UE-to-Network Relay Discovery in ProSe-enabled LTE Networks

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***Abstract*—The UE-to-Network Relay functionality was introduced to Long Term Evolution (LTE) cellular networks by the 3rd Generation Partnership Project (3GPP) in Release 13. In this technology, User Equipment (UEs) acting as Relay UEs are used to extend network coverage to cell-edge and out-of-coverage Remote UEs. One important part of this functionality is direct discovery, which is used by the Remote UEs willing to reach the network to detect the Relay UEs in proximity that can provide the desired connectivity service. In this paper, we study this protocol considering both discovery models defined in the LTE standard, and we develop analytical models to characterize the average time a Remote UE takes to discover a Relay UE using each discovery model. We validate the analytical models using system level simulations and we study the sensitivity of the metrics to different parameters of the protocol and number of UEs involved in the UE-to-Network Relay discovery.**

***Index Terms*—LTE, D2D, ProSe, UE-to-Network Relay, Discovery, Network Modeling**

I. Introduction

The 3rd Generation Partnership Project's (3GPP) Long Term Evolution (LTE) Proximity Services (ProSe) technology allows User Equipment (UEs) to communicate on a Device-to-Device (D2D) basis, directly sending information to one another (if the range permits it) via a direct link known as the sidelink (SL). This technology not only allows direct communication in areas within the network coverage, where an eNodeB (eNB) could coordinate SL resource allocation, but it also enables out-of-coverage UEs to communicate using the SL, in which case autonomous resource allocation is used based on pre-configured parameters [1].

One important feature of the ProSe technology is the UE-to-Network Relay functionality, where in-coverage UEs (Relay UEs) can act as network relays, redirecting traffic to and from another UE (Remote UE) in proximity of the network. Using UE-to-Network Relay UEs to extend coverage is critical to Public Safety users, especially in emergency scenarios where communication between intervening team members and incident command stations should not be interrupted. Thus, team members equipped with ProSe-enabled UEs can act as Relay UEs and ensure service continuity to out-of-coverage or cell-edge team members whose UEs will act as Remote UEs.

In order to reach the network, a Remote UE should search for Relay UEs in proximity using a ProSe direct discovery procedure, select the most suitable one, and connect to it using the one-to-one ProSe direct communication procedure [2]. In this paper, we focus on the ProSe direct discovery procedure for UE-to-Network Relay.

Both ProSe direct discovery models defined in the 3GPP standard (A and B) can be used for UE-to-Network Relay discovery [3]. In Model A, Relay UEs periodically broadcast *announcement* messages to advertise their presence and the connectivity service they can provide. Remote UEs actively listen for those messages. In Model B, the procedure is initiated by the Remote UE, which broadcasts *solicitation* messages with the connectivity service it is looking for. Listening Relay UEs that provide the solicited service will then send a *response* message. The received discovery announcements (Model A) or responses (Model B), and their associated signal strengths, are then used by the Remote UE to conduct the Relay UE selection and start the one-to-one ProSe direct communication procedure.

ProSe-enabled UEs use the Physical Sidelink Discovery Channel (PSDCH) to broadcast discovery messages on the SL. The UEs are provisioned with a pool of discovery resources to use, which repeats periodically in time. The resource allocation within each pool can be either *network-assisted*, i.e., the eNodeB persistently schedules the resources to be used by the UEs, or *UE-selected*, where each UE selects randomly the resources to be used.

In this paper, we focus on the UE-selected allocation, as eNodeB scheduling information may not be always available for the Remote UEs, e.g., when they are out-of-coverage. The UE-selected allocation brings a risk of collision interference if multiple UEs pick the same resources for a given transmission, which may result in Relay UEs not being discovered by a Remote UE even though they are in proximity. To alleviate this issue, a transmission probability was defined in the 3GPP standard as part of the discovery resource pool, which is used by each transmitter UE to decide whether to transmit a discovery message in a given discovery period. We developed an analytical framework to quantify the time taken by a Remote UE of interest to discover any Relay UE and also a given Relay UE in proximity depending on the discovery pool parameters and the discovery model used by the UEs. We validated the theoretical models using system level simulations performed in our ns3 ProSe module described in [4] and enhanced with the UE-to-Network Relay functionality.

The rest of the paper is organized as follows. We discuss prior works related to ProSe direct discovery and the contributions of this paper in Section II. In Section III, we describe the models that allow us to obtain the time a Remote UE takes to discover any Relay UE and a given Relay UE in proximity. In Section IV, we provide numerical results to validate the models and we discuss the protocol sensitivity to the model parameters. Finally, Section V summarizes our contributions and discuss future work.

II. Related Work

As discussed in the previous section, the direct discovery resource allocation can be either network-assisted or UE-selected. Early works have focused on network-assisted direct discovery. In [5], Xenakis et al. provide an analytical model to determine the probability that two UEs in the network detect each other using a D2D link and provide a sensitivity analysis considering several network parameters such as transmission power and eNodeB density. In [6] and [7], the authors rely on centralized scheduling schemes to avoid collisions and expedite the discovery process. These studies assume full knowledge of the network and deviate from the 3GPP standard procedures in place for ProSe direct discovery.

The following works address direct discovery with UE-selected allocation. In [8], the authors present a model based on stochastic geometry and use it to calculate how many UEs can be discovered in a given number of discovery periods considering channel conditions. Bagheri et al. consider similar metric in [9], and propose that UEs randomly select their transmit power to alleviate interference in the discovery channel. Both models consider that the UEs are sending discovery messages every discovery period, disregarding the transmission probability mechanism.

Li and Liu proposed an alternative to the transmission probability to avoid collision interference [10]. Instead of the UEs deciding each period if they should transmit based on the transmission probability, they randomly decide in which discovery period to transmit within a set of successive periods.

In [11], Griffith and Lyons developed an analytical model used to obtain the optimal transmission probability for a given discovery resource pool configuration and number of UEs performing discovery. This optimal transmission probability minimizes the time required for a successful discovery message transmission, and near-optimal performance can be achieved when rounding it up to the next higher multiple of 1/4 to be consistent with the values in the 3GPP standard. These results are used in [12] to develop an adaptive algorithm in which the UEs adjust their transmission probabilities depending on the number of discovered UEs over time.

In this paper, we build upon the model in [11] and generalize it to differentiate between Remote UEs and Relay UEs. We also complete it to determine the average time a Remote UE needs to find an unspecified Relay UE. Additionally, we characterize Model B discovery using state machines as has been explored by Griffith et al. in [13], obtain equivalent performance metrics, and compare both models performances for a given discovery pool configuration. Finally, we validate the models using system level simulations of the actual standard protocol implementation.

III. Analytical Model

The notation we use in the paper is summarized in Table I.

A. System Model

1) Scenario: We consider a group of N_x Remote UEs (G) and a group of N_y Relays UEs (H) deployed without prior knowledge of the area. All the devices are in each other's respective ranges, X is a given Remote UE and Y a given Relay UE; both randomly chosen. We consider that devices are either Remote or Relay UEs (i.e., $G \cap H = \varnothing$).

2) The Discovery Resource Pool: Resource allocation will happen by UEs choosing their own resources in the PSDCH discovery resource pool independently from each other. The PSDCH resource pool is a periodical grid in the time-frequency plane composed of Physical Resource Blocks (PRB) that we model as a $N_f \cdot N_t$ matrix as depicted in Fig. 1. Each row corresponds to a PRB pair and each column to a subframe set. Each resource is a single transport block composed of a pair of adjacent PRB that occupy the same subframe. Any UE wishing to transmit is to generate a uniformly distributed random value $p_1 \in [0, 1]$ that it compares with a given threshold value denoted by *txProbability*. The 3GPP standard defines that *txProbability* can take the values 0.25, 0.50, 0.75, or 1.00. The discovery message is sent if $p_1 <$ *txProbability*. If successful, the UE picks a resource in the pool with uniform probability. Let $\theta = P(p_1 \leqslant \textit{txProbability})$ for the rest of this paper.

3) Metrics of interest: This paper focuses on two metrics: The average time a given Remote UE of interest needs to find:

- A given Relay UE, and
- Any Relay UE, referred to as First Relay UE.

We will establish analytical models for these two metrics for Model A and B. We elected a probabilistic approach and looked into the behaviors of our system in a given PSDCH period and deduced how many periods are necessary on average to complete the discovery for each case. For the rest of the paper, let $Z_1 \rightarrow Z_2$ be the event 'UE Z_1 successfully sends UE Z_2 a message', $Z_1 o Z_2$ be 'UE Z_1 discovers UE Z_2', $Z?$ be 'UE Z successfully sends a message to a Relay/Remote UE' and $Z\sim$ be 'UE Z discovers a Relay/Remote UE'. Note that Z, Z_1, and Z_2 can designate interchangeably a Relay or Remote UE, depending on the model in context.

4) Final Considerations: The following assumptions were made for the development of the analytical models presented in the next sections:

- We assume that all UEs belong to the same security domain and are authorized to perform UE-to-Network Relay discovery. This approach could be deemed Open Access although its long-term applications are focused around Restricted Access in the Public Safety context.
- We assume a worst-case transmission scenario were the devices other than our devices of interest are permanently trying to send messages.

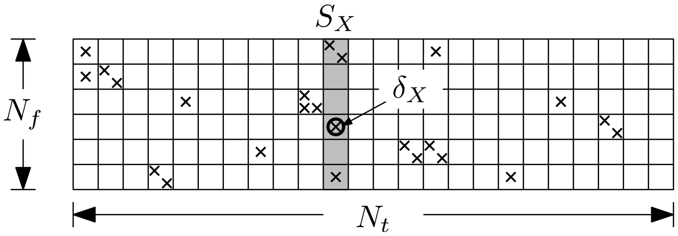


Fig. 1. The discovery resource pool model, showing the transmissions of various UEs and indicating the location of X's discovery message δ_X and the set of subframes it occupies S_X [11, Fig. 3].

TABLE I
LIST OF SYMBOLS

Symbol	Definition
$P(A)$	Probability of event A
G	The set of Remote UEs in context
N_x	card(G)
UE X	Randomly chosen Remote UE of interest from G
H	The set of Relay UEs in context
N_y	card(H)
UE Y	Randomly chosen Relay UE of interest from H
δ_X	Discovery message sent by UE X
S_X	Set of subframes occupied by δ_X
N_r	Number of resources in discovery pool
N_f	Number of PRB pairs in discovery pool
N_t	Number subframe sets in discovery pool
θ	Probability that a given UE transmits
T	Markov state transition matrix
P_1,P_2	Illustration probability functions
N	T's Fundamental Matrix
Z, Z_1, Z_2	Arbitrary UEs ($\in G \cup H$)
$Z_1 \to Z_2$	$'Z_1$ successfully sends a message to Z_2'
$Z_1 o Z_2$	$'Z_1$ discovers Z_2'
$Z?$	$'Z$ successfully sends a message to a Relay/Remote UE$'$
$Z \sim$	$'Z$ discovers a Relay/Remote UE$'$

- We assume that senders other than our UEs of interest do not stop sending discovery messages after receiving responses from other devices. This condition guarantees us a stable environment to work in.
- The half-duplex effect prevents devices from transmitting and listening simultaneously on the SL. Although it is a factor that could impact the discovery when using Model B, we assume the Remote UEs transmit solicitations every other discovery period. This allows that the following period is dedicated to the reception of the Relay UE responses.
- Lastly, this paper will neglect processing times completely. As soon as there is an intent to transmit, the involved device attempts to do so. These delays are probably not as significant as control channel loss probability and other phenomena but do still exist.

B. Relay Discovery Model A

1) Given Relay UE: In Model A, given the absence of transmission from Remote UEs and the systematic one of all Relay UEs, XoY is equivalent to $X \to Y$ and furthermore to 'Y's discovery message does not collide'. By Bayes' Theorem on the universe $\{\{$'Y emits'$\}, \{$'Y does not emit'$\}\}$:

$$P(X \to Y) = P(\text{`}Y\text{ emits'})P(\text{`}Y\text{'s message does not collide'}) \tag{1}$$

with $P(\text{`Y emits}') = \theta$.

To determine P('Y's message does not collide') , we condition on how many of the other $N_y - 1$ Relay UEs transmit, which has a binomial distribution with probability mass function $f(k; N_y - 1; \theta) = \binom{N_y-1}{k}\theta^k(1-\theta)^{N_y-1-k}$. The probability that a Relay UE other than Y picks the same resource if it transmits successfully is $\frac{1}{N_r}$. By applying the Binomial Theorem, we get:

$$P(XoY) = \theta\left(1 - \frac{\theta}{N_r}\right)^{N_y-1}. \tag{2}$$

<u>N.B</u>: This method is reminiscent of the one used in [11].

2) First Relay UE: A discovery ($X \sim$) is equivalent to a successful transmission ($X?$) in Model A. The only way $X?$ does not happen is if all transmissions collide. By conditioning on the number of devices that transmit and using Bayes' Theorem:

$$P(X?) = \sum P(\text{`at least one request does not collide'} \;|\text{`k requests are emitted'})P(\text{`k requests are emitted'}). \tag{3}$$

Let C_k be the event 'All of k requests collide'. Determining $P(C_k)$ now comes down to a classic balls in bins problem where we look for the number of combinations leaving no ball alone in a box:

$$P(C_k) = \sum_{i=0}^{min(k,N_r)} (-1)^i \binom{N_r}{i}\binom{k}{i} i! \left(\frac{1}{N_r}\right)^i \left(1 - \frac{i}{N_r}\right)^{k-i}. \tag{4}$$

$Proof$: The probability that no ball is alone in a box is $P(C_k) = 1 - P(\text{`at least one ball alone'})$. Let ν be the number of balls that are alone after k balls are randomly distributed into N_r bins. We can define a set of k events, $S = \{A_i\}_{i=1}^k$ such that event A_i occurs if the ith ball is alone in a box. Jordan's formula gives the probability that at least j events in the set S occur, which is

$$P(\nu \geqslant j) = \sum_{i=j}^{j} (-1)^{i-j}\binom{i-1}{j-1} B_i, \tag{5}$$

where $B_i = \sum_{1 \leqslant m_1 \leqslant m_2 \leqslant \ldots \leqslant m_i \leqslant k} P(A_{m_i} \cap \ldots \cap A_{m_i})$ is the ith binomial moment of ν, which here corresponds to the probability of balls numbered $m_1, ..., m_i$ being alone in i bins. We compute this probability by taking the ratio of the number of ways that k distinguishable balls can be arranged so that the balls with the index values $m_1, m_2, \ldots, m_i$ are alone in i distinguishable bins to the number of ways that k balls can be arranged in N_r bins. The former is the product of the number of ways to choose i bins out of N_r bins, the number of ways to arrange the i isolated balls among the i chosen bins and the number of ways to arrange the remaining $(k - i)$ balls among the remaining $(N_r - i)$ bins (note that this can include cases where some of these balls end up alone, but we are concerned only with balls $m_1, m_2, \ldots, m_i$) whereas the latter is simply N_r^k. We now have

$$\begin{aligned} P(A_{m_i} \cap ... \cap A_{m_i}) &= \binom{N_r}{i} i! \frac{(N_r - i)^{k-i}}{N_r^k} \\ &= \binom{N_r}{i} \frac{i!}{N_r^i} \left(1 - \frac{i}{N_r}\right)^{k-i}. \end{aligned} \quad (6)$$

We can now deduce

$$B_i = \binom{k}{i} \binom{N_r}{i} \frac{i!}{N_r^i} \left(1 - \frac{i}{N_r}\right)^{k-i}. \quad (7)$$

And finally

$$\begin{aligned} P(C_k) &= 1 - P(\nu \geqslant 1) \\ &= \sum_{i=0}^{min(k,N_r)} (-1)^i \binom{N_r}{i} \binom{k}{i} i! \left(\frac{1}{N_r}\right)^i \left(1 - \frac{i}{N_r}\right)^{k-i}. \end{aligned} \quad (8)$$

This results leads us to:

$$\begin{aligned} P(X \sim) = \sum_{k=1}^{N_y} \binom{N_y}{k} \theta^k (1-\theta)^{N_y - k} \\ \sum_{i=0}^{min(k,N_r)} (-1)^{i+1} \binom{N_r}{i} \binom{k}{i} i! \left(\frac{1}{N_r}\right)^i \left(1 - \frac{i}{N_r}\right)^{k-i}. \end{aligned} \quad (9)$$

3) Deducing desired metrics: For both these models, given that the resource selection process is independent in distinct periods, the number of PSDCH periods to accomplish the aforementioned events has a geometric distribution. We can conclude that the mean time (in number of periods) for each of the scenarios is the inverse of the probabilities, given by:

$$t(XoY) = \frac{1}{P(XoY)} \quad (10)$$

and

$$t(X \sim) = \frac{1}{P(X \sim)}. \quad (11)$$

N.B: In model A, the probability of X discovering a given group of Relay UEs is equal to the one where all the Remote UEs discover the same Relay UEs, given that messages are broadcasted to all Remote UEs in range.

C. Relay Discovery Model B

With Model B, other Remote UEs than X will be using and competing for resources. Thus, N_x will now logically appear in the models and all N_x Remote UEs we take into account are active. The approach we used for Model A cannot lead us to the time metric for Model B as the geometric distribution criteria is no longer fulfilled. We elected Markov models as the most appropriate to handle Model B. In fact, the sojourn times of the states in our model do not exactly follow the geometric distribution, which is a requirement for Markov chains. Nevertheless, using a semi-Markov chain adds considerable complexity to the model for an incremental gain in accuracy and does not bring any significant insight to this paper. Therefore, we can reasonably approximate the sojourn times and continue using standard Markov chains.

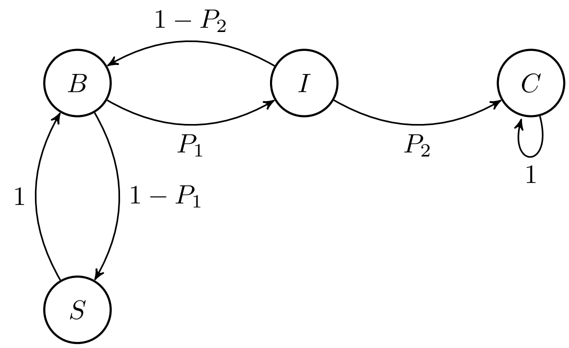


Fig. 2. Markov chain modeling the system when using discovery Model B.

We propose to study a simplified version of Model B, were PSDCH pools are divided into solicitation and response periods, meaning that Remotes UEs would attempt to send solicitations only every other period and that Relay UEs would have the following period to try responding. The discovery is now achieved when a successful solicitation and response happen in any pair of neighboring PSDCH periods. Any of the Remote UEs in G can trigger a response that allows X to discover the concerned Relay UE. This simpler approach still depicts Model B's behaviors and metrics appropriately, whilst neglecting timer expirations and the half-duplex effect.

1) The Model: The Markov chain depicted in Fig. 2 models our system when using discovery Model B and is used for obtaining both metrics of interest. We define P_1 to be the probability that a Remote UE's solicitation is successfully received by a Relay UE, and define P_2 to be the probability that a Relay UE's response is successfully received by a Remote UE in the general case. In our model, the Remote UE starts in the Beginning state, B, and progresses to the Intermediary state, I, if a Relay UE receives its solicitation. Otherwise the Remote UE moves to sleeping state S (as the current period is not a Remote UE transmission one) and then returns to state B to attempt transmission once again. If the Relay UE's response reaches the Remote UE, then it progresses to the Completion state, C, which is the sole absorbing state in the Markov chain.

The chain in Fig. 2 has the following transition matrix:

$$T = \begin{bmatrix} 0 & P_1 & 1-P_1 & 0 \\ 1-P_2 & 0 & 0 & P_2 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (12)$$

That we can partition likewise:

$$T = \begin{bmatrix} Q & R \\ \mathbf{0} & 1 \end{bmatrix}. \quad (13)$$

This chain's fundamental matrix defined by $N = (1-Q)^{-1}$ with $Q = T_{[1;3][1;3]}$ can be determined directly by the cofactor method:

$$N = \frac{1}{P_1 P_2} \begin{bmatrix} 1 & P_1 & 1-P_1 \\ 1-P_2 & P_1 & (1-P_1)(1-P_2) \\ 1 & P_1 & 1-P_1(1-P_2) \end{bmatrix}. \tag{14}$$

By definition, the average time to reach the absorbing state (in periods) when starting at state B is:

$$t(B \to C) = \sum_{j=1}^{3} N_{1,j} = \frac{2}{P_1 P_2}. \tag{15}$$

For both our metrics P_1, i.e., the probability of a successful solicitation, is essentially the same as Model A's first Relay UE model with the Remote UEs being the transmitters. This is the case because any of the Remote UEs can solicit a specific (or any) Relay UE for it to answer X, our Remote UE of interest. Given our assumptions, we can be certain of the solicitation reaching our Relay UE of interest if it does not collide, and therefore

$$P_1 = P(X?) = \sum_{k=1}^{N_x} \binom{N_x}{k} \theta^k (1-\theta)^{N_x-k} \sum_{i=1}^{min(k,N_x)} (-1)^{i+1} \binom{N_r}{i} \binom{k}{i} i! \left(\frac{1}{N_r}\right)^i \left(1 - \frac{i}{N_r}\right)^{k-i}. \tag{16}$$

The response however does vary depending on the desired metric. The given Relay UE Model will have one Relay UE competing with others for resources to reach X, whereas the first Relay UE Model requires any Relay UE to reach X.

a) Given Relay UE: For the Given Relay UE model, we simply have:

$$P_2 = P(Y \to X) = \theta \left(1 - \frac{\theta}{N_r}\right)^{N_y - 1}, \tag{17}$$

which leads to:

$$t(XoY) = \frac{2}{P(Y \to X)P(X?)}. \tag{18}$$

b) First Relay UE: For the First Relay UE model, the response can be issued by any Relay UE, leading to:

$$P_2 = P(Y?) = \sum_{k=1}^{N_y} \binom{N_y}{k} \theta^k (1-\theta)^{N_y-k} \sum_{i=1}^{min(k,N_y)} (-1)^{i+1} \binom{N_r}{i} \binom{k}{i} i! \left(\frac{1}{N_r}\right)^i \left(1 - \frac{i}{N_r}\right)^{k-i}, \tag{19}$$

and finally:

$$t(X \sim) = \frac{2}{P(Y?)P(X?)}. \tag{20}$$

IV. Numerical Results

A. System Level Simulations

We validated the models using system-level simulations. We used the ns-3 ProSe model described in [4] enhanced to support the UE-to-Network Relay functionality. We deployed N_y Relay UEs and N_x Remote UEs in proximity and all UEs are configured with the same discovery pool parameters (N_f, N_t, *txProbability*). The discovery period was set to 320 ms which is the minimum value defined in the standard. All UEs start the direct discovery at the same time. Relay UEs send discovery announcement messages on every period when using Model A, and Remote UEs send discovery solicitations every other period when using Model B. We considered ideal channel conditions and discovery messages sent by multiple UEs in the same resources are dropped to be consistent with the analytical models. Message recovery depending on Signal to Interference plus Noise Ratio (SINR) and error models will be addressed in future work. The metrics of interest were calculated for a given Remote UE, which was chosen randomly in each trial. In the simulations, we consider that a Remote UE discovers a Relay UE when it successfully receives an announcement (Model A) or response (Model B) message from that Relay UE. We performed 1000 independent trials for each configuration, and all results are presented using the mean values and 95 % confidence intervals for each metric.

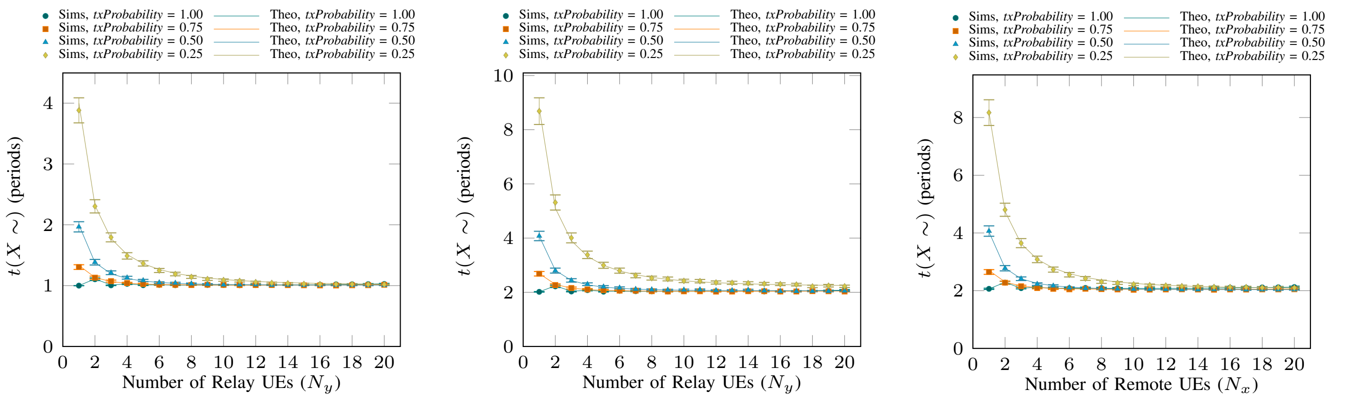
B. Results Discussion

The results shown in Fig. 3 and Fig. 4 were generated using a resource pool of $N_f = 2$ PRBs and $N_t = 5$ subframes (SFs), and we present results for the four values of *txProbability* defined in the 3GPP standard $(0.25, 0.50, 0.75, 1.00)$. We observe a close agreement between the theoretical and the system level simulations results, validating the accuracy of our models.

The results illustrate the effect of the number of UEs contending for resources in the discovery time for the Remote UE of interest. On the one hand, we observe in Fig. 3(a) and Fig. 3(b) that $t(X \sim)$ decreases when N_y increases, as the probability of at least one Relay UE choosing a non-colliding discovery resource increases with N_y. The scenario with $N_y = 1$ and *txProbability* = 1.00 is of course the exception, as there is no contention for resources and the discovery messages are received in every discovery period. On the other hand, Fig. 4(a) and Fig. 4(b) show that $t(XoY)$ increases with N_y, as the number of UEs contending for discovery resources increases, the probability that the Relay UE of interest choose a non-colliding discovery resource decreases, thus delaying the discovery.

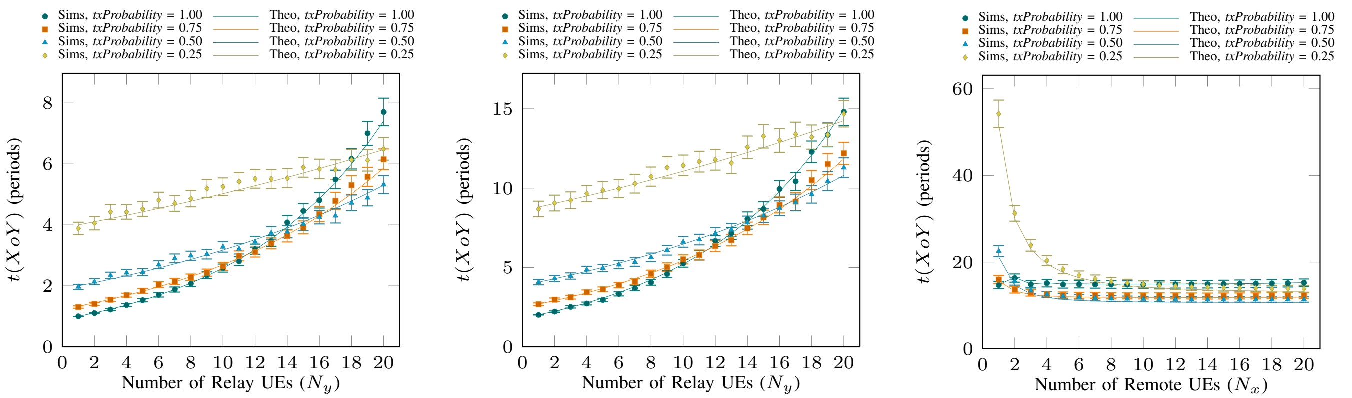
While Fig. 3(b) and Fig. 4(b) shows results for $N_x = 10$ Remote UEs, we observed similar trends depending on N_y for different values of N_x when using Model B.We do not show these results due to space limitation. Please note that in this evaluation, the results for Model A are independent of N_x, as Remote UEs are only listening for announcements and all Remote UEs receive them at the same time.

Fig. 3(c) and Fig. 4(c) show the trend when varying N_x for Model B and $N_y = 20$ Relay UEs. The discovery time



(a) Model A. (b) Model B, N_x = 10 Remote UEs. (c) Model B, N_y = 20 Relay UEs.

Fig. 3. Average number of discovery periods needed by a Remote UE to discover the first Relay UE ($t(X \sim)$). Mean and 95 % confidence intervals are shown for the system level simulation results.



(a) Model A. (b) Model B, N_x = 10 Remote UEs. (c) Model B, N_y = 20 Relay UEs.

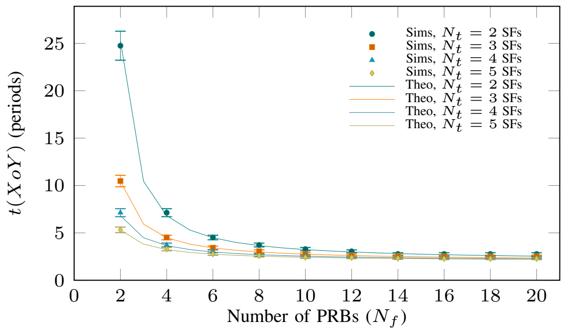
Fig. 4. Average number of discovery periods needed by a Remote UE to discover a given Relay UE ($t(XoY)$). Mean and 95 % confidence intervals are shown for the system level simulation results.

decreases when N_x increases because the probability that at least one solicitation is sent in a non-colliding discovery resource increases with the number of Remote UEs sending solicitations (N_x). Then, the discovery time is affected by all N_y Relay UEs trying to respond to this solicitation in the following discovery period, similar to Model A behavior with $N_y = 20$. Similar trends were observed for other values of N_y and results are not shown due to space limitations.

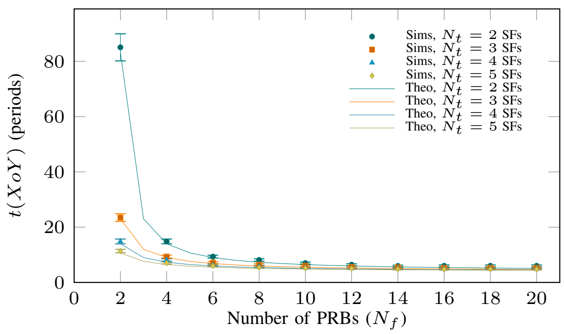
Fig. 3 and Fig. 4 also allow us to see the effect of *txProbability* on the discovery time. When the number of UEs contending for resources is small, the largest discovery times are observed in all plots for *txProbability* = 0.25. When N_y and N_x increases, the benefits of reducing concurrent transmissions with a lower transmission probability become more evident; as seen in Fig. 4 the value of *txProbability* that minimizes the discovery time varies depending on N_y and N_x. These observations are consistent with similar evaluations made for group member discovery in [11].

We observe that the discovery time with Model B is longer than with Model A when using equivalent pool configuration. This is expected, as the Relay UE discovery depends on the successful reception of two messages by different UEs when using Model B, i.e., the solicitation from the Remote UE and the response from the Relay UE. Thus, the average discovery time is at least doubled when using Model B. However, when looking at different pool configurations and for low number of UEs, Model B can provide lower discovery times than Model A. For example, if we consider $N_y = 4$ Relay UEs, Fig. 4(a) shows that for Model A the average discovery time for *txProbability* = 0.25 is 4.32 discovery periods, while in Fig. 4(b) the given Relay UE can be discovered in 2.77 discovery periods for *txProbability* = 1.00, or in 3.41 discovery periods for *txProbability* = 0.75 when using Model B. Although we have focused our analysis on time metrics, it is important to keep in mind that the difference in the dynamics of the discovery models impacts other metrics such as energy consumption, which may balance out the extra time needed by Remote UEs when using Model B.

In Fig. 5 we illustrate the impact of the resource pool size on the discovery time for both models. Increasing N_f



(a) Model A.



(b) Model B.

Fig. 5. Average number of discovery periods needed by a Remote UE to discover a given Relay UE ($t(XoY)$). Parameters: *txProbability* = 0.50, $N_y = 20$ Relay UEs and $N_x = 20$ Remote UEs. Mean and 95 % confidence intervals are shown for the system level simulation results.

impacts favorably the discovery time, but we observe that the benefits become negligible for larger values of N_f. Increasing N_t provides considerable reductions in the discovery time. However, increasing the discovery resource pool size may come to the expense of reducing the time and frequency resources available for other ProSe operations.

Our analytical models and system level simulator could be used by network operators to select a suitable configuration depending on the targeted performance, expected deployment, and use cases. A typical use case example in the public safety context is a group of First Responders working on an incident in an area with partial network coverage. In this scenario, N_y units stay in the in-coverage area and their devices act as Relay UEs. The other N_x units move to the out-of-coverage area and their devices act as Remote UEs. In this context, operators can use our models to search for the combination of N_f, N_t, and *txProbability* parameters that minimizes the discovery time, i.e., $t(XoY)$ or/and $t(X \sim)$, for the N_x out-of-coverage units, and thus minimize the impact on their service continuity. As the number of units responding to an incident is highly variable, operators can use the models to find a configuration that can provide acceptable results for the largest number of expected N_x and N_y combinations. Furthermore, dynamic algorithms that choose suitable configurations depending on local conditions could help to further improve the discovery performance and are currently open research topics.

V. Conclusions and Future Work

The UE-to-Network Relay discovery time in UE-Selected mode is affected by the discovery pool configuration, the amount of UEs contending for discovery resources, and the discovery model used by the ProSe-enabled UEs. In this paper, we developed a model to quantify the average time taken by a Remote UE of interest to discover any Relay UE and a given Relay UE in proximity depending on those parameters. We validated the model using system level simulations and we have shown the sensitivity of the protocol to the discovery model, number of UEs participating on the discovery, and pool configurations. In future work we plan to extend the models to quantify the time a Remote UE of interest takes to discover all the Relay UEs in proximity and study its impact on the Relay UE selection process. Further extensions of our work will analyze the UE-to-Network Relay discovery protocol under non-ideal channel conditions, considering different propagation environments, and discovery packet recovery based on SINR.

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