Providing Fast Discovery in D2D Communication with Full Duplex Technology

Gatnau, Marta; Berardinelli, Gilberto; Mahmood, Nurul Huda; Alvarez, Beatriz Soret; Mogensen, Preben Elgaard

Published in:
Multiple Access Communications

DOI (link to publication from Publisher):
10.1007/978-3-319-51376-8_8

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

Providing Fast Discovery in D2D Communication with Full Duplex Technology

Marta Gatnau Sarret[1(✉)], Gilberto Berardinelli[1], Nurul H. Mahmood[1], Beatriz Soret[2], and Preben Mogensen[1,2]

[1] Department of Electronic Systems, Aalborg University, Aalborg, Denmark
mgs@es.aau.dk
[2] Nokia Bell Labs, Aalborg, Denmark

Abstract. In Direct Device-to-Device (D2D), the device awareness procedure known as the discovery phase is required prior to the exchange of data. This work considers autonomous devices where the infrastructure is not involved in the discovery procedure. Commonly, the transmission of the discovery message is done according to a fixed probability. However, this configuration may be not appropriate to meet the 10 ms control plane latency target defined for the next 5th generation (5G) system. In this work, we propose a distributed radio resource management framework supporting full duplex technology to provide D2D fast discovery. Such framework provides an algorithm to estimate the number of neighbor devices and to dynamically decide the transmission probability, for adapting to network changes and meeting the 10 ms target. Finally, a signaling scheme is proposed to reduce the network interference. Results show that our framework performs better than a static approach, reducing the time it takes to complete the discovery phase. In addition, supporting full duplex allows to further reduce the discovery time compared to half duplex transmission mode.

1 Introduction

Device-to-Device (D2D) communication has drawn significant attention for the design of 5th generation (5G) systems to offload the infrastructure and to cope with the continuous growth of wireless applications and services. In D2D communication, devices are allowed to communicate directly, without the involvement of the infrastructure. However, prior to the establishment of such communication, devices must discover their peers. This device awareness procedure is known as discovery phase. According to the latest specifications for next generation systems [1], the control plane latency cannot exceed 10 ms. Such requirement poses challenges on how to facilitate fast device discovery. Full duplex (FD) technology, which allows for simultaneous transmission and reception in the same frequency band, may speed-up the discovery process.

The execution of the D2D discovery procedure can be controlled by the infrastructure or performed autonomously by the devices. The first option requires the exchange of messages with the base station, generating additional

T.K. Madsen et al. (Eds.): MACOM 2016, LNCS 10121, pp. 98–108, 2016.
DOI: 10.1007/978-3-319-51376-8_8

control overhead and increasing the latency. The latter option, where devices send the discovery message periodically, has potential to diminish the control overhead and provide lower latency [2].

Autonomous device discovery using conventional half duplex (HD) transmission mode has been studied by the research community [4,5,7], whereas few works consider FD technology [8–10]. A synchronous distributed ad-hoc network is studied in [5], focusing on optimizing the discovery latency and the number of discovered devices. The authors propose a resource structure as well as a resource selection. However, the feedback mechanism is not considered and their system operates in a larger time scale than that specified by [1]. A discovery message design to minimize collisions is proposed in [4]. The work analyzes an autonomous D2D system where devices transmit the discovery message with a fixed probability, showing an improvement in the number of discovered devices. The authors in [7] propose using a small portion of the resources for new devices appearing in the network, such that their discovery message can be transmitted with a shorter delay. In [8], a strategy to reduce idle slots and collisions is presented. FD is used to detect the activity of other devices. The work assumes that a device stops transmitting when it is discovered. Nevertheless, this assumption may not be valid in networks with dynamic (de)activation of the nodes where transmitting the discovery message is always required. In [10], FD is combined with compressed sensing to overcome the drawbacks from HD and single packet reception. The authors claim that the discovery phase is completed in a single time slot. However, a very limited number of neighbors is considered and the feedback procedure for discovery acknowledgment is not addressed. The authors in [9] evaluate FD with directional antennas, where each device selects a transmission direction randomly at each time slot. It is important to notice that the mentioned works assume the transmission of the discovery message with a fixed probability. This principle does not allow to control the generated idle slots and collisions, thus posing critical challenges in meeting the latency requirements.

In our previous work [2], we showed that adapting the rate of discovery message transmission to the number of active devices may be beneficial, and we identified challenges in terms of interference management in a large network. In this paper, we propose a radio resource management (RRM) framework for autonomous D2D communication supporting FD technology. It provides a mechanism to estimate the number of neighbors as this information is not available in realistic ad-hoc networks, and an adaptive scheme to select the most appropriate transmission probability for the discovery messages. The interference can be better coordinated by allowing the devices to exchange their transmission probability, which captures the number of neighbors in our proposal. Thus, each terminal can dynamically set the most appropriate transmission probability using not only the current value and own information but also information from the neighbors. Results show that our solution achieves lower latency than a static approach. Moreover, supporting FD allows to further reduce the discovery time compared to HD transmission mode.

The paper is organized as follows. Section 2 describes the proposed RRM framework. Section 3 presents the system model and discusses the simulation results. Finally, Sect. 4 concludes the paper and states the future work.

2 D2D Fast Discovery

2.1 General System Overview

We focus on autonomous ad hoc networks with a dedicated band of the spectrum for the discovery procedure. Devices communicate directly with each other and the infrastructure is not involved in the discovery phase, but still provides time and frequency synchronization. This design allows to avoid interference between cellular and D2D users.

A time slotted system is considered. At each transmission opportunity, there is possibility of exploiting a pool of orthogonal frequency resources, where the resource to be used is randomly chosen. It is assumed that, on reception, devices can simultaneously listen to all frequency resources. The discovery message is transmitted in a broadcast manner according to a certain transmission probability ρ and it contains the information required to perform the discovery phase, e.g., the device identifier and its position. Since the discovery procedure needs to be completed in a short time to meet the strict control plane latency requirements [1], the number of link failures should be minimized. This can be achieved by transmitting the discovery message with a robust modulation and coding scheme (MCS) at the expense of a larger message, and by using one spatial stream, often referred as transmission *rank* one, assuming that devices are equipped with 4×4 multiple-input multiple-output (MIMO) transceivers. The dimensioning of the discovery message is left for future work. In this paper, we assume that the discovery message can be mapped over a single time/frequency resource.

The discovery phase is required to set a unicast/multicast communication. Therefore, the devices involved in such communication should be acknowledged of the fact that their peers are aware of their presence. We propose a design for the discovery message that includes a *feedback* field, containing the identifiers of the devices that have been discovered by the transmitting device. Since the discovery message is broadcast, a device that receives and decodes the message will check if its identifier is piggybacked. If so, the receiving device will know that it has been discovered by the transmitting device. The discovery time is then based on the feedback reception time, and it depends on the transmission probability ρ. Using a high ρ causes a large number of collisions which increases the discovery time. On the other hand, using a small ρ creates a large number of idle slots due to the inactivity of the devices, which also increases the time needed to complete the discovery procedure. Furthermore, in case of HD transmission, the necessity of transmitting the discovery message leads to a reduction of the opportunities for listening to neighbors' transmissions. We investigate the potential of FD technology in reducing the discovery time, since it eliminates the HD constraint by allowing simultaneous transmission and reception on the same frequency band.

2.2 RRM Design

In our previous work [2], we showed that the transmission probability that leads to the minimum discovery time depends on the scenario, e.g., on the number of neighbors. Such result indicates that a dynamic choice of ρ can be beneficial for the system. In addition, we identified challenges in terms of interference management in large networks. Let us define *cluster* as the set of neighbors within the coverage range of a device, plus the own device. Therefore, the cluster and its size is a device-specific parameter. In case every device is able to reach all the other devices in the network, all the devices' clusters coincide. We refer to this case as *single cluster* network. The opposite case is a *multi-cluster* network. Figure 4 shows an example of a portion of a multi-cluster network, where the clusters from two devices, C and G, are highlighted. In particular, the number beside each device refers to their cluster size. In this specific example, C only reaches G, while the latter reaches C, Y and W. Let us focus on G, which has two neighbors perceiving a larger cluster size (W and Y) and C, which only reaches G. Since G is not aware of the overall interference perceived by W and Y and it has only three neighbors, it would benefit from using a high ρ. However, using a high ρ may increase the number of collisions to W and Y, who have a larger number of neighbors, consequently increasing their discovery time. On the other hand, C will benefit from such a high ρ because it has a cluster of size 2.

From the previous example we can extract that an exchange of information among devices can be beneficial to reduce the overall network interference and to avoid increasing the discovery time. Furthermore, in a realistic network, the information related to the number of neighbors is not available. To solve the mentioned problems, we propose a RRM framework to dynamically adjust the transmission probability allowing devices to adapt to network changes. It consists of two parts: the instantaneous estimation of the number of neighbors, and the dynamic adjustment of ρ based on network information exchange. The proposed solution is distributed, so it does not require a centralized controller that collects information from the network.

Pseudo Code 1. Algorithm for estimating the number of neighbors

$\rho \leftarrow$ Current transmission probability. Initial value $\rho = 0.5$
$\tilde{M} \leftarrow$ Estimated number of neighbors. Initial value $\tilde{M} = 0$
repeat At each time slot
  Extract ρ according to the selected information exchange approach (Table 1)
  if Transmission time, based on ρ, **then**
    Transmit the discovery message
  else
    Receive discovery messages from neighbors, and estimate $\tilde{M}$ as:

$$\tilde{M} = \frac{\#\text{decoded signals}}{\rho} \quad (1)$$

  end if
until The device turns off

Estimating the Number of Neighbors. The estimation of the number of neighbors is done based on the available information at each device: the own ρ and the number of signals successfully decoded in each receiving time slot. The estimation of the number of neighbors with HD is done as described in Pseudocode 1. In case of FD, the *if* statement encapsulates only the transmission part, since a FD device is continuously receiving. In Eq. 1, the *#decoded signals* refers to the number of instantaneous messages that a device on reception can successfully decode. Then, the equation is equivalent to the number of active neighbor devices that a node can detect.

Signaling Scheme. To reduce the network interference, we propose that devices send ρ within the discovery message, since it is related to the number of estimated neighbors: a low number of estimated devices leads to a high transmission probability, and vice versa. The value of ρ can be represented with different number of bits, depending on the desired resolution and the allowed control overhead. Table 1 lists the proposed approaches to extract ρ, according to the signaled information. The difference among these approaches is the amount of extra information sent within the discovery message and how this information is utilized to decide the ρ to be used. With the *selfish* approach, devices do not signal any information about their ρ, and they behave in a selfish

Table 1. Information exchange approaches

Approach	Signaling	Principle
Selfish (ρ_{sf})	None	Use ρ extracted from the estimated number of devices without considering information from the neighbors. Section 3.1 describes the function that, depending on the estimated number of devices, provides the most appropriate ρ.
Cooperative minimum	ρ_u	Set ρ as the minimum between: a. The ρ extracted from the estimated number of neighbors (ρ_{sf}) b. The minimum ρ received from the neighbors
Cooperative maximum	ρ_u and ρ_{sf}	Set ρ taking into account: a. The ρ extracted from the estimated number of neighbors (ρ_{sf}) b. The used ρ received from the neighbors ($\rho_{u,nb}$) c. The estimated ρ received from neighbors ($\rho_{sf,nb}$) The decision is taken as follows: 1. Extract the minimum of $\rho_{u,nb}$ and $\rho_{sf,nb}$ of all the received messages from my neighbors 2. If $\rho_{u,nb} = \rho_{sf,nb} = \rho_{nb}$: select the minimum between ρ_{sf} and ρ_{nb} 3. If $\rho_{u,nb} < \rho_{sf,nb}$: select the minimum between $\rho_{sf,nb}$ and ρ_{sf}

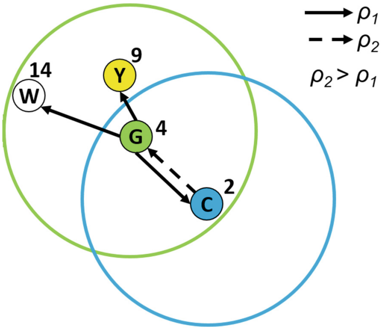

Fig. 1. Example of a multi-cluster network with 2 highlighted clusters (Color figure online)

manner. Hence, the control overhead is not increased but the network interference is uncontrollable. With the *cooperative minimum* option, devices signal the used ρ, which is extracted as indicated in Table 1. In this case, the control overhead is slightly higher but the interference is reduced. Finally, with the *cooperative maximum* approach, devices transmit two values of ρ: the one used for transmission, extracted by applying the *cooperative maximum* approach, and the one extracted from the estimation of the number of neighbors, i.e., the *selfish* ρ_{sf}. The difference between the second and the third approaches is that the latter avoids for the minimum ρ to spread across the network, at the cost of limited extra overhead.

Let us focus again in the example depicted in Fig. 1. Using the *selfish approach*, G and C will use a high transmission probability, hence G will be highly interfering W and Y, causing unsuccessful transmissions. If the *cooperative minimum approach* is used, the ρ extracted by W will be the one that the other devices in the network will use. However, C should be able to transmit with a higher ρ because it is not interfering W. This situation can be solved with the *cooperative maximum approach*.

3 Performance Evaluation

The RRM framework techniques proposed in Sect. 2 are evaluated using our own developed Matlab simulator. Firstly, we want to prove that a dynamic ρ selection has advantages over using a fixed one. Secondly, the performance of the single and the multi-cluster scenarios is discussed.

For our D2D network, we assume a simple path loss model $\gamma = d^{-\alpha}$, where α is set to 4, and no fading. The packet decoding is threshold-based: a collision occurs if the signal to noise-plus-interference ratio (SINR) is below such threshold, which is set to 0 dB, assuming Quadrature Phase Shift Keying (QPSK) with a coding rate of 1/3 and a block error rate of 0.01%. The representation of ρ is ideal in this study, i.e., it is represented with maximum resolution. Finally, ideal self-interference cancellation in FD devices is assumed [3].

According to the findings in [2], one of the requirements to meet the strict 5G control plane latency target is to use interference cancellation (IC) receivers. These receivers are able to suppress the $N - K$ strongest interfering streams, where N is the number of MIMO receive antennas and K is the transmission rank. For example, according to our simulation setup (transmission rank one and devices equipped with 4 receiving antennas), the three strongest interfering streams can be suppressed. We assume ideal IC in this work. The SINR reads then:

$$SINR_{IC} = \frac{\gamma_d \cdot P_T}{\sum_{i=k}^{rxSignals} I_i + N_0} \tag{2}$$

where γ_d is the pathloss between the receiver and the desired transmitter, P_T is the transmit power, N_0 is the noise power, $k = N - K + 1$ and the interfering streams I_i are sorted based on the signal strength from the strongest to the weakest one. In this work, the transmit power is 0 dBm and a noise power in each time/frequency resource is −95 dBm.

The devices are randomly deployed in a certain area. Two scenarios are analyzed, a single and a multi-cluster scenario. The former suffers only from intra-cluster interference, while the latter is affected by intra and inter-cluster interference, since clusters may be partially overlapped or totally isolated. The single cluster scenario refers to a $100 \times 100\,\text{m}^2$ area with the number of deployed devices ranging from 10 to 50. An area of $1000 \times 1000\,\text{m}^2$ is considered for the multi-cluster scenario, where the number of deployed devices goes from 10 to 300. In particular, the average cluster size ranges from 3 to 44.

We assume that a discovery message opportunity occurs every 0.25 ms. This is consistent, for example, with the assumption in terms of frame duration of our 5G small cell concept presented in [6]. The discovery time is defined as the time needed for a device to be discovered by all its neighbors, based on the feedback reception time. It is extracted, individually for each node, as the maximum time among all the neighbor feedback reception times. For the single cluster scenario, results are presented in terms of average discovery time, since the interference conditions for all the devices are, in average, the same. In case of the multi-cluster scenario, results are presented in terms of the 95^{th} percentile of the discovery time. For both scenarios, the performance of FD is compared against the HD performance. Finally, the variable θ provides an indication of the system congestion, and it is defined as:

$$\theta = \frac{\text{number of network devices}}{\text{number of frequency resources}} \tag{3}$$

3.1 Dynamic Transmission Probability

Let us consider the single cluster scenario with its corresponding parametrization, and setting the size of the frequency resource pool to 1, 2 and 4, to have different system level congestion representations. In our previous work we proved that the optimal ρ which minimizes the discovery time is scenario-dependent. Figure 2 shows such optimal ρ as a function of θ, for the ideal case where the

devices know the exact number of neighbors. From the figure we can observe that, as the system congestion increases, the optimal ρ diminishes due to the constraint on the number of collisions. We can also see that FD allows for a higher ρ in some cases, specially at low system congestion. This is because, as explained in Sect. 2, FD solves the constraint that HD poses on the ρ selection. Therefore, since FD operates in a larger range of ρ, we expect to have larger gains from using a dynamic approach with FD compared to HD. This two curves can be easily approximated by a simple multiplicative inverse function $\rho = f\big(\tilde{M}, \text{frequency resources pool size}\big) = f(\theta) \approx \frac{a}{\theta^b}$, where a and b are fitting parameters. Such approximations allow us as to have a representation of the optimal ρ based on the system congestion.

3.2 Single Cluster Performance

As the next step, we evaluate the proposed RRM framework in the single cluster scenario, assuming a frequency resource pool of size 4. In this case, the considered approach is the selfish one, since the interference conditions of all the devices are, in average, the same. Consequently, the three approaches described in Table 1 show the same performance. The evaluation is done by comparing: the optimal discovery time, extracted under the assumption of ideal information at the devices; the performance of the proposed RRM framework, extracting ρ_{SF} from the inverse approximation of the curves shown in Fig. 2; and a fixed ρ of 40%, since it provides a good trade-off on the HD performance given its limitation of not being able to receive messages while transmitting. Figure 3 shows the performance comparison between the mentioned cases. We can observe that the HD performance is barely affected from the usage of a dynamic ρ, except when the number of network devices is large. This is caused by the small operational range of ρ, given the HD constraint. However, in case of FD, we can observe that a dynamic ρ selection allows to get very close to the optimal system performance. The maximum difference between the optimal and the algorithm performance is 0.83 ms, at high congestion. At low congestion, the maximum difference is 0.13 ms.

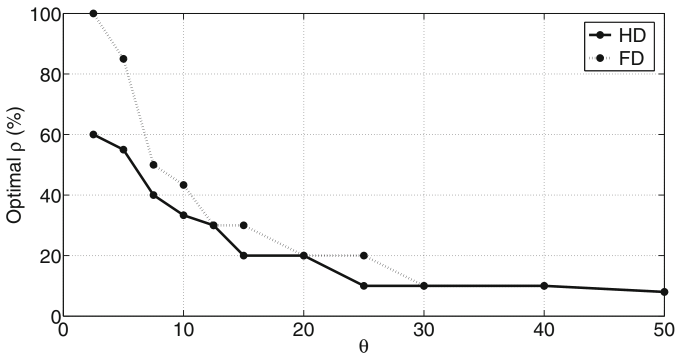

Fig. 2. Optimal ρ as a function of the system congestion θ

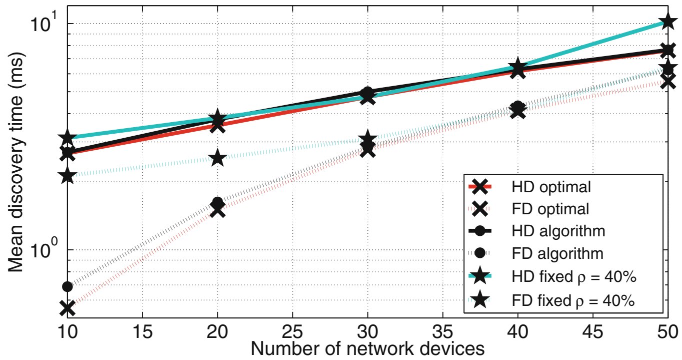

Fig. 3. Single cluster. Performance comparison between the proposed algorithm, the optimal performance and a fixed ρ

We want to emphasize that the robustness of the approximated ρ curves have also been evaluated, by varying the path loss model or the deployed area. Results show that the maximum difference between the ideal discovery time and the one extracted by using our proposed framework and the approximations is ~0.5 ms.

3.3 Multi-cluster Performance

We focus here on the multi-cluster scenario, assuming a frequency resource pool of size 4, and we will analyze the performance of the three approaches presented in Table 1 and the fixed 40% transmission probability. For HD, only two performance curves are presented, the selfish and the fixed 40% one, since the performance with the other two proposed algorithms is nearly the same as the selfish one. The reason for that, as explained before, is the smaller range of ρ with HD since a device cannot listen while transmitting, leading to an increase of the discovery time if a too high ρ is used. Figure 4 shows the 95$^{\text{th}}$ percentile of the discovery time. The results show that, with HD, the latency requirement of 10 ms can be achieved with up to 200 network devices, but the discovery time is always larger than the one achieved with FD. Focusing on the FD performance, we can observe that providing a dynamic solution for the ρ selection brings benefits in terms of reduction of the discovery time, independently of the network density. In case of few devices in the network, the selfish approach shows the best performance in terms of discovery time, since it is the most aggressive scheme and using interference cancellation receivers allows the system to use a high ρ. The cooperative minimum approach is too conservative at low network density, since the ρ used by the device in the worst interference conditions spreads across the network. Note that the drawback of such approach can be solved by using the cooperative maximum approach, since it allows to increase the transmission probability in case the neighboring nodes are not affected by this ρ increase. As the network density increases, we observe that the cooperative minimum and maximum approaches reach the optimal system performance. In this case,

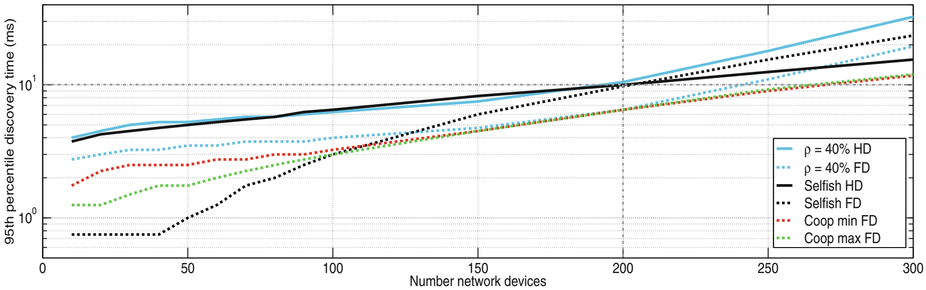

Fig. 4. Multi-cluster. Performance comparison between the proposed algorithm, the optimal performance and a fixed ρ

both approaches perform equally since the optimal ρ is already small, to avoid generating a large interference and hence a large number of collisions. Notice that with the proposed cooperative algorithms, the system can support higher network density while still meeting the 10 ms latency requirement.

Finally, Fig. 5 shows the cumulative distribution function (CDF) of the discovery time with HD and FD for the cooperative maximum approach, for the cases of 70 and 150 number of network devices. The curves show that, beyond the mean gain of FD over HD, HD suffers from larger time variances, with some devices perceiving large discovery time and others finishing their process much faster.

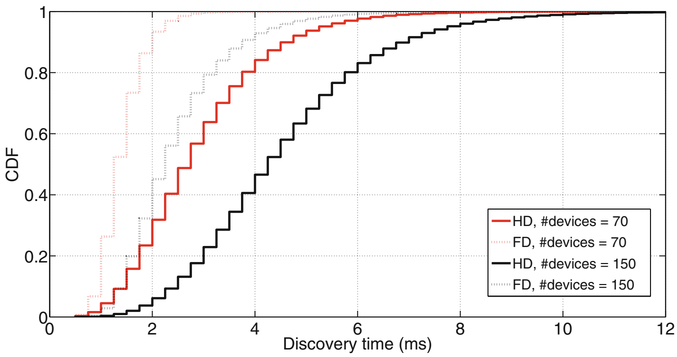

Fig. 5. Multi-cluster. Cooperative maximum algorithm CDF

4 Conclusion and Future Work

In this paper we have proposed a RRM framework supporting FD technology to provide fast discovery in autonomous D2D communication. The framework provides a mechanism to estimate the number of neighbor devices and a scheme

to dynamically adjust the transmission probability, in order to reduce the number of collisions and idle slots and decrease the latency for discovery. The proposed signaling exchange mechanism allows to reduce the network interference and improve the system performance. System level results show that our proposed dynamic solution allows to reduce the discovery time compared to traditional static approaches, especially in case full duplex technology is used. Future work will focus on the control message design and on applying the framework in scenarios with high mobility such as vehicle-to-anything (V2X) applications.

Acknowledgments. This work has been performed within the framework of the Horizon 2020 project FANTASTIC-5G (ICT-671660) receiving funds from the European Union. The authors would like to acknowledge the contributions of their colleagues in the project, although the views expressed in this contribution are those of the authors and do not necessarily represent the project.

References

1. 3GPP TR 38.913 V0.3.0: Study on scenarios and requirements for next generation access technologies, March 2016
2. Gatnau, M., Berardinelli, G., Mahmood, N.H., Soret, B., Mogensen, P.: Can full duplex reduce the discovery time in D2D communication? In: 13th International Symposium on Wireless Communication Systems (ISWCS), Accepted June 2016
3. Heino, M., et al.: Recent advances in antenna design and interference cancellation algorithms for in-band full duplex relays. IEEE Commun. Mag. **53**(5), 91–101 (2015)
4. Hong, J., Park, S., Choi, S.: Neighbor device-assisted beacon collision detection scheme for D2D discovery. In: 2014 International Conference on Information and Communication Technology Convergence (ICTC), October 2014
5. Jung, S., Chang, S.: A discovery scheme for device-to-device communications in synchronous distributed networks. In: 16th International Conference on Advanced Communication Technology, February 2014
6. Mogensen, P., et al.: Centimeter-wave concept for 5G ultra-dense small cells. In: IEEE 79th Vehicular Technology Conference (VTC) (2014)
7. Park, S., Choi, S.: Expediting D2D discovery by using temporary discovery resource. In: IEEE Global Communications Conference (GLOBECOM), December 2014
8. Sun, G., Wu, F., Gao, X., Chen, G.: PHED: pre-handshaking neighbor discovery protocols in full duplex wireless ad hoc networks. In: IEEE Global Communications Conference (GLOBECOM), December 2012
9. Xu, R., Li, J., Peng, L., Ye, Y.: A neighbor discovery algorithm for full duplex ad hoc networks with directional antennas. In: The 27th Chinese Control and Decision Conference (CCDC), May 2015
10. Yang, X., Wang, X., Yang, R., Zhang, J.: Full-duplex and compressed sensing based neighbor discovery for wireless ad-hoc network. In: IEEE Wireless Communications and Networking Conference (WCNC) (2015)