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Device discovery in LTE networks: A radio access perspective

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Device discovery is an integral part of Device-to-Device communications and a key prerequisite for the introduction of proximity-aware services in Long Term Evolution (LTE) networks. In this concept, we provide a comprehensive study on device discovery protocols and we examine the key design aspects towards an LTE-tailored device discovery. We give insights into the radio access approach that can be used for device discovery, considering in-coverage synchronized devices that exploit a dedicated spectrum portion to discover each other. Useful remarks on the optimal theoretical performance in terms of the number of required discovery transmissions and time-slots are presented, while comparative simulation results for various radio access approaches are provided.

1. Introduction

Direct communication has already been introduced by various wireless technologies, such as Bluetooth and WiFi Direct, while its introduction to mobile networks is intensively studied under the term device-to-device (D2D) communications. D2D communications include both unicast and multicast transmissions, which may be performed in one or multiple hops. Compared to the current direct communication technologies, D2D may exploit the coordination from the mobile network and the use of the licensed spectrum to guarantee high quality data and voice connections with no manual network detection/selection. Compared to the conventional mobile communication, the short distance between D2D peers provides better link conditions and, thus, more efficient connection with lower energy consumption. Since the intermediate transmissions to a base station are avoided, higher spatial spectrum reuse levels may be achieved, leading to higher overall spectral efficiency. From the operators' point of view, new business models may be designed, while new types of services or charging policies may be launched. Additionally, the opportunity for D2D communication in out-of-coverage scenarios will inevitably affect the way that current social media and public safety services are provided.

Considering all the aforementioned potential benefits, several works in the literature deal with the technical challenges towards realizing the D2D concept. The main network related aspects for introducing D2D communication in mobile networks are presented in [1] and [2], while thorough surveys on open D2D technical challenges can be found in [3] and [4]. Specific issues related to D2D for Long Term Evolution (LTE) networks are listed in [5]. A key point that emerges from these studies is that the critical prerequisite for the establishment of a D2D connection is the solution of the device discovery problem, i.e., the problem of meeting the communication peers in time, frequency and space prior the establishment of the actual direct communication [6]. Device discovery is also recognized as the main tool that provides devices with an augmented sense of the surrounding network, and, hence, it can be seen as the main vehicle towards enabling proximity-aware services. Presently, there are numerous device discovery approaches in the literature for different technologies and scenarios, defining a vital reference pool for the design of the device discovery in modern mobile networks, such as the LTE [7]. On this basis, we provide a comprehensive study of the device discovery problem in LTE networks. First, we classify state-of-the-art device discovery protocols and provide the key aspects towards an LTE-tailored device discovery. Subsequently, we examine various radio access approaches for device discovery, and discuss the optimal theoretical radio access approach. Finally, we present comparative evaluation results for the access approaches under study.

The remainder of the paper is organized as follows. An overview of the most important categories of device discovery protocols is presented in Section 2. Section 3 focuses on the LTE system and describes comprehensively recent device discovery standardization efforts and LTE-tailored discovery protocols. In Section 4, design constraints toward efficiently exploiting a frequency-time block for discovery are described, while the main radio access approaches that can be used for device discovery are presented. Section 5 deals with performance aspects, and describes useful remarks on the optimal theoretical performance of the radio

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Table 1
An overview of device discovery protocols.

Classification criterion	Categories	Advantages	Disadvantages	Example
Network assistance level	Network-assisted	■ Collisions control ■ Radio resource optimization ■ Multi-hop discovery	■ Inapplicable to out-of-coverage scenarios ■ Signaling	[11,22,23,26,27],
	Direct discovery	■ Applicable to out-of-coverage scenarios ■ Scalability	■ Collisions ■ Synchronization	[13,19,24,25,28–31]
Spectrum sharing approach	Multiplexed	■ On demand discovery ■ Dynamic radio resource utilization	■ Inapplicable to out-of-coverage scenarios ■ Prolonged discovery time ■ Scalability issues	[11,27]
	Frequency-time block	■ Flexibility ■ Scalability	■ Collisions ■ Synchronization	[12,13,19,20–26,28–31]
Radio access approach	Random-access	■ Applicable to out-of-coverage scenarios ■ Simplicity	■ Collisions ■ Scalability issues	[11,21,22,25,26,28–31]
	Contention-based	■ Applicable to out-of-coverage scenarios ■ Collision avoidance	■ Scalability issues ■ Extra radio resources for the contention resolution	[19,20]
	Dedicated-access	■ Radio resource optimization ■ Collision avoidance	■ Signaling ■ Complexity	[12,13,24,27],
Discovery signal format	Data signal	■ One-step discovery ■ Fast D2D establishment after discovery	■ High radio resource consumption	[13,22,26,27,29]
	Sequence-based	■ Low radio resource consumption ■ No modulation/demodulation	■ Sequence mapping to device identities is required	[11,23,24]
	Hybrid	■ More flexible than Data-signal and more efficient than sequence-based	■ Complexity	[22]
Handshaking approach	Request-Response	■ Reliability ■ On demand discovery	■ Time and radio resource consumption	[20,23,25,27,28]
	Announcing	■ Scalability ■ Applicable for continuous discovery	■ Multiple device discovery ■ Scalability issues	[11,13,19,21,22,24,26,29–31]
Synchronization level	Synchronous	■ Efficient spectrum access	■ Applicable to scenarios with infrastructure or GPS support	[11,13,21,22,23,26,27,29,30]
	Asynchronous	■ Applicable to ad hoc/out-of-coverage scenarios	■ Additional radio resources for the synchronization mechanism ■ Higher energy consumption	[19,20,24,25,28,31]
User dependence	Autonomous	■ Applicable to M2M communications ■ User Transparency	■ Privacy issues	[11,13,21–24,26]
	User/Application -Triggered	■ Privacy control ■ On demand discovery	■ Scalability issues	[19,20,25,27,28]

access procedure. Section 6 presents quantitative evaluation results, and, finally, Section 7 contains our conclusions.

2. Device discovery protocols

In this section, different classifications of the device discovery protocols in the literature are presented. More specifically, seven classification criteria are studied, namely the *network assistance level*, the *spectrum sharing approach*, the *radio access approach*, the *discovery signal format*, the *handshaking approach*, the *synchronization level*, and the *user dependence*. The key protocol categories for each one of these classifications are described below. For the convenience of the reader, Table 1 summarizes the major advantages and disadvantages of each protocol category together with a set of representative references.

Network assistance level. This classification criterion categorizes the discovery protocols according to the level of the network involvement in the discovery process, i.e., the level of dependence on discovery management from an access or core network entity. On the one hand, the *network-assisted device discovery protocols* include protocols where the network: (i) defines the radio resources that will be used for discovery, and/or (ii) specifies the access priority to the radio resources (resource allocation), and/or (iii) collects discovery information to identify the vicinity of each device. On the other hand, discovery protocols, in which the discovery process is not supported/controlled by the network, called here *direct device discovery protocols*, are based on the pure ad hoc mode, and the discovery peers have to deal with synchronization and spectrum sharing/access in a distributed manner.

One of the advantages of the *network-assisted device discovery protocols* is that potential collisions can be avoided (e.g., [8]), while the discovery time can be effectively managed by the network. Additionally, the discovery information can be centrally collected and exploited to optimize radio resource utilization for single-hop and multi-hop D2D communication. Moreover, the discovery process can be accelerated through various ways, such as by exploiting information about the cell that the discovering peers are associated with, or by enabling discovery signal transmissions only when there is a high probability to find discovery peers subscribed to the same service [9]. The drawback for the *network-assisted device discovery protocols* is the signaling overhead and the need for a continuous attachment to a central node. On the other hand, the key advantage of the *direct device discovery protocols* is the scalability and the applicability in out-of-coverage scenarios, offered due to the distributed and network-independent notion of the approach. The disadvantage here is that for in-coverage scenarios vital information from the network is not exploited, while collision and synchronization issues have to be faced. For instance, the network may be aware of the fact that a target device is attached to a different cell from that of the discovery transmitter. This information is vital in order to avoid discovery transmissions to a physically unreachable target device.

Spectrum sharing approach. This classification criterion categorizes the discovery protocols according to the way the radio resources are shared between transmissions for communication (either direct or cellular) and transmissions for discovery. The first category here is the *device discovery protocols with multiplexed transmissions* where communication and discovery transmissions can be multiplexed in the frequency and time domain (FDM/TDM). Practically, in this category there is no specific spectrum portion that is assigned to a group of discovery peers for the device discovery procedure. Accordingly, the second category of this classification includes device discovery protocols where a specific frequency-time block is dynamically or statically assigned to a set of discovery enabled devices. We refer to the protocols of the latter category as *device discovery protocols in frequency-time block*.

The *device discovery protocols with multiplexed transmissions* are more suitable when the discovery needs are not continuous and practically the discovery procedure is triggered on demand for specific devices. For instance, in the case where a device wants to check whether a target peer that uses a specific service is in its vicinity. However, for large numbers of discovering peers the discovery process can be prolonged with negative effect on the devices' battery life. The protocols in this category belong also to the category of network-assisted protocols (e.g., [11]), since the involvement of the network (e.g., the eNB) is required for multiplexing the discovery transmissions with the conventional cellular ones. Practically, the eNB should have the full control of the spectrum sharing procedure to dynamically serve individual discovery requests and conventional cellular communication requests (e.g., [10]). On the other hand, the *device discovery protocols in frequency-time block* allow the discovery devices to wake up only in a specific time-period to take part in the discovery process. Also, since a frequency-time block is devoted for discovery transmissions, high flexibility is provided for the radio resource sharing among discovery transmitters.

Radio access approach. The categorization here is based on how the discovery peers access the radio resources to transmit device discovery signals. The first category is the *random-access device discovery protocols,* referring to a totally random selection of radio resources for a discovery signal transmission. The second category is the *dedicated-access device discovery protocols* where the spectrum access problem is resolved by following a centralized or distributed radio resource allocation scheme. Finally, a contention-based collision-avoidance access can be applied, which defines the *collision-avoidance device discovery protocols*.

For the *dedicated-access device discovery protocols* there are two main approaches. The first is the centralized one where a central node decides how the available spectrum resources are allocated to the devices (e.g., [12]). The advantage here is that potentially an optimal allocation can be achieved, at the cost of extra signaling to build the proximity map at the central node. The second and more challenging approach for the *dedicated-access device discovery protocols* is the distributed one where pseudorandom sequences or frequency hopping schemes are used (e.g., [13]). As shown in [14], the performance of the protocols in this category is much better than that of the totally random access schemes. Based on this observation, a set of solutions has been proposed exploiting mainly the properties of prime numbers (e.g., [15–18]). However, the simplicity and the independence of the network support provided by the *random-access device discovery protocols* are quite appealing characteristics. On the other hand, the key advantage of the *collision-avoidance* approaches is that they can sufficiently handle the potential collisions among discovery transmissions in a fully distributed fashion [19,20], at the cost of spending some radio resources to resolve the contention.

Discovery signal format. Device discovery protocols can also be classified according to the format of the discovery signal, referring to the information that is included in the discovery signal. Three different categories are identified. The first one, called here as the *sequence-based device discovery protocols*, refers to protocols where a specific sequence is used as a beacon for the discovery process. The second category, called here as the *data-signal device discovery protocols*, includes protocols where specific information is included in the discovery signals. Finally, there are protocols that lie in-between these two categories, called here as the *hybrid-signal device discovery protocols,* where the discovery process exploits both sequence beacons and information-rich discovery signals.

The simplicity and the low radio resource consumption are the main advantages of the *sequence-based device discovery protocols.* However, for these protocols a second discovery step (e.g., [11]) or an indirect map of device identities to sequences is required (e.g., [21]) to complete the device detection. On the other hand, in *data-signal device discovery protocols,* the discovering signals are enriched with useful information, which may lead to a neighbor discovery in one step (with a single transmission) and can be used for accelerating the establishment of a D2D communication after the discovery. However, more radio resources are required and modulation/demodulation is needed for each discovery signal. The main difference between the sequence-based protocols and the data-signal ones is that in the former the discovery signals do not carry data that refer to the transmitter. Actually, in sequence-based protocols each device is assigned a sequence that indirectly refers to its identity. This means that no modulation demodulation is applied to the discovery signal. An example of this procedure is the operation of the physical random access channel (PRACH) of the LTE system, where orthogonal sequences are generated from the same Zadoff-Chu sequence and used by the devices to access the spectrum. Finally, *hybrid-signal device discovery* protocols have been proposed. They try to reap the benefits of both approaches by using a sequence as a prefix to the data-enriched discovery signal [22].

Handshaking approach. This classification criterion divides the device discovery protocols into those that are based on a request-response procedure, refer to here as the *request-response device* *discovery protocols*, and the *announcing device discovery protocols*, which are based on beacon transmissions that announce the presence of a device to its neighborhood and listen to other devices' announcing signals.

In the first category, each discovering device sends a request and waits for response from one or multiple discoverable peers. In the case of multiple discoverable devices the use of sequences is preferable [23]. This category of protocols is appropriate for a low number of devices and applicable in discovery scenarios for discovery peers that are subscribed to the same application. On the other hand, for continuous discovery, the request-response handshaking is time and resource consuming and the *announcing device discovery protocols* are preferred. The *announcing device discovery protocols* are also suitable for constantly tracking the evolution of the network topology. However, for these protocols the selection of the announcing period is an open issue.

Synchronization level. This criterion examines whether a device discovery protocol is applicable to synchronized devices. The first category includes protocols that assume synchronization among the devices and are referred to as *synchronous device discovery protocols*. The second category, called here *asynchronous device discovery protocols,* includes protocols that provide jointly discovery and synchronization. To be more precise, the difference between the synchronous and asynchronous discovery protocols is that the former apply only to an environment that the synchronization is guaranteed. Asynchronous protocols, on the other hand, provide integrated solutions where the neighborhood detection is applicable in asynchronous environments (in other words, loss of synchronization does not affect their applicability). As expected, the *synchronous device discovery protocols* have a head start in terms of performance. However, they require a central coordinator or a common global clock. On the contrary, the *asynchronous device discovery protocols* are appropriate for out-of-coverage scenarios, at the cost of higher energy and spectrum consumption. Some of the *asynchronous device discovery protocols* resolve the synchronization prior to the actual discovery transmissions, such as the WiFi ad hoc mode in [19] and the Firefly-inspired scheme in [24], while other protocols of this category bypass the problem by using collision-avoidance methods [25]. Actually, the approaches in the latter case do not force the devices to transmit on a slotted basis; instead, they let discovery enabled devices to access the radio resources on demand by postponing their transmissions according to a random back-off time window.

User dependence. This classification criterion examines whether the users are directly or indirectly involved in the discovery process. The involvement refers either to a direct triggering of the discovery process by the user or a specific proximity application; thus, we use the term *user-triggered device discovery protocols*. On the contrary, *autonomous device discovery protocols* have been defined where the devices discover each other in a continuous and user/application transparent way.

User-triggered protocols support on demand discovery, controlled manually by the user or initiated by a discovery application. In user-triggered device discovery protocols, end-users have full control of the process. This approach guarantees privacy, but lacks scalability. The application-triggered device discovery protocols restrict the number of devices that can be discovered to those that have subscribed to a specific service. This may save energy and resources for a single application; however, useless discovery repetitions may be performed in the physical layer when multiple independent proximity applications are used. To clarify this statement, assume that an application requests proximity information, and thus the physical layer sends discovery signals (a consequence of some neighbors being detected). If a second application requests proximity information, the procedure is repeated. However, the second transmission of the discovery signals may be redundant, since proximity information is already available at the application layer. In other words, in the case that the discovery process is performed on demand, triggered by the application layer, cross-layer coordination or collaboration of the proximity applications is required. The *autonomous device discovery protocols* refer to an open discovery approach where all physical neighbors of a device are discoverable. These protocols are applicable to Machine-to-Machine (M2M) communications where autonomous devices discover their neighbors and establish direct communications. However, a minimum permission of the end-user is needed to guarantee privacy.

3. Device discovery protocols for LTE networks

Standardization efforts for the device discovery procedure in LTE networks have already begun in 3GPP Rel. 12 ([32–34]), while recent recommendations for the main discovery scenarios can be found in [35]. In parallel, a variety of LTE discovery protocols has been proposed in the literature (e.g., [11,23,26]). In this section, first we discuss standardization efforts for device discovery in LTE networks, in combination with the classification criteria introduced in Section 2. Subsequently, we summarize the important aspects that should be considered towards an LTE-tailored device discovery, and refer to some related solutions.

3.1. LTE device discovery aspects

Network assistance level. 3GPP promotes both in-coverage and out-of-coverage D2D communication with priority to public safety services. For the in-coverage scenarios, the discovery procedure is expected to adopt network-assisted protocols to increase the efficiency of the discovery procedure, as well as to guarantee that the control of the communication remains at the operator's hands (owner of the spectrum).

Spectrum sharing approach. In terms of spectrum sharing, both device discovery protocols in a frequency-time block and protocols with multiplexed transmissions abide by the 3GPP recommendations. In 3GPP TR 36.843 [32], the first category is referred to as discovery Type 1, while the second category as Type 2. More specifically, in Type 1, a pool of radio resources is allocated to discovery enabled devices or Users Equipment (UE), while, in Type 2, specific discovery resources are allocated to each UE either for instant transmission or in a semi-persistence way. For both Type 1 and Type 2 discovery, UEs transmit their discovery signals and receive discovery signals from other UEs subject to half-duplex constraint, one of the key practical constraints for the transceivers that affects the performance of the discovery process, as explained in the next section.

Radio access approach. The radio access approach for device discovery in LTE systems is an open issue. The main dilemma is which part of the conventional cellular spectrum, DL or UL, could "donate" some radio resources for the discovery transmissions. This donation means that part of the cellular spectrum (DL or UL) will be allocated for discovery transmissions (LTE Type 1 discovery (e.g., [13])) either exclusively or under a spatial spectrum reuse scheme ([36,37]). In both cases, potential interferences may occur among the discovery transmissions, resulting in discovery collisions that exacerbate the performance of the discovery process. However, in the UL case, the performance is further affected, since there is also interference from the cellular transmissions. The option of exploiting the UL band for discovery transmissions is recommended by 3GPP [35]. This option is also adopted by the majority of the approaches in the literature, mainly due to the fact that the UL spectrum portion is more appealing for spatial spectrum reuse and it is less utilized compared to the DL band (the end-devices commonly demand more DL than UL resources).

Another important aspect that should be considered in designing LTE-compliant radio access is that both UEs in RRC_IDLE mode and in RRC_CONNECTED mode should be supported. Note that the discovery approaches that use the conventional resource allocation process may involve only RRC_CONNECTED UEs, since the RRC connection process is required before the base station or evolved Nobe B (eNB) performs the radio resource assignments to UEs [27,38]. Thus, they are more valid for checking the proximity of two UEs during the D2D communication, or in device discovery scenarios where the transmission of interference-free discovery signals is of high importance (e.g., public safety scenarios). In [38], it is shown that discovery approaches that are applicable in cases where the UEs are in IDLE mode consume less energy, but, after the detection of the peers, they need more time for the establishment of the D2D connection. It is worth noting that the discovery solutions that involve UEs in IDLE mode should be conducted in a dedicated spectrum portion, i.e., a spectrum portion exclusively allocated for discovery transmissions. A potential approach is to adopt a periodic semi-persistent allocation of a frequency-time block for device discovery transmissions. Since the UEs in IDLE mode do not listen to the DL resource allocation messages in each subframe, the allocation messages for the device discovery transmitters may be included in a System Information Block (SIB).

Discovery signal format. The main approach that is supported by 3GPP for the discovery signal format is to be a data-enriched signal. However, there is also option of transmitting a “discovery preamble” prior to transmission of a discovery data-signal, which will be composed by a sequence similar to the D2DSS signal [32].

Handshaking approach. 3GPP endorses the design of both *request-response device discovery protocols* and *announcing device discovery protocols*. Actually, the protocols in the latter category may follow the discovery Model A ("I am here") while the former ones the discovery Model B ("who is there"/"are you there"), as described by 3GPP in [51].

Synchronization level. Regarding the synchronization level, synchronization through D2D synchronization sequences is considered for both in-coverage and out-of-coverage scenarios. To this end, a D2D synchronization source (the base station or a delegate UE in out-of-coverage scenarios) transmits D2D synchronization signals (D2DSS), which may be used by UEs to obtain time and frequency synchronization. Consequently, the main focus is on synchronous device discovery protocols.

User dependence. Regarding the user dependence criterion, two basic categories have been defined by 3GPP. The *Open ProSe Discovery* and the *Restricted ProSe Discovery*. The open ProSe Discovery refers to the case where there is no explicit permission from the UE being discovered, while the Restricted ProSe Discovery only takes place with explicit permission from the UE being discovered. The potential restriction is an application layer operation, and, thus, the physical layer device discovery procedures are identical for both categories.

3.2. LTE-tailored discovery protocols

Various LTE-tailored discovery protocols have been proposed in the literature (e.g., [11,26,22]). In [11], a device discovery protocol is proposed for the in-coverage scenario, considering a set of UEs attached to the same cell. The key advantage of this work is that it is compliant to the 3GPP standardization requirements (for in-coverage discovery) and also the fact that the proximity map of the network is constructed at the eNB, providing an important asset for potential one-hop or multi-hop D2D resource allocation. However, this scheme inherits the disadvantages of the *device discovery protocols with multiplexed transmissions,* where the total duration of the discovery procedure (construction of the proximity map) is long, i.e., UEs RF need to be active for a long period leading to a shorter battery life. In [26], the device discovery among UEs attached to the same cell is also examined. In this case, UEs request for resources for device discovery transmissions through the random access channel (RACH), and the eNB allocated for discovery a frequency-time discovery block with size proportional to the number of UEs. The discovery block here includes a set of non-adjacent subframes, and it is allocated in a semi-persistent way, following a frequency hopping scheme on the Physical Uplink Shared Channel (PUSCH). A weak aspect of this approach is that the protocol forces all the UEs to transmit in every discovery block. Another example for discovering UEs attached to the same cell is proposed in [12]. In [12], the eNB allocates to each RRC_CONNECTED UE a specific spectrum portion from a predefined frequency-time block to transmit its discovery signal. In [23], a device discovery protocol that can be exploited for discovery between UEs attached to different cells of the same public land mobile network (PLMN) is proposed. The eNB allocates resources for discovery transmissions using a D2D-SIB messages that can be listened by UEs in neighboring cells. However, since it follows a request-response handshaking approach the optimization of protocol parameters, such as the respond time offset, is an open challenge.

A key discovery solution for LTE networks has been described by Qualcomm [39] under the term *LTE-Direct*. LTE-Direct uses the uplink resources in an LTE FDD system and dedicated frames in an LTE TDD system. The device discovery procedure in LTE-Direct takes place in a frequency-time resource block, such as that defined by 3GPP [35] (i.e., radio resources that lasts 64 ms every 10 s in 10 MHz spectrum band), while all discovery enabled UEs can broadcast their needs and services via a 128-bit beacon called “expression”, which includes a service-layer identifier. The solution describes also how devices, subscribed to different operators, can discover each other. Open challenge here is the radio access approach for efficiently exploiting the frequency-time resource block. For the rest of the paper we focus on this challenge.

4. Radio access approaches for device discovery

In this section, we concentrate our interest in the radio access part of the discovery process. We focus on synchronized discovery enabled devices which are in-network coverage, and use a periodically available frequency-time block for discovery purposes. We discuss design constraints related to the use of this frequency-time block for efficient discovery, and we list the key access approaches that can be adopted.

4.1. Radio resources for device discovery

Adopting recent 3GPP recommendations [35], we assume that a portion of the UL cellular spectrum composes a frequency-time block available for device discovery. It consists of N_F *Resource Blocks* (*RBs*) for a period of N_T (adjacent or not) slots, as shown in Fig. 1. A RB spans over 180 KHz in frequency domain, while a slot lasts 0.5 ms. The radio resources included in a RB for the duration of a slot define a *physical RB* (*PRB*) and can carry a single discovery signal.

Since a frequency-time block is used, practical issues are raised by the principle characteristics of radio transceivers. The major one is called *half-duplex constraint* and refers to the inability of a radio transceiver to receive and transmit concurrently. This means that, regardless the number of available channels, a transmitting device cannot discover other devices during its transmission. Additionally, the *finite dynamic range* of the transceiver device should be taken into account, referring to the inability of the receiver to receive a weak signal if concurrently receives a strong signal in another frequency. Discovery performance is strongly correlated with those characteristics, since they affect the number of radio

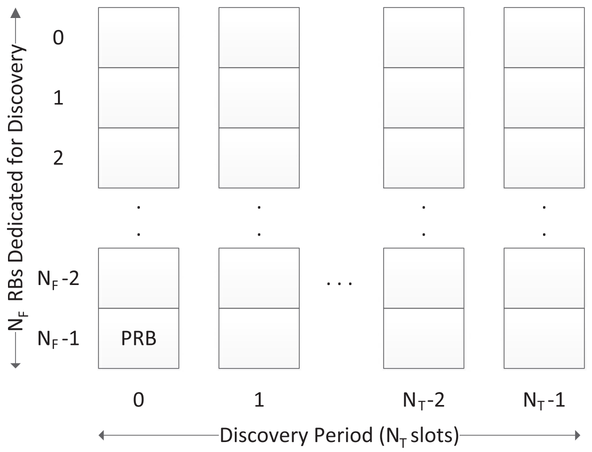


Fig. 1. The $N_F \cdot N_T$ frequency-time block that is exploited for discovery transmissions.

resources (PRB) that can be selected by a device for the discovery transmissions. As shown in [13], for both the *half-duplex constraint* and the *finite dynamic range* problems, frequency hopping provides an efficient solution. Another constraint that resides at the radio transceiver is the robustness in reception of time and/or frequency shifted signals due to the loose synchronization between the peers. For the LTE networks, where the Orthogonal Frequency Division Multiplexing (OFDM) technique is adopted, the use of an adapted cyclic prefix (CP) in each transmitted symbol seems to be a reasonable choice [13].

Beyond the constraints defined by the transceivers, wireless environment constraints can affect the way that the radio resources are exploited. In this context, one of the main questions is whether the detection of a discovery signal at one of the discovery peers, is enough for establishing a bidirectional D2D link. In other words, the question is whether the wireless link between two peers can be considered equal for both directions. Generally, such *communication symmetry* is a common assumption in the literature, which assists the protocol design and analysis. Another issue is the discovery signal variations due to multipath fading, user mobility etc., requiring frequency and time diversity of the discovery transmissions (e.g., through frequency hopping). These signal variations can lead to miss detection or false discovery, representing either the case where a failed decoding of a discovery signal erroneously translated to inability for D2D communication or the case where a discovery signal is detected but the establishment of D2D communication is not guaranteed.

4.2. Overview of radio access approaches for device discovery

In this section, we study representative radio access candidates for device discovery. The approaches under study have been borrowed from synchronous discovery protocols dedicated to mobile networks, or they are simple extensions of neighbor discovery solutions initially proposed for wireless ad hoc networks (e.g., [29–31]).

4.2.1. Random picks over the discovery block

The **Random Picks (RP)** approach assumes a fixed discovery block with N_T slots and N_F channels and forces each device to transmit in every discovery block. Specifically, each device (e.g., a discovery enabled UE in the LTE network) selects independently and with probability $\frac{1}{N_F \cdot N_T}$ one PRB to transmit, and listens to all the other PRB subject to the half-duplex constraint. This is a simple approach, which is applicable to any in-coverage synchronized discovery scenario, and, for an LTE network, it can be used by both UEs in connected and idle mode. The main drawback is the high number of collisions expected when the number of devices attempting discovery is much higher that the discovery block size. To alleviate this problem, an extension of the PR approach has been proposed in [26], in which, the size of the frequency-time block can be adjusted based on a specific policy. For example, if the number of attempting devices is available, the size of the frequency-time block can be adjusted accordingly. Practically, the performance is controlled due to dynamic change of the resources allocated for discovery. However, in communication systems like LTE, to retrieve in a central node the number of devices that attempt device discovery is a complicated issue, especially when they are in idle mode.

4.2.2. Aloha based solutions

Multiple variations of the well known Aloha protocol can be exploited for device discovery. We list the most important of them below. The main difference from the random picks approaches is that the number of transmitting devices is reduced based on a transmission probability. Thus, fewer collisions are expected at the cost of higher discovery latency.

Multi-Channel Slotted Aloha (SA-MC). It is an extension of the pure slotted Aloha approach and represents the case where the discovery block is defined by $N_F \cdot 1$ PRBs. The pure slotted Aloha approach states that in each single slot, every device independently chooses to transmit a discovery message with probability p and listen with probability $1-p$. As has been shown in [31], for m devices in the network the optimal value that minimizes the discovery time is $p=\frac{1}{m}$. In a multichannel environment, where N_F PRBs are available, each device chooses with equal probability a PRB to transmit, and thus, on average we have m/N_F devices per PRB. Subsequently, each device that has selected a specific PRB transmits with probability $p=\frac{1}{m/N_F}$. Note that when $m < N_F$ each device transmits with probability one. The main drawback of this approach is that the knowledge of number of attempting devices is required at each device, or else a central node need to broadcast the transmission probability that may be used. However, approaches that relax this requirement may be designed. For the single channel case, the study in [40] validates the hypothesis that an overestimation of the number of neighboring devices is preferable to an underestimation, when it comes to the calculation of the transmission probability. Additionally, in [41], the authors propose a phase-based discovery process, where each phase, r, lasts for $2^{r+1} e \ln 2^r$ slots, and the transmission probability in the specific phase is $p=\frac{1}{2^r}$. In this way, they guarantee that the discovery time is no more than twice the time that would be needed in the case that the number of devices was known.

Block-Channel Slotted Aloha (SA-BC). This approach uses the same principles as the SA-MC, but here the discovery block is defined by $N_F \cdot N_T$ PRBs. Each device selects a PRB randomly and then transmits with probability $p=\frac{1}{m/(N_F \cdot N_T)}$. Similarly to the SA-MC approach, when $m < N_F \cdot N_T$, each device transmits with probability one. Practically, when $m < N_F \cdot N_T$, the devices behave as in the very simple and information-free RP approach. Actually, instead of changing the size of the discovery block to serve more devices, some of devices refrain from transmitting with specific probability, which is related to the number of attempting devices. Thus, as in SA-MC approach, the number of attempting devices is required to be known at the devices.

4.2.3. Resource allocation

Centralized or distributed resource allocation schemes can also be exploited for the radio access of discovery transmissions. Resource allocation can provide optimal performance especially when the approach is fully centralized. However, for device discovery the distributed approaches are more appealing, since the collection of the required information at a central node is practically a demanding process. Fundamental and distinguishing resource allocation approaches are listed below.

Basic Resource Allocation (RA-B). In this approach, a specific PRB of the frequency-time block is allocated to a device to transmit a discovery signal. A centralized or a distributed procedure guarantees that different PRBs are allocated to each one of the first $N_F \cdot N_T$ devices, thus, orthogonal PRBs are allocated, avoiding collisions. For the rest devices (above the first $N_F \cdot N_T$), the PRBs are assigned randomly. This approach is quite appealing, especially in case that a distributed scheme can guarantee the orthogonality in the allocation. However, more sophisticated approaches may be used for dense scenarios where $m > N_F \cdot N_T$. An example is the Location-based Resource Allocation (RA-LB). In this approach, towards maximizing the spatial reuse, a PRB is allocated to multiple devices, targeting at minimizing the mutual interference, and thus, the number of collisions. That can be performed by exploring devices location information. The allocation is as follows. A central node (e.g., the eNB for an LTE network) allocates orthogonal PRBs to each randomly selected device until all PRBs are occupied (i.e., for the first $N_F \cdot N_T$ discovery attempting devices). If the number of devices in more than $N_F \cdot N_T$, i.e., $m > N_F \cdot N_T$, then the rest devices are selected in random order, and for each selected device, the central node allocates the PRB which is used by other devices of which the minimum distance to the selected device is maximized. Practically, in this approach a reselection process is needed to avoid deadlock scenarios, due to the half-duplex constraint. Additionally, one key requirement is collection of the location information at the central node, which by itself is a quite challenging problem. For applying such an approach in an LTE network, we should consider that the devices attempting discovery have to be in connected mode to be able to participate in the resource allocation procedure.

FlashLinQ Random (FQ-R) [13]. In this approach, the PRBs are represented by a set of IDs called PDRIDs (Peer Discovery Resource IDs). Each one of the $N_F \cdot N_T$ PDRIDs refers to a pair of indices (J, I), where J is between 0 and $N_F - 1$ and I is between 0 and $N_T - 1$. A device selects randomly one of the PDRIDs and then is utilizes a time and frequency hopping sequence to decide in which PRBs will transmit for a repetition period defined by N_T frequency-time blocks (recall that each block consists of $N_F \cdot N_T$ PRBs). The time and frequency hopping approach is based on prime number properties and alleviate the performance reduction due to the half-duplex and the finite dynamic range constraints. To this end, the durations of the frequency-time block N_T is chosen to be a power of a prime number. This approach can be seen as a realization of the RA-B in a distributed manner.

FlashLinQ Greedy (FQ-G) [13]. As in the FQ-R, in this approach the PRBs are represented by a set of PDRIDs. Each one of the $N_F \cdot N_T$ PDRIDs refers to a pair of indices (J, I), where J is between 0 and $N_F - 1$ and I is between 0 and $N_T - 1$. Each PDRID defines a time and frequency hopping sequence for N_T sequential frequency-time blocks. However, here a device selects randomly one of the 5% less congested PDRIDs after a sensing process. For the sensing realization, a device refrains from transmission based on a specific transmission probability. The main intention of this procedure is to provide devices with the energy level in each PRB and assist them to select a low-congestion PDRID. Practically, this is a distributed way to apply a resource allocation scheme where each device is allocated the PRB with the least interference (as in the RA-LB approach), at the cost of sacrificing some resources for sensing. The random selection among the 5% of the less congested PDRIDs, as an alternative of the direct selection of the less congested PDRID, is introduced toward alleviating the local collision problem. This problem arises since devices that are in close proximity may see similar energy for all the PDRIDs and inevitably select the same PDRIDs for a long period, without managing to discover each other. Overall, the FQ-G approach provides a solid and LTE compliant solution for device discovery radio access. However, the transmission probability is an important performance factor and the choice of a proper value for it is an open problem for further study.

5. Performance aspects

Various performance metrics can be considered to efficiently evaluate a discovery protocol that exploits a frequency-time block for the discovery transmissions. The most important of them are the energy consumed, the amount of resources used, and the latency.

The energy consumption is close-related with (i) the duration of the duty cycle, i.e., the percentage of time where a device is on for transmitting discovery signals or listening to other devices, and (ii) the amount of discovery transmissions needed per device before the completion of the discovery process. Since devices are generally battery-powered and current battery capacities cannot afford always-on radio, a spectrum access approach has to take into consideration that a long duty cycle exacerbates the battery life of the devices, while a short one prolongs the discovery time. Additionally, since the most energy consuming process in wireless communications is the radio transmission, a main target should be to minimize the useless discovery transmission, referring mainly to interfering transmissions by two or more devices (collisions) and to transmissions that lead to missed-discoveries due to the half-duplex constraint.

The amount of radio resources that are used for the discovery process is another key performance metric. On the one hand radio resources are sparse, requiring sophisticated utilization and smart exploitation, while on the other hand, device discovery is introduced as an additional prerequisite for the D2D communication, and, thus, its impact on the expensive licensed spectrum should be minimized. For a discovery scheme, this performance metric can be quantified as the ratio between the amount of useful PRBs (lead to a discovery) and the total amount of the PRBs used.

Finally, another important performance metric for the device discovery process is the discovery latency, measuring the time required for discovery. Practically, this metric refers to the number of time-slots needed either at a device to detect all its neighbors or at a central node to build the total discovery map (proximity map). Discovery process should keep this value low to abide by D2D application layer constraints and to avoid miss detections due to users' mobility.

5.1. Remarks on the optimal performance

As a radio resource management problem, the performance of the discovery process can be optimized through a central resource allocator that decides which devices will transmit to each PRB of the discovery block. Theoretically, for the optimal performance in terms of energy consumption, the allocation process should guarantee that the lowest number of discovery transmissions is used. In the following, we investigate allocation schemes that achieve the minimum latency subject to the use of the lowest number of discovery transmissions. We consider two scenarios: (1) the *neighbor discovery scenario*, where the target is each device to detect the presence of all its neighbors, and (2) the *proximity map scenario*, where the target is the central resource allocator to retrieve the complete proximity map.

5.1.1. Performance bounds for the neighbor discovery scenario

For the *neighbor discovery scenario*, a key remark is that under the minimum energy consumption, the allocation scheme guarantees zero collisions and zero missed-discoveries due to the half duplex constraint. Practically, this means that, in the optimal case, the number of PRBs needed for the discovery procedure equals the number of devices m. This is a straightforward result, since each device should transmit at least once to announce its presence. The question that arises is about the allocation scheme that can guarantee the minimum latency, subject to the use of only m PRBs for the discovery process. Theoretically, when a $N_F \cdot N_T$ block of resources is available and the allocator has the full knowledge of the network topology, we can achieve this by allowing the devices not in proximity (i.e., the devices located at a distance higher than the discovery range) to transmit in PRBs of the same slot. The challenge for the allocator is to find the minimum number of independent (not in proximity) sets of devices, and allocate each set to PRBs of the same slot. In that way, the lower bound of the latency is achieved. Note that, since the number of PRBs of the same slot is up to N_F, when the devices in an independent set are more than N_F, the allocator may exploit PRBs of a following frequency-time block or empty PRBs in the same block. For simplicity, in the analysis below we assume that the number of elements in each set is less than or equal to N_F. Let the proximity graph $G(V, E)$, where V is the set of vertices and E is the set of edges. A vertex represents one device and therefore the size of the set V equals the number of devices, i.e., $m = |V|$. Also, an edge between two vertices indicates the proximity of the devices represented by these vertices. Remark 1 can be used to calculate the minimum number of independent sets, and, thus, the lower bound of the discovery latency.

Remark 1. Under the neighbor discovery scenario, the minimum discovery latency, denoted here by L^-, subject to (i) use of m PRBs, (ii) avoid miss discoveries due to the half-duplex constraint, and (iii) guarantee zero collisions, equals the chromatic number of the proximity graph, $\chi(G)$, i.e.,

$$L^- = \chi(G) \tag{1}$$

Proof of Remark 1. By the definition of the half-duplex constraint, two devices in proximity that transmit in the same slot cannot discover each other. Thus, to avoid miss discoveries due to the half duplex constraint, in each slot, only devices that are not in proximity and, thus, are represented with vertices that are colored with the same color can transmit concurrently. Consequently, the minimum number of slots required for the discovery process equals the minimum number of colors needed to color the proximity graph, i.e., the chromatic number, $\chi(G)$.

Based on graph theory, for the minimum discovery latency, L^-, it holds that

$$\frac{|V|}{a(G)} \leq L^- \leq \Delta + 1 \tag{2}$$

where $a(G)$ is the independent number of the proximity graph G (i.e., the number of nodes that define the maximum independent set), and Δ the maximum degree of the graph G. Focusing on the left branch of inequality (2), a vertex coloring of graph G corresponds to a partition of each vertex set into independent subsets. Hence, the *minimum number of colors* needed in a vertex coloring, i.e., the chromatic number $\chi(G)$, is at least the ratio of the number of vertices in G and the independent number $a(G)$, i.e., $|V|/a(G)$. The second branch of inequality (2) is a direct application of Brooks Theorem [42], according to which the chromatic number of a graph is at most the maximum degree Δ, unless the graph is complete or an odd cycle, where $\Delta + 1$ colors are required. Thus, $\frac{|V|}{a(G)} \leq \chi(G) \leq \Delta + 1$, and by using Remark 1, $\frac{|V|}{a(G)} \leq L^- \leq \Delta + 1$. Note that for a set of devices that define a clique, i.e., their proximity graph is a complete graph, the lower bound of discovery latency, L^-, equals the number of devices m, since in a clique graph the chromatic number equals the number of vertices and $m = |V|$.

5.1.2. Performance bounds for the proximity map scenario

In the *proximity map scenario*, the performance bounds provided above still hold, but they can become tighter since the requirement here is to acquire the proximity map at a central node and not each device to detect its neighbors. Remark 2 below defines the minimum number of devices that should transmit to retrieve the proximity map.

Remark 2. Let A denote the maximum independent set of vertices of the proximity graph, and $a(G) = |A|$ denote the cardinality of this set (i.e., the independent number), then the set difference $V' = V \backslash A$ is the minimum set of vertices with which all the edges of the proximity graph are attached. Since the proximity of two devices is represented by an edge, Remark 2 means that $|V'| = |V| - |A|$ is the minimum number of devices that should transmit to retrieve the proximity graph.

Proof of Remark 2. (proof by contradiction). Assume that there exists a set of vertices V'', with $|V''| < |V'|$, where all the edges of the proximity graph were attached to vertices of the V'' set. This means that the remaining vertices, i.e., the set of vertices $V \backslash V''$ should define an independent set A' with cardinality $|A'|$, where $|V''| = |V| - |A'|$. However, the assumption that $|V''| < |V'|$ leads to the inequality $|V''| - |A'| < |V| - |A|$, $|A'| > |A|$, i.e., the hypothesis that the set A is the maximum independent set is violated.

Based on Remark 1 and Remark 2 the following result for the discovery latency can be extracted under the proximity map scenario.

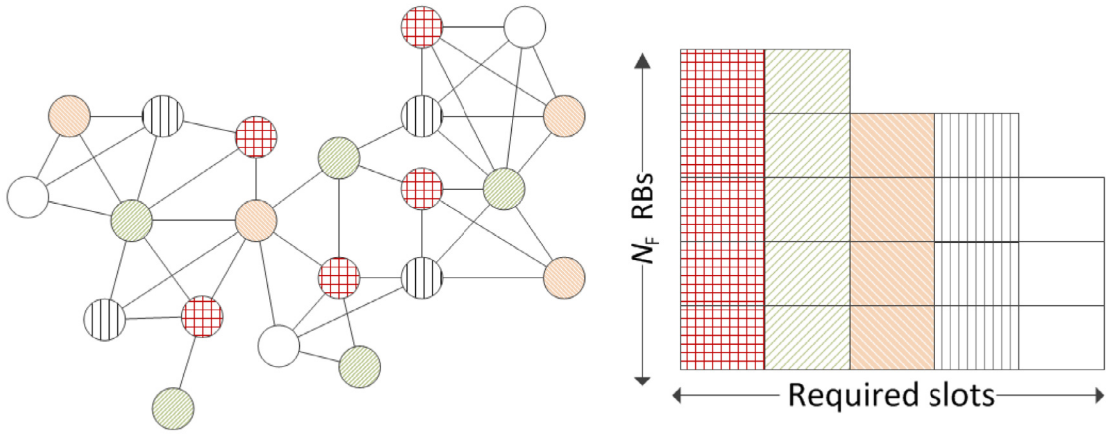
Remark 3. Under the proximity map scenario, for the minimum discovery latency, L^-, subject to (i) use of $|V'|$ PRBs, (ii) avoid miss discoveries due to the half-duplex constraint, and (iii) guarantee zero collisions,, it holds that

$$L^- \leq \chi(G) - 1 \tag{3}$$

Proof of Remark 3. As stated in Remark 1, only devices that are not in proximity should transmit in the same slot, i.e., only devices that are represented by vertices that are colored with the same color can transmit concurrently. Additionally, according to Remark 2, the number of transmitting devices in the proximity map scenario is $|V'| = |V| - a(G)$. However, the maximum independent set includes at least the vertices of one color class (vertices colored with the same color), since by definition a color class is an independent set, and thus, if some vertices of a specific color class are included in the maximum independent set the rest of vertices of the same class should be included. Otherwise, the definition of the maximum independent set is violated, since there are remaining independent vertices that are not included in the set, and thus, the set is not the maximum. Consequently, the discovery latency can be reduced by at least one slot, a slot that includes the transmissions of a single color class.

5.2. Feasibility of the optimal performance – the discovery validation case

Taking into account that the device discovery process is a continuous process where the devices need to frequently validate their proximity [43], the analysis above can be used to accelerate the discoveries that follow the initial discovery. From this perspective, instead of repeating the device discovery process, the devices can exploit past discovery results and follow a *proximity validation* approach. In other words, the knowledge of the devices that have been detected in recent past can drive the radio access in sequential discoveries. Note that the graph representation of the devices' proximity, which is used in the analysis above, is a widely accepted approach, and it is currently exploited for various problems such as the D2D resource allocation [44–46].



(a) Proximity graph (b) Allocation of the PRBs

Fig. 2. A colored proximity graph, $G(V, E)$, with chromatic number $\chi(G) = 5$ and the representative allocation of the PRBs to the devices that minimizes the number of discovery transmissions. Each device is allocated only one PRB, while the neighbor discovery scenario is considered (all the devices should transmit).

5.2.1. Radio resource allocation for device discovery validation

Consider that a $N_F \cdot N_T$ frequency-time block (as this depicted in Fig. 1) is available for the validation process and that a resource allocator is responsible for allocating the PRBs to discovery transmitters. Exploiting the results in previous section, the main steps for validating the proximity with the minimum number of transmissions are the following:

Step 1. The resource allocator creates the proximity graph $G(V, E)$ that represents the valid direct connections as resulted by the initial discovery process (discovery history).

Step 2. The graph is being colored using the minimum number of colors. Practically, this can be achieved by a greedy algorithm, such as the DSATUR graph coloring algorithm [47]. Additionally, the maximum independent set A for the proximity graph is found. An approximation of this quantity can be given by the maximum set of vertices with the same color.

Step 3. The devices that are represented by vertices in the set $V \backslash A$ or the set V, referring to the *proximity map scenario* or the *neighbor discovery scenario*, respectively, transmit their discovery signal in PRBs of the frequency-time block as follows:

- The devices that their corresponding vertices have the same color are allocated to the same slot (parallel transmissions in different PRBs)
- If the number of devices that their corresponding vertices have the same color is higher than the number of available RBs (N_F) (i.e., PRBs in the same slot), the exceeding devices use the next available slot of the discovery block.

An example for the discovery validation described above is depicted in Fig. 2. Fig. 2(a) includes the proximity graph after initial discovery, and Fig. 2(b) the resulted allocations in the discovery block for discovery validation.

6. Evaluation results

In this section, we evaluate the performance of the radio access approaches described in Section 4 and compare them with the optimal theoretical bounds defined in Section 5. More specifically, we focus on the RP, SA-MC, SA-BC, RA-B and FQ-G approaches and assess them in terms of discovery latency and number of transmissions required. To this end, we performed simulations in Matlab, using the parameters depicted in Table 2.

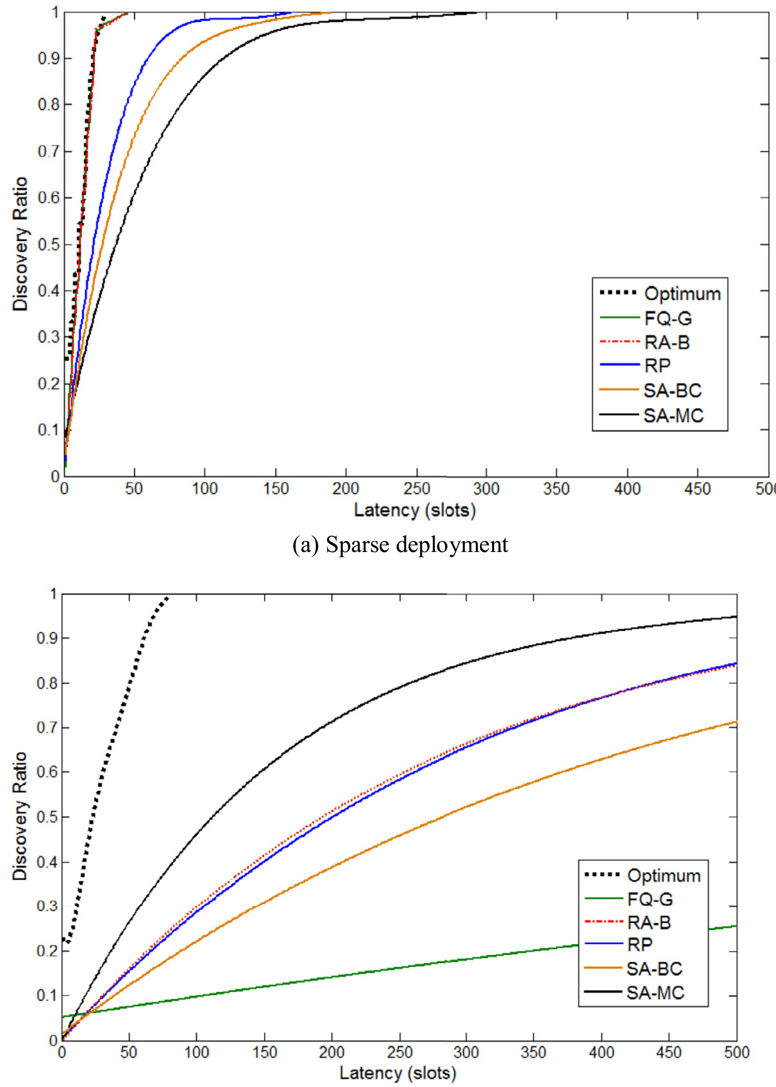
Table 2
Basic simulation parameters.

Parameter	Value
Device distribution	Random
Number of devices (sparse scenario)	100
Number of devices (Dence scenario)	400
Device density	$2.5 \cdot 10^{-5}$
Discovery range	500 *m*
SIR threshold	0 *dB*
Path loss model	ITU-1411 LOS
Radio band	2.6 *GHz*
Discovery transmission power	23 *dBm*
Number of RBs in the discovery block (N_F)	7
Number of slots in the discovery block (N_T)	23

The devices are randomly deployed in the grid, and each one of them transmits discovery signals with fixed transmission power, assuming an interference limited environment. The path losses are calculated according to the ITU-1411 LOS model [48] in 2.6 GHz frequency, one of the main models suitable for device discovery simulations [35,49,50]. The *neighbor discovery scenario* is adopted, meaning that each device targets at detecting all its neighbors, since it is the most challenging scenario, and also it is compliant to all the approaches under evaluation. At the initial stage of the evaluation process no discovery information is available at any device, while for the FQ-G approach we assume that the devices enter the system sequentially to acquire an initial estimation of the expected energy level at each PRB. The discovery process is terminated when every device in the network have found all its neighbors.

A two-step evaluation methodology is followed, named the *pure decoding* and the *SIR-based*, respectively. In the first step, pure decoding receivers are considered, meaning that when two or more devices transmit at the same PRB a collision occurs. This is a quite useful step since it allows us to fairly compare the selected approaches with the optimal bounds defined in Section 5. In the second step, a reasonable SIR threshold is considered at each receiver, thus, a collision occurs only when the interference results to lower SIR than this threshold.

The evaluation process for each step considers two different cases: *the sparse deployment case*, where the number of devices attempting discovery is lower than the available PRBs in the



(a) Sparse deployment

(b) Dense deployment

Fig. 3. Number of slots required for pure decoding discovery.

discovery block, and the *dense deployment case,* referring to the case where the number of devices attempting discovery is higher than the available PRBs in the discovery block. Note that towards a fair comparison between the sparse and the dense case, we use the same network density for both cases, meaning that the mean number of neighbors per device remains the same.

6.1. Evaluation step 1 (pure decoding)

6.1.1. Discovery latency

In Fig. 3, the behavior of each scheme is depicted for the sparse and the dense deployment case (Fig. 3(a) and Fig. 3(b), respectively). Discovery ratio in y axes depicts the percentage of proximity devices that have been detected, while the latency in x axes the number of slots uses. As depicted in Fig. 3(a) the resource allocation approaches (FQ-G and RA-B) have identical behavior and perform very close to optimum. The RP and the SA-BC seem to require the same number of slots (∼170 slots), but RP approach detects more of the neighbors at the beginning. On the other hand, the SA-MC has much worst performance than the other approaches requiring about 300 slots. In Fig. 3(b), the behavior of the approaches changes, and SA-MC performs better than the other approaches. In FQ-G the proximity information seems to be acquired very slowly as multiple discovery devices are locked to the same PDRID and the interference based reselection does not help for the pure decoding approach. This is an interesting result since it implies that for high SIR thresholds, i.e., for low sensitive receivers, the intelligence of the FQ-G approach is hardly exploitable.

6.1.2. Transmissions required

Fig. 4 depicts the transmissions required prior every device in the network detects its vicinity for the sparse and the dense deployment cases (Fig. 4(a) and Fig. 4(b), respectively). As can be observed in Fig. 4(a), the resource allocation approaches (FQ-G and RA-B) have better performance than their competitors, since the collisions are avoided via a hard allocation of each device to different PRB. Additionally, the number of transmissions they require is close to optimum and the depicted difference is due to the half-duplex constraint. In Fig. 4(a), it is also notable that the performance of the SA-MC approach is significantly lower than that of its competitors, since the number of devices attempting discovery at each slot are more than the N_F available PRBs, and thus,

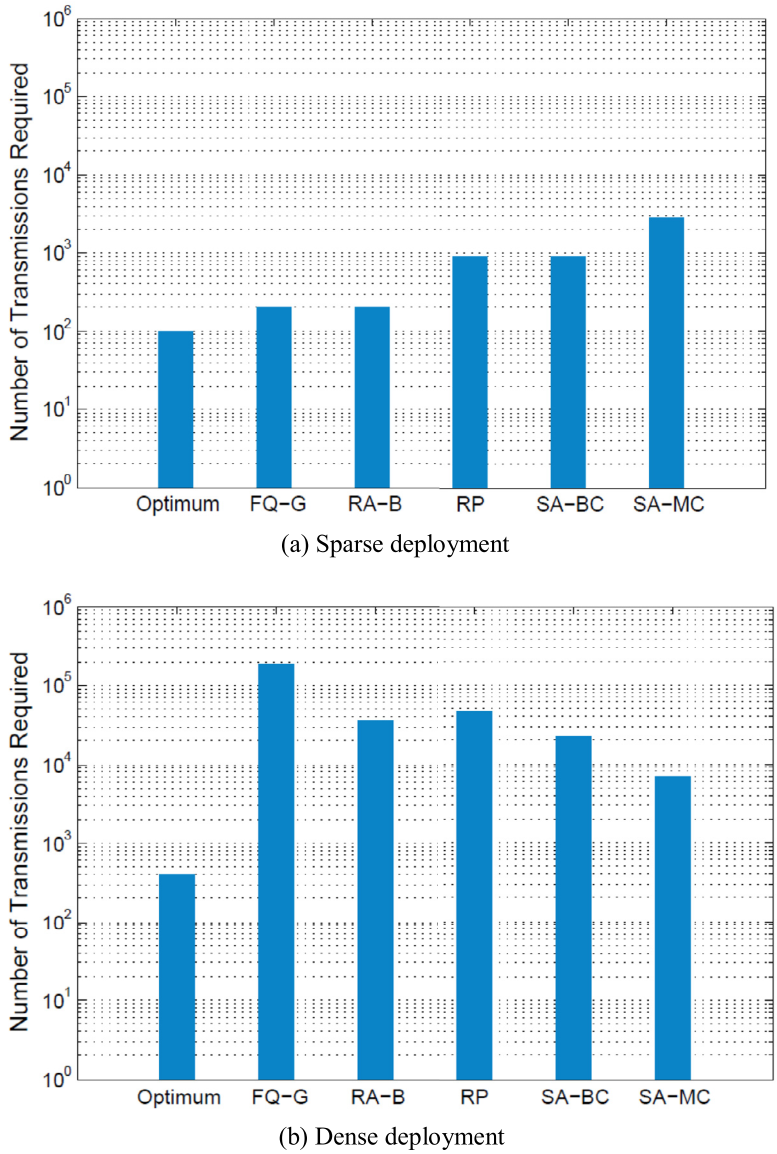


Fig. 4. Number of transmissions required for pure decoding discovery and.

more collisions occur. The performance in the dense case deteriorates for all the approaches and the number of required transmissions in much more than the optimum (Fig. 4(b)). This is reasonable since the number of collisions is increasing rapidly (due to the pigeonhole principle). In Fig. 4(b), the random and the aloha based approaches perform better than the FQ-G approach, since FQ-G has been designed towards exploiting the interference temperature that is available for spatial spectrum reuse, and this characteristic is hardly exploited in the pure decoding scenario.

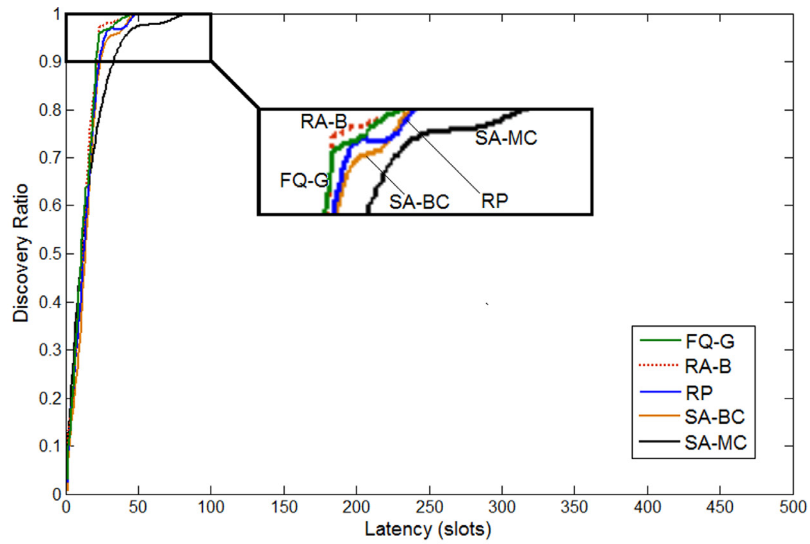
6.2. Evaluation step 2 (SIR-based)

6.2.1. Discovery latency

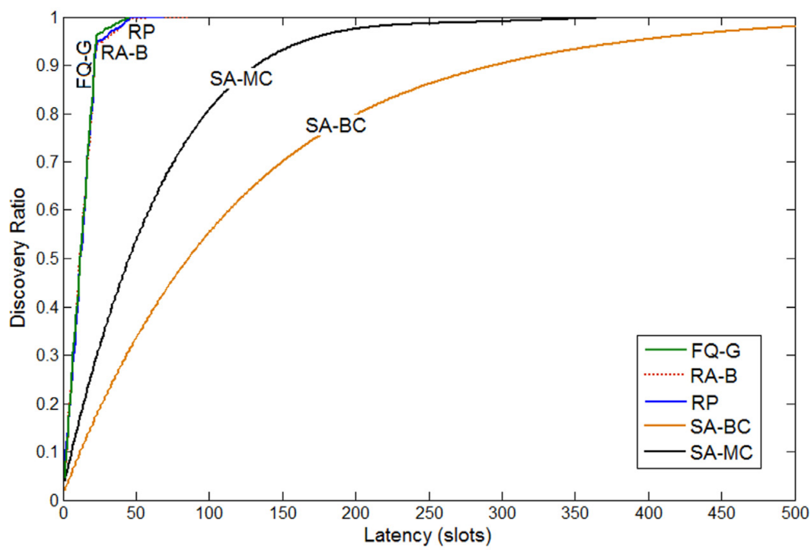
In Fig. 5, we depict the discovery ratio for SIR-based receivers in the sparse and the dense deployment cases (Fig. 5(a) and Fig. 5(b), respectively). Improved performance for all the approaches is observed, since the SIR level at the receivers provides interference tolerance, allowing the spatial spectrum reuse of the PRBs. Especially the RP, RA-B, and the FQ-G approaches perform very well for both the sparse and the dense deployment cases (Fig. 5(a) and Fig. 5(b)). The performance of the RP in terms of latency is quite noticeable, pointing out that even with 2,5X more devices than the available PRBs (there are 400 devices for 161 PRBs) there is no need for sophisticated access to the radio resources. Additionally, for the dense deployment case (Fig. 5(b)) we can observe that the SA-MC performs better than the SA-BC approach. This is because in the SA-BC the transmission probability per PRB is lower. Practically, since we target on the neighbor discovery scenario, i.e., each edge of the proximity graph should be detected from both directions, the discovery process is slower when a low transmissions probability is used.

6.2.2. Transmissions required

Fig. 6 depicts the transmissions required for the neighbor discovery per evaluated approach, considering the SIR-based scenario. Fig. 6(a) focuses on the sparse deployment case, while Fig. 6(b) on the dense one. The main result here is that the FQ-G is resilient to an increase of the number of devices attempting discovery, providing better scalability in comparison with the other approaches. This is an important asset for the FQ-G approach;



(a) Sparse deployment



(b) Dense deployment

Fig. 5. Number of slots required for SIR-based discovery.

however, it should be noted that we have considered here the best sensing probability for this approach, the calculation of which is in practice a quite challenging issue. Another observation revealed from both figures is that the increased number of required transmissions for the RP approach in comparison to the more sophisticated FQ-G approach, which actually quantifies the cost of the simple practice of the RP approach, where all devices transmit in every discovery block.

7. Conclusions

The proliferation of D2D communications in cellular networks is expected to be beneficial from a variety of perspectives. However, it will shift the current cellular communication paradigm to a more flexible and dynamic state, raising new technical challenges, such as the device discovery problem. We have studied the main categories of device discovery protocols in the literature and examined discovery design directions posed by 3GPP standardization process. Focusing on the main LTE discovery scenario, where a frequency-time block is dedicated for discovery purposes, various radio access approaches have been discussed and evaluated, while key performance aspects and useful remarks on the optimal theoretical performance have been provided. Random access approaches seem to have adequate performance, since they exploit the diversity on the radio resource utilization. However, more sophisticated approaches are needed in scenarios where the number of devices attempting discovery exceeds the number of available radio resources. Although the centralized resource allocation approach can optimize the performance even in such scenarios, further work is needed on designing distributed resource allocation schemes, since the involvement of the eNB in the resource allocation procedure requires devices in connected mode. In this view, the design of distributed proximity validation schemes, which exploit the proximity validation principles described in this paper, is an appealing approach. Additionally, the plethora of available discovery solutions already used for WLANs provides a fertile basis towards designing access schemes for LTE device discovery, especially for the less studied out-of-coverage scenario.

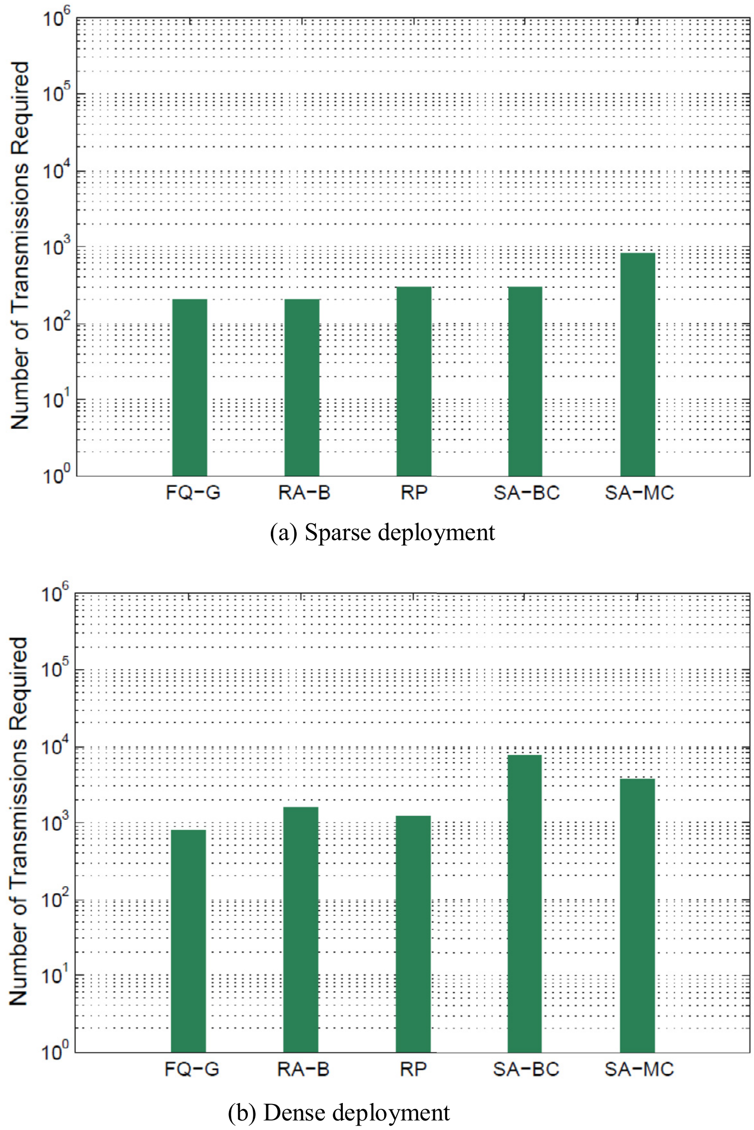


Fig. 6. Number of transmissions required for SIR-based discovery.

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