A Novel Adaptive Transmission Algorithm for Device-to-Device Direct Discovery

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***Abstract*—In this paper we study and improve one service used for Proximity Services and Device-to-Device (D2D) communications: D2D Direct Discovery. As defined in the Third Generation Partnership Project, for both in-coverage and out-of-coverage cases, resource pool parameters, including the transmission probability (in *UE-Selected* mode), are configured in advance. This means that they are independent of the network conditions and the number of users. Thus, we propose an adaptive algorithm which takes into account the available resources and the number of nearby users as they are being discovered, and adapts the transmission probability accordingly. This algorithm improves the overall performance of the discovery process. It reduces the time needed to complete the discovery within a group of UEs and makes it dynamic and adaptable to changing environments.**

***Index Terms*—Long Term Evolution (LTE), Device-to-Device (D2D), Discovery, Proximity Services (ProSe), Simulations, Performance, Adaptive Algorithm**

I. Introduction

The Third Generation Partnership Project (3GPP) introduced the notion of Proximity Services (ProSe) to Long Term Evolution (LTE) in its Release 12. ProSe enable Device-to-Device (D2D) communications services between nearby User Equipment (UE) [1]. It is incorporated in the existing LTE Advanced services and networks [2] with the goal to offload traffic from the network and provide extra capacity. It also extends the network coverage in scenarios with failed or non-existent infrastructure [3]. One of the new services that was defined to enable this D2D communication was the discovery of nearby users and applications. This service was initially limited to UEs within network coverage for both commercial and public safety usage. In Release 13, it was extended to work in out-of-coverage cases for public safety applications.

In the in-coverage scenarios, the discovery configuration is broadcast to the discovery-eligible UEs through messages from the Evolved Node B (eNB) [4]. However, if no network assistance is used, the UEs use pre-configured parameters. The relevant configuration comprises the discovery period of configurable length (between 0.32 and 10.24 seconds), the resource blocks to use, and the discovery bitmap that indicates which subframes could be used for discovery. It also specifies the number of repetitions (i.e. how often this bitmap is repeated within the discovery period), the number of retransmissions of the discovery message, and the transmission probability.

In [3], operators are given the option of using either Evolved Packet Core (EPC)-level discovery, so that the core network has more control over the discovery process, or direct discovery. In addition, for privacy reasons, discovery can be either open or restricted. In the latter case, explicit permission is required from the device that is being discovered.

3GPP defined two discovery models where Model A is an unconditional broadcast of announcements described as “Here I am!” sent by UEs, and Model B is based on a request/response process (“Who is there?” “I am here!”). Furthermore, the way discovery resources are allocated defines the type of discovery. Type 1, referred to as “UE-selected”, allows the device to autonomously and randomly select the radio resources from the resource pool to transmit the discovery message. In type 2B, noted “scheduled”, the eNB provides a dedicated resource allocation for each announcing UE on a UE-specific basis. We are interested in D2D direct discovery, model A, type 1 where UEs do not rely on eNBs for resource selection and vicinity awareness. In such scenarios, independently of the network coverage, the discovery parameters are defined beforehand. They do not take into account the potential diversity in group topologies nor the dynamics introduced by the users’ mobility. Therefore, a flexible and adaptive discovery algorithm is needed in order for the discovery process to be executed efficiently and without requiring a large number of resources.

In this paper, we propose an algorithm that allows UEs performing discovery to tune the transmission probability based on the available resources and the number of UEs discovered throughout the discovery process. This allows a quick convergence to the optimal transmission probability, resulting in a faster and more efficient discovery.

This paper is organized as follows: In Section II, we provide a review of the related work and literature. We describe our novel adaptive algorithm and the relevant assumptions we used in Section III. In Section IV, we use system-level simulations to evaluate its performance and efficiency. Finally, we draw the conclusion and outline our future work in Section V.

II. Related Work

The available research on D2D has mostly focused on the communication performance. Nevertheless, there are a few significant contributions in the literature that provide insight into this process. Sun et al. [5] provide a summary on D2D synchronization, discovery, and communication, as stated in the 3GPP specifications at the time (March 2014). Xu et al. [6] show that if UEs are using scheduled mode and are within cell coverage, it is easier to avoid collisions and improve discovery. The authors propose to use the eNB to gain knowledge of the UEs that want to participate in D2D, and allocate the resources for discovery based on their position and the number of UEs in the network. Similarly, Choi et al. [7] propose another network-assisted model where the eNB efficiently allocates resources for discovery as it is aware of all the discovery traffic going on in the cell. Also, using the eNBs to improve the discovery process, Ngo et al. [8] use two eNBs to calculate the relative distance between UEs, and presume that this knowledge can be used to accelerate the discovery process. However, these proposals focus only on network-assisted discovery where the eNB is in control, therefore limiting their improvements to in-coverage scenarios.

The most notable contribution to out-of-coverage discovery in the literature is the proposal by Li et al. [9] of a static scheme to control interference. Instead of basing the transmission of discovery messages on a transmission probability, the authors propose using a scheme that replaces the randomness of the probability with predictable deterministic "equivalent" transmissions (i.e., instead of a transmission probability of 0.25 each period, they propose one transmission every 4 periods). However, this model cannot react to changes in the size of the group or in the transmission conditions.

Griffith and Lyons [10] propose a theoretical model that calculates the optimal value of the probability of transmission for a given set of parameters (i.e., number of UEs and resources). The model assumes a prior knowledge of the number of users in the discovery group, which is most likely not the case in reality. In addition, it considers an ideal propagation environment, disregarding fading and interference factors. In this paper, we build upon their research by using the analytical model proposed in [10] as the basis of an adaptive algorithm where the UEs adjust their transmission probabilities over time. By doing this, we manage to first overcome the requirement of knowing the number of UEs to be discovered, and then make the enhanced discovery process work with more realistic propagation environments, taking into account loss and recovery probabilities.

To the best of our knowledge, this work is the first one to propose such an algorithm that improves the overall performance of out-of-coverage discovery by dynamically adjusting one of its parameters to different environments, group topologies, and resource configurations.

III. Adaptive Algorithm

A. System Model

In Table I, we provide a list of symbols we use in this paper. We assume that each UE sends one discovery message (i.e., one announcement) after checking its transmission probability threshold, each time it is supposed to do discovery. For clarity, and without loss of generality, we will consider that the number of applications is equal to the number of UEs. In a general case, some UEs would be interested in monitoring just one or two applications in order to discover their corresponding UEs. However, at the physical layer, the UEs receive all announcements from all surrounding UEs independently of their applications of interest, and the filtering happens in the upper layers. That is why we consider that all UEs are interested in announcing their own application and in monitoring all other applications within the group.

TABLE I: List of Symbols

Symbol	Definition
N_f	Number of resource block pairs available for discovery
N_t	Number of subframes available for discovery
N_r	Total number of resources in discovery pool
UE_X	Randomly chosen UE
n	Number of UEs discovered by UE_X
N_n	Number of new UEs discovered by UE_X
N_o	Number of UEs previously discovered by UE_X
N_u	Number of UEs in the discovery group
N_X	Number of UEs discovered by UE_X plus UE_X itself
θ	Optimal transmission probability for UE_X
UE_n	Late arrival UE

When sending announcements, UEs choose the resources to use from a defined resource pool. The pool is defined by given numbers of subframes N_t and of resource block (RB) pairs N_f. The total number of resources N_r is equal to $N_t \times N_f$.

According to the 3GPP working assumptions [3], the channel used for D2D is half-duplex. So, if a UE transmits a discovery message in one subframe, it cannot receive any other discovery message transmitted by any other UE in that same subframe. Taking this into account, [10] presents an analytical model proving that D2D direct discovery performance can be enhanced using an optimal value of the transmission probability θ, defined by Eq. (1). The use of this value makes the discovery faster.

$$\theta = \frac{2N_r + N_t(N_u - 1) - \sqrt{4N_r(N_r - N_t) + N_t^2(N_u - 1)^2}}{2N_u}. \tag{1}$$

An exception has been identified when the number of UEs is small compared to the number of resources available for discovery: If the condition in Eq. (2) is fulfilled, the optimal value of θ is 1 (meaning that the UEs will transmit discovery announcement messages all the time).

$$N_u < \frac{N_r(N_t - 2) + N_t}{N_t - 1} \quad \text{where} \quad N_t > 1^1. \tag{2}$$

As we can see, the computation of the optimal transmission probability requires prior knowledge of the number of UEs in the group (N_u), which means that in a changing environment the UEs need to learn that information dynamically.

B. Adaptive Discovery Process

We consider a group of N_u users that decide to start using D2D communication at the same time (e.g., when a group of

[1] If $N_t = 1$, UEs would always announce at the same subframe and would never be able to discover each other because of the half-duplex constraint.

emergency responders arrives at an incident location). They hold discovery-capable equipment, and start sending discovery messages using a pre-configured transmission probability and allocated resources N_f, N_t, and N_r.

We assume that each UE (noted as UE_X) has already detected N_o UEs in previous discovery periods (i.e. $N_o = 0$ at the beginning of the discovery process). At the end of the current period, UE_X successfully receives discovery messages from n different UEs. However, only N_n of those n received discovery messages have never been received before. N_X represents the total number of UEs that UE_X succeeded to discover, including itself. When the discovery process is complete, and if the UE_X succeeded to discover every UE in the group, N_X should be equal to N_u.

$$N_X = N_o + N_n + 1\,; \tag{3}$$

where $N_o < N_u$, $N_n \leq n < N_u$, and $N_X \leq N_u$.

The adjusted transmission probability of UE_X for the next period is the approximation to the nearest non-zero multiple of 0.25 less than or equal to 1 (to conform to the values allowed by 3GPP) of the final result of Eq. (1) and (2) using Eq. (3).

C. Proposed Algorithm

For any given UE_X, the computation of the adjusted transmission probability will follow Algorithm 1.

Data: N_o is the total number of different UEs discovered by UE_X in previous discovery periods
for *any given UE_X performing D2D discovery* **do**
  UE_X receives discovery messages from n UEs;
  $N_n = 0$;
  for i *in* $[1, n]$ **do**
    if *UE_i was never discovered before* **then**
      increment N_n;
    end
  end
  $N_X = N_o + N_n + 1$;
  if $N_X > 1$ **then**
    compute θ (based on Eq. (1) and (2), replacing N_u by N_X) ;
    round θ to the nearest multiple of 0.25;
    use the resulting value of θ to announce;
  end
  $N_o = N_X - 1$;
end

Algorithm 1: Adjusted Transmission Probability

IV. Simulation and Results

In this section, we present the validation of our algorithm from Section III through simulations in the discrete event network simulator ns-3 [11]. The tool was used to implement D2D direct discovery type 1 according to 3GPP specifications [12] and our adaptive algorithm.

TABLE II: Scenarios

Scenario	Number of UEs	Optimal θ	Approximated θ
A	10	1	1.00
B	20	0.84703	0.75
C	40	0.46184	0.50
D	60	0.31644	0.25

TABLE III: Simulation Parameters and Values

Parameters	Values
UE transmission power	23 dBm
Propagation model	Friis, Cost231
Available bandwidth	50 RBs
Carrier frequency	700 MHz
Discovery period	0.32 s
Number of retransmission	0
Number of repetition	1
Number of resource block pairs	4
Number of subframes	5
Total number of resources	20
Total number of UEs	10, 20, 40, 60
Area Size	200 m $\times$ 200 m
Discovery start	2 s
Total simulations per scenario	100

A. Assumptions

We examined different UEs group sizes varying from 10 to 60 UEs while fixing the resource pool configuration, consisting of 4 resource block pairs ($N_f = 4$) and 5 subframes ($N_t = 5$), which provides a total of 20 discovery resources ($N_r = 20$).

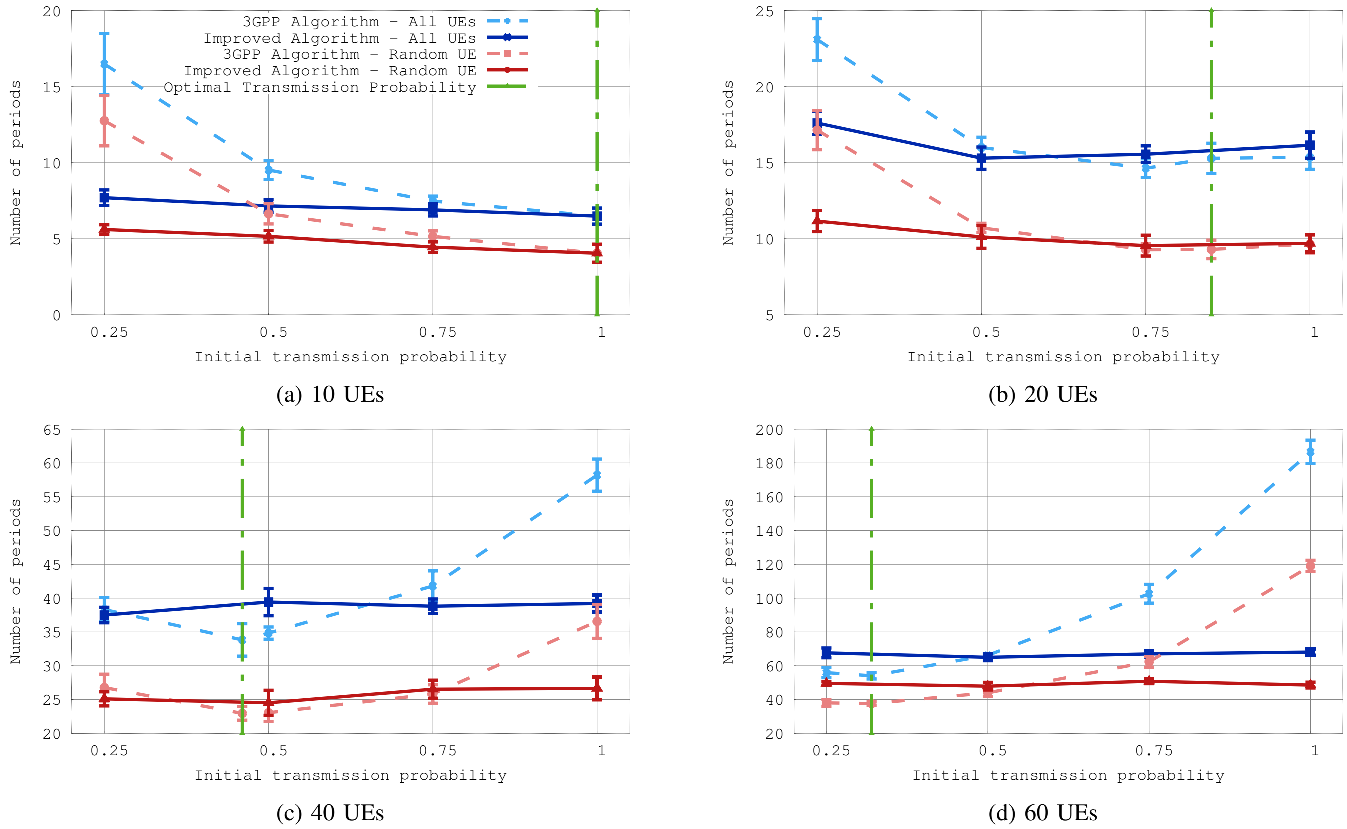
Table II outlines the individual scenarios based on the UE populations used, their optimal transmission probabilities θ and the corresponding transmission probability values allowed by 3GPP. Table III summarizes a list of simulation parameters and their default values.

In each simulation, every UE is able to send announcements using a randomly chosen discovery resource. Users were deployed using a uniform random distribution within an area of 200 m $\times$ 200 m, ensuring that all UEs are within range of each other and therefore every UE can discover all other UEs in the group. We are aware that this doesn't address the hidden nodes problem, but the focus of this paper is on efficient mechanisms for a faster direct discovery.

We compare our adaptive algorithm to the standard 3GPP algorithm. Initially, we set the transmission probability to a defined value. As the 3GPP discovery algorithm is static, this pre-configured value will be used for the whole simulation when that algorithm is used. However, when using our proposed algorithm, all UEs will compute and update the value of their own transmission probability over time.

B. Stationary Topology

We assumed that all UEs are stationary. We were interested in computing and evaluating the time (measured in number of periods) required for all UEs in the group to discover each other, and the time required for one random UE to discover everyone else. We started our validation process with a baseline configuration where we discard all colliding discovery messages, and we used a simple propagation model with minimal propagation errors as assumed in [10].



(a) 10 UEs

(b) 20 UEs

(c) 40 UEs

(d) 60 UEs

Fig. 1: Stationary Topology: Number of periods needed for all UEs to discover all other UEs in the group and for one random UE to discover everyone else in the group (Baseline)

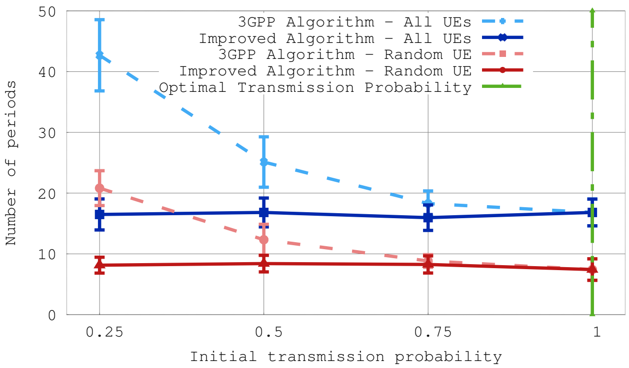
We ran simulations for all four scenarios from Table II. Fig. 1 represents the corresponding averaged results, along with a confidence interval of 95 %.

We observe that, in most cases, our algorithm (represented by the solid lines) outperforms the 3GPP algorithm (represented by the dashed lines), and only performs slightly worse when the transmission probability is configured with the optimal value from the start. The results for the number of periods needed for all UEs to discover all other UEs show trends similar to the results for the number of periods needed for one random UE to discover everyone else. In addition, the line corresponding to the adaptive algorithm performance fits a flat plot, which means that, independently of the initial transmission probability used, the number of periods needed to complete discovery is roughly the same.

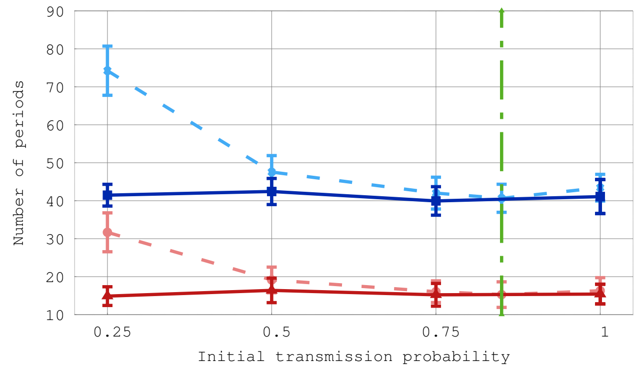
For each scenario from Table II we can see how, without prior knowledge of the size of the group, there is a 25 % chance of starting the discovery process with the optimal transmission probability value. For that case, the 3GPP discovery algorithm would present better results given that the discovery process uses, since the beginning, the optimal configuration. However, we showed that the adaptive algorithm succeeded to perform similarly. For the other 75 % of the possible cases, using the pre-configured transmission probability, the UEs take longer to discover each other using a static algorithm. Our adaptive algorithm allows the UEs to complete the discovery faster, independently of their initial transmission probability, with the performance increase being significant in some cases. As we can see in Fig. 2d, using a transmission probability of 1 makes the 3GPP discovery take twice as long as our adaptive algorithm. This is due to our algorithm succeeding to detect the presence of a large number of UEs in the vicinity and adapting the transmission probability to the optimal value. We also note that, by the end of the discovery process, all UEs end up using the same transmission probability value. Therefore, the adaptive algorithm helps the UEs converge to the optimal θ, which means that future changes to the groups (e.g. new UEs arriving) will be discovered more efficiently, as the UEs are already carrying out the discovery process with an optimal configuration. This statement will be explored in Section IV-C, when a dynamic topology is considered.

Once we have obtained promising results with the baseline configuration, we need to evaluate the performance when the channel is not ideal. For this purpose, we modify the previous configuration to represent a more realistic environment by using the propagation model "cost231" [13] and we try to retrieve at most one discovery message when there are collisions. Results of this Loss and Recovery configuration, along with a confidence interval of 95 %, are shown in Fig. 2.

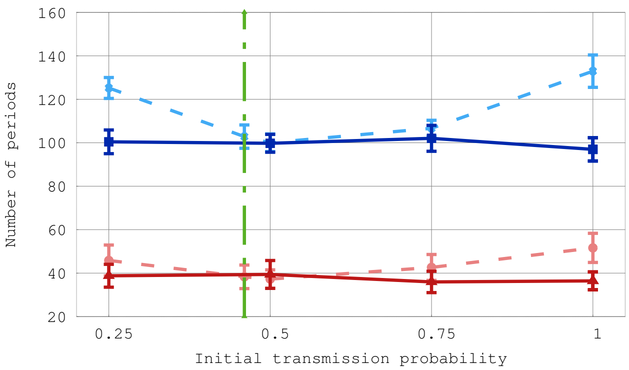
As we can see, we obtained homogeneous plots with



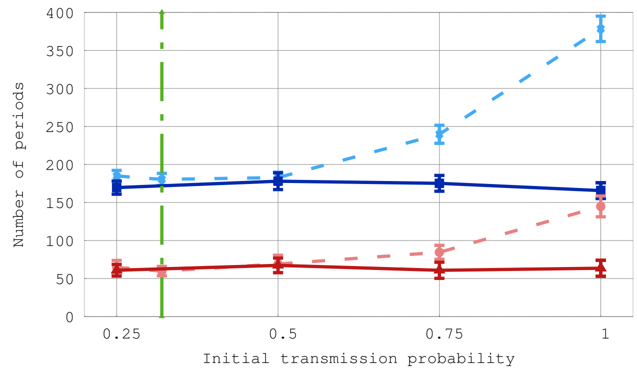
(a) 10 UEs



(b) 20 UEs



(c) 40 UEs



(d) 60 UEs

Fig. 2: Stationary Topology: Number of periods needed for all UEs to discover all other UEs in the group and for one random UE to discover everyone else in the group (Loss and Recovery)

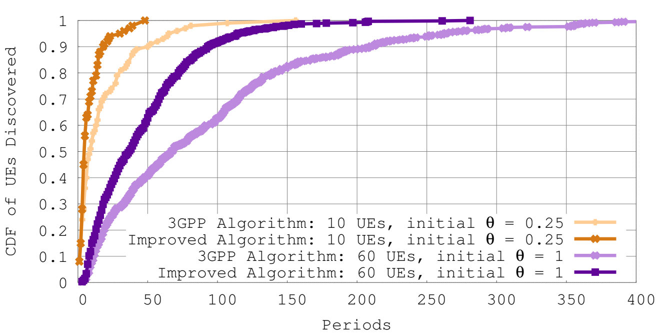


Fig. 3: Stationary Topology: CDF of UEs discovered in the group versus number of periods (Loss and Recovery)

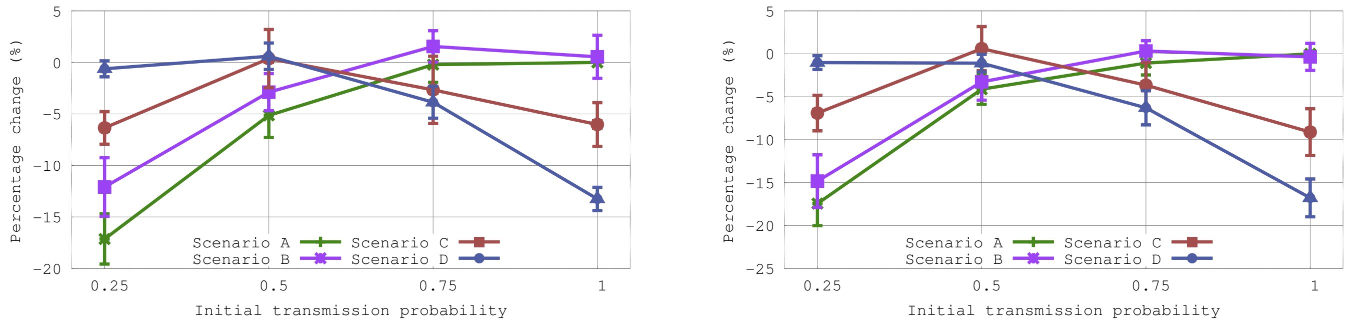
conclusions similar to those of the baseline scenario regarding the algorithm performance and matched curves. As expected, using a more stringent propagation model means that the discovery takes longer, even though the recovery process manages to save some of the announcements. We notice that the theoretical optimal value of the transmission probability is still valid even when using a more realistic error model.

Another way of showcasing the difference that our algorithm makes in the performance of the discovery process is to plot the Cumulative Distribution Function (CDF) of UEs discovered over time for two specific cases. We compared the number of UEs discovered in the group using the 3GPP algorithm and our adaptive algorithm. Fig. 3 shows the plots for scenario A using an initial transmission probability equal to 0.25, and scenario D for an initial transmission probability equal to 1. We have validated that the rest of the cases also show similar behaviors, with the distance between the curves being proportional to the differences shown in Fig. 2.

As we can see, our algorithm provides a significantly faster discovery. For example, for scenario D, when using the 3GPP algorithm, 95 % of the UEs are discovered in 263 periods. However, this value is reduced by more than half (115 periods) when our algorithm is applied, which is a significant improvement in the overall performance.

C. Dynamic Topology

To further evaluate our adaptive algorithm, we assume that one UE, noted UE_n, is joining the discovery group later on. Using its preconfigured transmission probability, UE_n will initiate discovery after the discovery process has already been completed for the other UEs. We verified that, for validation and testing purposes, the introduction of this additional UE does not change the approximate value of the optimal transmission probability in each scenario, mentioned in Table II, despite increasing the number of UEs in each group.



(a) for UE_n

(b) for all UEs in the group, including UE_n

Fig. 4: Dynamic Topology: Percentage change of the number of periods needed to complete discovery

This scenario allows us to evaluate the effect of new arrivals on the UEs' convergence to the optimal transmission probability. We are interested in assessing the time for UE_n to discover the rest of the UEs in the group, and the time for other UEs to detect UE_n's presence. In Fig. 4, we compute the percentage change (comparing the performance of our algorithm to 3GPP's) for UE_n (or all UEs, including UE_n) discovering the rest of the group (or all other UEs, respectively). A confidence interval of 95 % is computed.

When we use the optimal value of the transmission probability since the beginning of the simulations, the difference can be positive (percentage increase) but close to zero. But it is negative (percentage decrease) when using other initial transmission probabilities (i.e., 75 % of the possible cases), which means a reduction in the maximum number of periods needed to complete discovery compared to the 3GPP standard.

In scenario B, the optimal transmission probability is equal to 0.75. If the discovery starts using that value as its initial transmission probability, we record for Fig. 4a an increase of less than 2 % of the time needed to complete the whole discovery process. This only constitutes the worst case. The best registered amelioration is displayed in both Fig. 4a and 4b, for scenario A, when starting with an initial transmission probability equal to 0.25. Our algorithm helped to reduce the maximum number of periods needed by more than 17 %.

Overall, those results show significant improvement, by just taking into account the number of UEs discovered to adjust the transmission probability. There is little cost associated with our simple but efficient proposal. Our adaptive algorithm outperforms the 3GPP algorithm, even in situations where we have UEs joining the discovery group at a later time. It adjusts dynamically to a growing topology, thanks to its adaptive nature.

V. Conclusion and Future Work

In this paper, we proposed a novel adaptive algorithm that allows UEs to improve the performance of the discovery process in UE-Selected mode for LTE D2D. It dynamically adjusts the transmission probability based on vicinity awareness. The efficiency of our proposal was validated with simulations and the results showed that our algorithm reduces the time required for the discovery process in a group of UEs for several configurations. Furthermore, we have shown how our proposal also makes the discovery process perform better when changes in the topology happen.

This contribution opens up several new possibilities for future studies, such as detection of UE departure, and tuning the algorithm for more dynamic scenarios with groups of UEs causing bulk arrivals to and departures from the discovery group.

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