

Robust and Fast Device Discovery in OFDMA-based Cellular Networks for Disaster Environment

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Abstract— Device-to-device (D2D) communication is a salient function of public safety networks for enabling communications, even in a disaster environment where the communication infrastructures are fully or partially destroyed. In order that devices directly communicate, they must first find and identify each other. Especially, in a disaster environment where wireless channel conditions may be very poor, discovery should be robust and fast for quick resume of the blocked communications again. In this paper, considering frequency selective fading which may lead to missing devices even though they exist, we propose a device discovery scheme using a simple physical layer waveform called signature. Typically, in a signature-based discovery under OFDMA-based system, a device advertises its presence by selecting a discovery channel and energizing subcarriers in the channel for a while (one subcarrier at a time). In the proposed scheme, we design discovery channels having well dispersed subcarriers to tolerate the frequency selectivity. By simulation, it is shown that not only successful discovery ratio of the proposed scheme is improved, but also our scheme is more frequency selective fading tolerant in comparison with other approaches.

Keywords— Device-to-device communication, device discovery, PS-LTE, disaster communication, cellular networks

I. INTRODUCTION

Over the recent years, great and small natural/man-made disasters such as a fire, earthquake, hurricane, and terrorism have been occurred. To manage such disasters and emergency situations, the necessity of a nation-wide public safety network has been raised. Public safety organizations have used communication technologies such as legacy radio system, commercial network (2G/3G), and broadband (LTE/WiFi). However, in order to operate efficient and effective public safety network, several particular functionalities not included in conventional communication technologies such as direct communication and group communication among devices are essential. Therefore, a new and dedicated network system for public safety is needed.

The public safety LTE (PS-LTE) is an LTE-based public protection and disaster relief communication system which the 3GPP has developed and standardized. The salient functions of the PS-LTE are device-to-device (D2D) communication,

group communication, operation of an isolated E-UTRAN, and mission-critical push-to-talk (MCPTT), etc [1]. A basic functionality of these functions is direct communication between devices.

Before devices directly communicate with each other, they must first find and identify each other. Thus, one of the indispensable techniques for the additional functionalities of the PS-LTE is device discovery. Device discovery means that a device detects the proximity of other neighbor devices to engage in direct communications between them. In order to discover each other, the devices have to meet in space, time, and frequency. This process may incur significant additional overhead, thereby reducing the overall system efficiency of the PS-LTE system. So, the device discovery protocol should be well designed not so as to dissipate wireless resource.

Device discovery for cellular networks can be categorized as packet-based and signature-based discovery [2] – [4]. The packet-based discovery uses an encoded packet or message that includes full unique device identification as well as other related information needed for discovery. This packet-based discovery may achieve two general goals of device discovery: detection of the presence of neighbor devices and identification of the devices. WiFi, Bluetooth, and many representative D2D systems use packet-based discovery. However, the packet is large in size, so it may incur delay or overhead to the overall system. On the other hand, in the signature-based discovery, a simple physical layer waveform is used to temporarily identify a device during the discovery process. This signature-based discovery can detect the neighbor devices faster than the packet-based discovery.

In this paper, we assume a hybrid scheme of packet-based discovery and signature-based discovery, for robust and fast discovery with low overhead in cellular networks. In such a scheme, a device first broadcast its full discovery information via packet. After that, it may repeat only the simple signature. There are a lot of works for the packet-based discovery, whereas the signature-based discovery has been rarely studied. Moreover, since the existing packet-based discovery scheme can be applied for the packet-based part of the hybrid discovery scheme, we concentrate on the signature-based discovery.

In a signature-based discovery under OFDMA-based system,

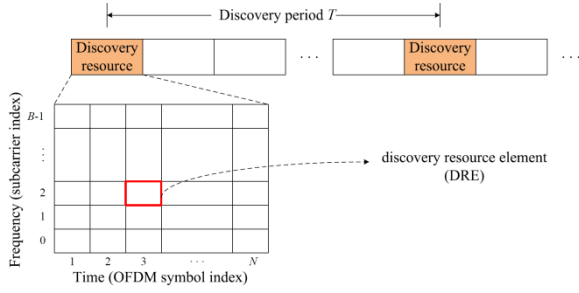


Figure 1. Discovery resource structure. A discovery resource is repeated at every T discovery period and it is composed of $N \times B$ discovery resource elements (DREs).

a device advertises its presence by selecting a discovery channel and energizing subcarriers in the channel for a while (one subcarrier at a time). To tolerate frequency offset¹ and frequency selective fading, the hopping patterns of the subcarriers should be well designed for discovering neighbors efficiently. In practice, the frequency offset may potentially cause disagreement between the transceivers of devices. Furthermore, due to frequency selective fading, some signature signals transmitted on a specific frequency band cannot be detected at a receiver. Therefore, the hopping patterns should be well dispersed in frequency axis. The goal of this paper is to design discovery channels for robust and fast detection of neighbor devices even in imperfectly synchronized and/or frequency selective fading environments (e.g., disaster environment).

The rest of this paper is organized as follows. Section II gives a brief description of the discovery resource model and hybrid device discovery model. Section III describes the proposed discovery channel generating algorithm and detection process of devices. The efficiency of the discovery channel generating algorithm is compared with other approaches in section IV. Finally, the paper is concluded with section V.

II. SYSTEM MODEL

A. Discovery Resource

In this paper, we assume a cellular system adopting OFDMA for link layer protocol. According to the regulation of the Federal Communications Commission (FCC) that only the cellular uplink is available for device discovery, we should consider the multiplexing of the discovery resource and cellular uplink resource. For keeping the battery life of mobile devices, the discovery resource and cellular uplink resource are multiplexed in time. Thus, as illustrated in Fig. 1 the devices can discover each other using only the discovery resource repeated periodically like in ad hoc WiFi and FlashLinQ [5].

A discovery resource consists of N OFDM symbols in time and B subcarriers in frequency. That is, there are $N \times B$ discovery resource elements (DREs) in a discovery resource. In consideration of practical OFDMA-based cellular systems, we assume $N \ll B$. For example, if the LTE-based cellular

¹In practice, any two devices may not be perfectly synchronized in time and frequency. But, the time offset can be absorbed by the cyclic prefix of OFDM symbol. Thus, we just consider frequency offset in this paper.

system adopts normal cycle prefix, 5 MHz bandwidth for uplink, the duration of a discovery resource of 1 ms, and the period of discovery resource (T) of 1 s, we can say that $N = 14$, $B = 512$, and the duty cycle is 0.1 %.

B. Hybrid Device Discovery

As we mentioned earlier, we consider a hybrid device discovery scheme which combines the packet-based discovery and signature-based discovery. Advantages of packet-based discovery are that full information is self-contained and it does not bring about additional signaling overhead. However, such packet-based discovery is not efficient in power and resource because of trying to decode potential discovery packets at all discovery resources. On the other hand, signature-based discovery does not deliver sufficient amount of information but may be efficient in terms of power and bandwidth.

Considering the change of device state (e.g., identification, location, power on/off, etc.) is relatively small during a discovery period T , the devices in discovery process does not need to broadcast a packet containing full related information at every discovery period T . Instead, once a device broadcasts the discovery packet in a discovery resource, for several subsequent discovery periods the device broadcast not the discovery packet but a signature corresponding to the previous packet. In fact, a signature represents a temporary discovery identification (TDID) used in the discovery process. We can get the effect of using a full discovery packet with the simple TDID unless the device state is greatly changed. In this way, devices can discover and trace each other efficiently and quickly.

III. PROPOSED DEVICE DISCOVERY

Separate and parallel B discovery channels ranging from 1 to B are mapped onto $N \times B$ discovery resource grid. Each channel consists of N DREs and corresponds with a TDID. That is, there is one to one mapping between a discovery channel and a TDID. To advertise its presence, a device broadcasts its TDID b by energizing the DREs belonging to the corresponding discovery channel b .² Each discovery channel contains one DRE at each OFDM symbol in order to concentrate the transmission power on a subcarrier at a time. Let c_n^b a DRE of discovery channel b at n th OFDM symbol which actually corresponds to a subcarrier index. Then, the discovery channel b can be represented by $\mathbf{c}^b = \{c_1^b, c_2^b, \dots, c_N^b\}$.

The authors in [2] used Galois field (GF) to create discovery channels corresponding to TDIDs. The GF-based scheme generates $B - 1$ separate discovery channels.³ No DREs of a discovery channel generated from the GF-based scheme have the same subcarrier index if $N \leq B$ is satisfied (i.e., $\nexists (c_n^b = c_m^b) \text{ for } n \neq m$). This property of the GF-based scheme is good for alleviating frequency offset.

However, the GF-based scheme does not consider frequency selective fading. As mentioned earlier, the detection capability

²Due to space limitation, we shall omit the TDID acquisition and update processes. However, it doesn't really matter what the discussions afterwards.

³The GF-based scheme generates a dummy discovery channel consists of $\mathbf{c}^b = \{B - 1, B - 1, \dots, B - 1\}$. Thus, we discard the dummy channel from B channels.

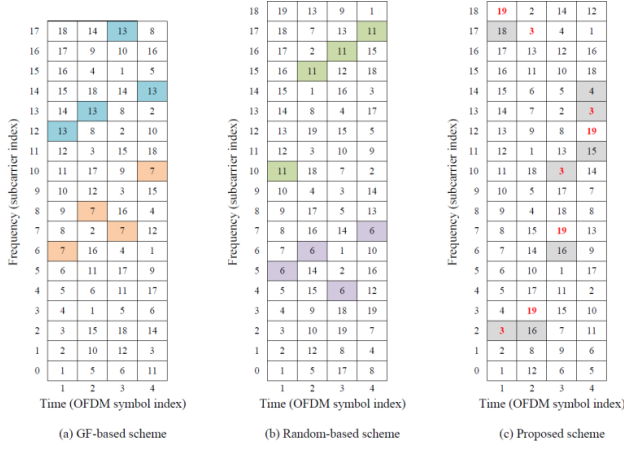


Figure 2. Example of discovery channels with $B = 19$ and $N = 4$.

of TDID may be decreased in frequency selective fading environments. In Fig. 2, we illustrate examples of discovery channels from several schemes when $B = 19$ and $N = 4$. The written number in a DRE represents TDID (or discovery channel) the DRE is included in. We highlight the DREs of TDID 7 and 13 in Fig. 2(a). If the number of subcarriers in coherence bandwidth of the above example is 4, three DREs of TDID 7 and 13 may belong to a coherence bandwidth, respectively. For example, the channel qualities of subcarriers 12, 13, and 14 (within the coherence bandwidth) between a device with TDID 13 and its receiver device may be poor, simultaneously. In this case, the three DREs may not be detected at the receiver. This may lead to missing the presence of device with the TDID 13, even though it exists. Therefore, the frequency selectivity as well as other requisites should be essentially considered for efficient and robust device discovery.

A. Discovery Channel Generating Algorithm

Considering frequency selective fading environments, the proposed discovery channel generating scheme tries to disperse the subcarriers in a discovery channel as much as possible so as to experience separate channel conditions. In the proposed Algorithm 1, we initialize the first DRE of any discovery channel b as $b - 1$ (line 1).⁴ In fact, the result of initialization has exactly the same effect as random initialization. The function, $\text{random}()$ in line 4, is a random non-negative integer number generating function and W is the number of subcarriers in the coherence bandwidth. Although the minimum separation among subcarriers in a discovery channel is enough with the W taking into consideration frequency selective fading only, we make the additional random separation r in order to prevent misunderstanding among TDIDs caused by frequency offset at a receiver device (line 4–5).

B. Detection of TDIDs

Now, we describe the TDID detection process. At a discovery resource, the devices participating in the discovery process broad-

⁴The range of subcarrier index is 0 to $B - 1$ while 1 to B for that of discovery channel (or TDID).

Algorithm 1 Algorithm for generating discovery channels

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1:  $c_1^b \leftarrow (b - 1)$  for  $b = 1, \dots, B$ 
2: for  $b = 1, \dots, B$  do
3:   for  $n = 2, \dots, N$  do
4:      $r \leftarrow \text{random}() \% W$ 
5:      $c_n^b \leftarrow (c_{n-1}^b + W + r) \% B$ 
6:     while  $\exists c_n^b = c_m^b$  for  $(m < n)$  do
7:        $c_n^b \leftarrow (c_n^b + 1) \% B$ 
8:     end while
9:   end for
10: end for
11: return  $\mathbf{c}^b \forall b$ 

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cast signals on the discovery channel according to their TDID with probability p and listen for TDIDs of other devices with probability $1 - p$. When several devices advertise their existence, a receiver device may detect energy above threshold value on DREs. To distinguish valid TDIDs from the energized DREs, the receiver device matches the energized DREs with predefined TDID table. If there are v or more matches on a TDID, the receiver device detects the presence of a device using the TDID.

For example, in Fig. 2(c), when two devices having TDID 3 and 19 respectively broadcast their presence on the corresponding discovery channel, the discovery channels of the devices are $\mathbf{c}^3 = \{2, 17, 10, 13\}$ and $\mathbf{c}^{19} = \{18, 3, 7, 12\}$, respectively. Note that miss detection and false detection may occur. Let assume that the detection results of a receiver device are as follows: $\{2, 17\}$ for 1st OFDM symbol, $\{2\}$ for 2nd OFDM symbol, $\{6, 10\}$ for 3rd OFDM symbol, and $\{11, 13, 14\}$ for 4th OFDM symbol. The gray-colored DREs in Fig. 2(c) are the detection results of the receiver. Then, the receiver can find three matches (2, 10, and 13) with $\mathbf{c}^3$ and no matches with $\mathbf{c}^{19}$. If $v = 4$, the receiver cannot find any TDIDs. But, with $v = 3$ the receiver detects the TDID 3. Actually, in the above example, there is frequency offset between the device having TDID 19 and the receiver. To overcome the frequency offset, the receiver repeatedly matches by shifting the detected DREs one by one in frequency axis with TDID table. Then, the receiver can find perfect matches with $\mathbf{c}^{19}$. Note that shifted version of a TDID does not have equal hopping pattern with any other TDIDs.

IV. NUMERICAL RESULTS

We compare the performance of the proposed discovery channel generating scheme with those of GF-based scheme in [2] and random scheme. In the random scheme, DREs are randomly selected for discovery channels. When a temporal set of discovery channels is generated, the validity (line 6 in the Algorithm 1) is checked.

To demonstrate how the DREs in a discovery channel are well dispersed, we examine the number of different coherence regions that the DREs occupy in frequency band. Let o^b the number of different coherence regions that the DREs in discovery channel b occupy. The range of an o^b is 1 to N . For instance, in Fig. 2, $o^7 = 2$ and $o^{13} = 2$ for the GF-based scheme and $o^6 = 1$ and $o^{11} = 2$ for random-based scheme

with $W = 4$. On the other hand, $\min_{1 \leq b \leq B} \{o^b\} = 3$ for the proposed scheme.

Table 1 shows the dispersive results of three discovery channel generating schemes where the used parameter values are $B = 491$, $N = 14$, and $W = 12$. The other parameter values also selected considering a typical LTE-based cellular system. Since the GF-based scheme cannot treat a non-prime value of B , we choose a prime number for B . In the case of random scheme, the discovery channel set which has the largest value for $\sum_b o^b$ among the candidate sets obtained from one hundred thousand experiments is finally chosen. The values of o^b are ranged from 9 to 14 in GF-based scheme and random-based scheme, whereas the proposed scheme have generated the discovery channels having $o^b = 12, 13$, or 14. Actually, the most of the discovery channels generated from the proposed scheme have $o^b = 14$, as shown in Table 1. This means that the proposed scheme is more detectable because of the frequency diversity in comparison with the other schemes.

Next, we evaluate how discoverable the generated discovery channels are. This can be assessed by the successfully detected TDID ratio. When a device broadcasts its TDID on the corresponding discovery channel, if another device successfully detects energy on more DREs than the minimum number of DREs for TDID detection (v), we can say that the receiver device detects the TDID of the transmitter.

For a realistic simulation for device discovery in the LTE-based cellular networks, we adopt the evaluation methodology in [6]. The representative simulation parameters are as follows. Uplink bandwidth is 5 MHz, device transmit power is 24 dBm, carrier frequency is 2 GHz, the number of subcarriers in a discovery resource (i.e., B) is 491, the number of OFDM symbols in a discovery resource (i.e., N) is 14, thermal noise density is -174 dBm/Hz, and the transmit/listen probability of each device (i.e., p) is 0.5. The path loss and fading model are also described in [6].

As seen in Fig. 3, almost the whole TDIDs can be detected all of three schemes, when the minimum number of DREs for TDID detection, v , is 10 or 11. When the v is 12 or above, the proposed scheme is superior to the other two schemes.

It is noted that the practical value of the v should be quite large for preventing fault detections. Fault detection means that a receiver device determines there is a device having a TDID even if actually there is no such a device. This kind of faults may cause severe penalty when the receiver device tries to communicate with the ghost device. Therefore, according to [2], we think 13 is a proper value for v in our system.

TABLE 1. DISPERSION OF DISCOVERY CHANNEL GENERATING SCHEMES

	GF in [2]	Random	Proposed
$o^b = 9$	9	5	0
$o^b = 10$	32	24	0
$o^b = 11$	95	73	0
$o^b = 12$	154	192	1
$o^b = 13$	153	136	7
$o^b = 14$	52	61	483
$\text{avg}(o^b)$	12.18	12.25	13.98

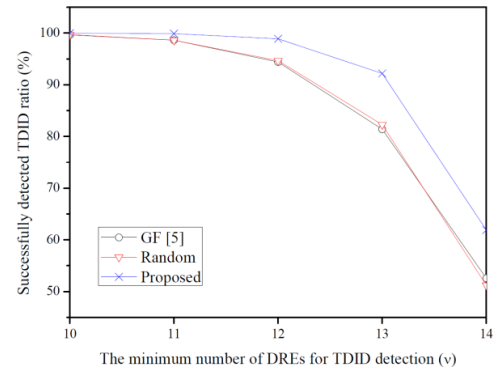


Figure 3. Successfully detected TDID ratio versus detection threshold v

The detecting ratios of the GF-based scheme, the random-based scheme, and the proposed scheme are 81.39%, 82.28%, and 92.18%, respectively when $v = 13$. That is, by using the discovery channels generated from the proposed scheme, a device can discover the 12% ~ 13% more devices in proximity in comparison with the other schemes.

V. CONCLUSIONS

In this paper, we have proposed a discovery channel generating scheme for signature-based device discovery in a disaster environment. Assuming the PS-LTE network, we have assumed a hybrid device discovery and focused on a signature-based discovery part for robust and fast device discovery. The simulation results show that the resultant hopping patterns of the discovery channels from the proposed scheme are well dispersed in frequency band, so that the channels are frequency offset and frequency selective fading tolerant. In addition, the successful discovery ratio is improved using the proposed discovery channels in comparison with other schemes.

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