that with small values of fs_{min} and α the algorithm is not able to create enough variability in the triggering of the SyncRef (re)selection process, which causes the need for the UEs to perform the process several times to finally arrive to a synchronized state. However, with $\alpha \geq 0.7$, Evaluation C exhibits the lower average convergence time, which highlights the importance of choosing an adequate α for the variable algorithm.

VII. CONCLUSION AND FUTURE WORK

In this paper, we studied the system level implications of the device-based synchronization protocol for LTE-A D2D-enabled UEs operating out-of-coverage. We showed that performing the synchronization reference (re)selection process periodically, i.e., at fixed intervals of time, can lead to convergence problems in scenarios when two synchronization references are simultaneously active. We proposed an effective technique that allows to avoid these problems, or to resolve them in a reasonable time if they occur. The solution is based on a random backoff to trigger the synchronization reference (re)selection process. We showed using system level simulations the trade-offs that should be considered for achieving a given level of performance and satisfy the 3GPP standard requirements.

In future work, we will consider the design and evaluation of algorithms that can dynamically adapt the triggering of the process depending on the UE transmission conditions, e.g., the traffic status, the scheduler configuration, etc.

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