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*Published in:*  
IEEE Transactions on Vehicular Technology

*DOI:*  
[10.1109/TVT.2019.2932046](https://doi.org/10.1109/TVT.2019.2932046)

Published: 01/10/2019

*Document Version*  
Peer reviewed version

*Please cite the original version:*  
Penda, D. D., Wichman, R., Charalambous, T., Fodor, G., & Johansson, M. (2019). A Distributed Mode Selection Scheme for Full-Duplex Device-to-Device Communication. *IEEE Transactions on Vehicular Technology*, 68(10), 10267-10271. [8781917]. <https://doi.org/10.1109/TVT.2019.2932046>

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# A Distributed Mode Selection Scheme for Full-Duplex Device-to-Device Communication

Demia Della Penda\*, Risto Wichman†, Themistoklis Charalambous†, Gábor Fodor\*‡, and Mikael Johansson\*

\* KTH Royal Institute of Technology, Emails: {demiadp, gaborf, mikaelj}@kth.se

† Aalto University, Emails: {risto.wichman, themistoklis.charalambous}@aalto.fi

‡ Ericsson Research, Sweden, Email: gabor.fodor@ericsson.com

**Abstract**—Networks with device-to-device (D2D) technology allow for two possible communication modes: traditional communication via the base station, and direct communication between the users. Recent studies show that in-band full-duplex (IBFD) operations can be advantageously combined with D2D communication to improve the spectral efficiency. However, no algorithms for selecting the communication mode of mobile users in IBFD networks have yet appeared in the literature. In this paper, we design a distributed mode selection scheme for users in D2D-enabled IBFD networks. The proposed scheme maximizes the users’ probability of successful communication by leveraging only existing signaling mechanisms.

## I. INTRODUCTION

Device-to-device (D2D) communication is a promising technology with which to manage the increasing volumes of data traffic for local services. The idea is to enable mobile users to establish a direct link (*D2D mode*), as opposed to the traditional way of communicating via the base station (BS) (*cellular mode*). The decision whether a transmitter-receiver pair should use D2D mode or cellular mode is known as mode selection (MS). Recognizing the importance of MS, several solutions have been proposed for half-duplex systems, aiming to optimize various performance measures such as throughput, energy efficiency, and load-dependent utility [1,2]. The practical implementation of existing schemes is challenging due to the extensive channel state information (CSI) required. In fact, for D2D networks, the CSI needs to be evaluated not only between mobile devices and the BS, but also for the direct links. This evaluation, with all needed updates in fast fading environments, requires significant system resources. Another concern is that both gathering the CSI and exchanging it among the involved nodes can add intolerable overhead to the system. Finding the best trade-off between CSI availability and accuracy, and signaling overhead is an important aspect of D2D-enabled networks.

The recent work in [3] aims at addressing these practical issues in a bandit model, but it involves several power-inefficient mode switches. Along another line of research, in-band full-duplex (IBFD) communication is emerging as a way of doubling the spectral efficiency if the self-interference (SI) (the interference that a transmitting IBFD terminal causes to itself) is kept sufficiently small [4]. Because of the small distance between D2D users, the transmit power is low and the SI is manageable, which makes D2D communication an appealing technology to integrate with IBFD operations. Studies on IBFD D2D-enabled networks with a stochastic geometry approach

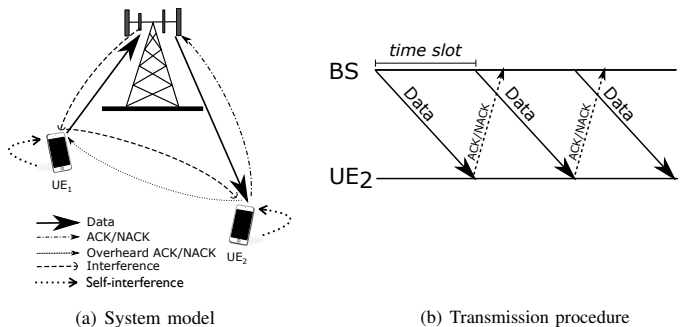


Fig. 1. (a) Cellular mode: the BS forwards the data from UE<sub>1</sub> to UE<sub>2</sub>. UE<sub>2</sub> replies with ACK/NACK signals that are overheard by UE<sub>1</sub>; (b) UE<sub>2</sub> sends the ACK/NACK signals to the BS after each transmission slot.

can be found in [5]–[7]. In particular, the authors of [6] focus on a cache-enabled D2D network and characterize the impact on the network performance from both the caching mechanism and the interference, while the authors of [7] propose a threshold-based MS scheme, in which D2D users select the nearest neighbor to form pairs. Although the increasing interest in IBFD D2D-enabled networks, a low complexity and low signaling MS algorithm is still missing. In this work, we fill this gap by proposing a MS scheme that: i) capitalizes on the IBFD device capability to infer whether a cellular transmitter should switch to D2D mode or not; ii) maximizes the probability of successful communication between devices in a multi-cell fast-fading environment; iii) runs in a distributed manner and does not require any pilot signaling or prior CSI. We present an alternative approach to the classical CSI-based decisions, that rather than introducing additional signaling leverages an already existing mechanism: the ACK/NACK control signaling.

## II. SYSTEM MODEL AND PROBLEM FORMULATION

### A. System model

We consider a multi-cell network in which each BS manages a set  $\mathcal{F}$  of orthogonal frequency channels to be assigned to the transmissions within its cell area. In line with the operation of LTE systems, users access the frequency channels in transmission time intervals (TTIs), and are scheduled both in time and frequency such that they do not interfere with each other. In particular, we assume that there is at most one user pair (a mobile transmitter and its intended receiver) assigned

to one of the available frequency channel in each cell<sup>1</sup>

All communications are initially set to cellular mode operating in full-duplex, but user pairs are allowed to switch to D2D mode when they deem it to be beneficial. When a user pair switches to D2D mode, it keeps the same channel that was initially assigned for the communication in cellular mode.

For simplicity of exposition, we focus on the unidirectional communication between two users, UE<sub>1</sub> and UE<sub>2</sub>, assigned to a certain channel in a given cell. However, the analysis presented in the sequel equally applies to all other communications on the available channels in the system. When UE<sub>1</sub> and UE<sub>2</sub> communicate in cellular mode, both data and control transmissions occur on the same channel; see Fig. 1. The BS is equipped with a multi-user MIMO antenna [4] and receives different uplink signals (i.e., data from UE<sub>1</sub> and control signals from UE<sub>2</sub>) on the same channel. Both the BS and the users are capable of IBFD operations. We model the SI as the attenuation factor  $\beta_{SI}$  multiplied by the transmit power of the nodes.

UE<sub>1</sub> transmits the data packet in every TTI using the assigned channel. Because the BS typically has better capabilities to handle interference than mobile devices, we assume that the downlink is the weakest link under deep fades in cellular mode. At the receiver UE<sub>2</sub>, the packets forwarded by the BS are checked for errors, and Acknowledge (ACK) or Negative Acknowledge (NACK) control messages (assumed error-free) are sent back to the BS at the end of each time slot; see Fig. 1. Furthermore, UE<sub>1</sub>, UE<sub>2</sub> and BS are synchronized and they all know when the ACK/NACK signals are sent. We use  $g_{ij}$  to denote the channel gain of the radio link between nodes  $i$  and  $j$ , where  $i$  and  $j$  are equal to 0, 1, or 2, depending on whether they indicate the BS, UE<sub>1</sub> and UE<sub>2</sub>, respectively. The channel gains are modeled as  $g_{ij} = \bar{g}_{ij}h_{ij}$  where  $\bar{g}_{ij}$  represents the distance-dependent power attenuation, and  $h_{ij}$  is an exponentially distributed random variable with unit mean, representing Rayleigh fading. We assume frequency non-selective block fading, with a block length of one time slot.  $P_1$  and  $P_0$  indicate the data transmit power used by UE<sub>1</sub> and the BS, respectively, while  $P_2$  is the power used by UE<sub>2</sub> to send the ACK/NACK feedback.  $P_0$  and  $P_2$  are fixed, while uplink powers are user-dependent and assigned with the LTE open-loop power control scheme. Finally, we use  $\sigma^2$  to denote the thermal noise power, and  $\gamma^d$  and  $\gamma^c$  to denote the minimum Signal-to-Interference-plus-Noise-Ratio (SINR) values to successfully decode the data and the control signals, respectively. In general,  $\gamma^c < \gamma^d$ , because of the large coding gain of the short (1-2 bits) uplink control signals.

### B. Problem formulation

Let us indicate with  $\gamma_2^{\text{Cell}}$  and  $\gamma_2^{\text{D2D}}$  the SINR at UE<sub>2</sub> when communicating with UE<sub>1</sub> in cellular mode and in D2D mode, respectively. Our objective is to find the communication mode that maximizes the probability of successful communication

<sup>1</sup>The channel assignment policy is out of the scope of this paper. However, we assume an LTE-like approach which avoids packet collisions among orthogonal transmissions, meaning that there can be as many concurrent communicating user pairs in each cell as the number of available orthogonal channels.

from UE<sub>1</sub> to UE<sub>2</sub>, in a distributed manner. To this end, UE<sub>1</sub> must solve the following problem:  $\underset{m \in \{\text{Cell}, \text{D2D}\}}{\text{maximize}} \text{Prob}(\gamma_2^m \geq \gamma^d)$ , given no prior information about the involved channels and network topology. Because the identification of potential D2D pairs is, in fact, the solution to this problem, there is no need for an *a priori*, separate device-discovery mechanism.

## III. MODE SELECTION

We build our distributed solution on the observation that if UE<sub>1</sub> listens to the ACK/NACK signals sent by UE<sub>2</sub>, it can infer the communication quality of both modes and thus select the best one. In what follows, we first give the intuition behind the MS solution, and then describe the proposed algorithm.

### A. Mode selection idea

UE<sub>1</sub> and UE<sub>2</sub> start communicating in traditional cellular mode. When UE<sub>2</sub> attempts to decode the data sent by the BS, two cases can occur depending on  $\gamma_2^{\text{Cell}} = P_0g_{02}/(I_2 + \sigma^2)$ :

- 1) UE<sub>2</sub> sends an ACK to the BS implying that  $\gamma_2^{\text{Cell}} \geq \gamma^d$ ;
- 2) UE<sub>2</sub> sends a NACK to the BS implying that  $\gamma_2^{\text{Cell}} < \gamma^d$ .

While UE<sub>1</sub> transmits data to the BS, it also listens to the ACK/NACK signals of UE<sub>2</sub>. Three cases can now occur depending on the value of  $\gamma_1 = P_2g_{21}/(I_1 + \sigma^2)$ :

- 1)  $\gamma_1 \geq \gamma^c$ , and UE<sub>1</sub> decodes a NACK. The downlink transmission to UE<sub>2</sub> is not successful but there may be a good direct-channel quality between the two users.
- 2)  $\gamma_1 \geq \gamma^c$ , and UE<sub>1</sub> decodes an ACK. There is a good channel condition for UE<sub>2</sub> in cellular mode communication and there may also be a good direct-channel quality between the two users.
- 3)  $\gamma_1 < \gamma^c$ : either UE<sub>1</sub> cannot decode the acknowledgment signal or it does not hear anything from UE<sub>2</sub> ( $\gamma_1=0$ ). In this case, switching to D2D mode is not favorable.

In our system model, all uplink and downlink transmissions assigned to the same channel, the control signals and the SI, contribute to  $I_1$  and  $I_2$ . A significant part of these terms is intra-cell interference emanating from the full-duplex operations (i.e., the downlink and the uplink transmissions that affect  $I_1$  and  $I_2$ , respectively). When UE<sub>1</sub> switches to D2D mode, these high interference terms vanish, while SI remains.

Because  $\gamma^c < \gamma^d$ , although UE<sub>1</sub> can decode the control signals from UE<sub>2</sub> when in cellular mode, UE<sub>2</sub> might not be able to successfully decode the data from UE<sub>1</sub> if in D2D mode. Therefore, a power adjustment for the D2D mode is needed. We set the power of UE<sub>1</sub> when in D2D mode to  $\tilde{P}_1 = \sqrt{\gamma^d/\gamma^c}P_2$ , to approximate the probability that UE<sub>2</sub> successfully decodes the D2D data from UE<sub>1</sub> to the probability that UE<sub>1</sub> successfully decodes the control signals from UE<sub>2</sub> when in cellular mode; see Appendix for the derivation of  $\tilde{P}_1$ .

### B. Mode selection algorithm based on sequential test

Let  $\mathbb{P}_{\text{cell}}$  be the probability of successful communication from the BS to UE<sub>2</sub>, and  $\mathbb{P}_{\text{d2d}}$  be the probability of successful communication from UE<sub>1</sub> to UE<sub>2</sub>. We want UE<sub>1</sub> to determine if  $\mathbb{P}_{\text{d2d}} > \mathbb{P}_{\text{cell}}$  on the basis of the information it gathers from the UE<sub>2</sub> ACK/NACK signals.

Let  $\mathbf{s} = [s_1, s_2, \dots, s_t]$  denote the sequence of control signals that UE<sub>1</sub> collects up to the  $t$ th time slot. Each element of  $\mathbf{s}$  is

$$s_t = \begin{cases} \text{A} & \text{if UE}_1 \text{ hears an ACK,} \\ \text{N} & \text{if UE}_1 \text{ hears a NACK,} \\ \emptyset & \text{if ACK/NACK signal is not heard.} \end{cases}$$

From  $\mathbf{s}$ , UE<sub>1</sub> builds two sequences,  $\mathbf{x}$  and  $\mathbf{y}$ , as follows:

$$x_t = \begin{cases} 1 & \text{if } s_t = \text{A,} \\ 0 & \text{if } s_t = \text{N,} \\ - & \text{if } s_t = \emptyset, \end{cases} \quad y_t = \begin{cases} 1 & \text{if } s_t = \text{A,} \\ 1 & \text{if } s_t = \text{N,} \\ 0 & \text{if } s_t = \emptyset, \end{cases}$$

where the symbol “-” indicates that the element is disregarded. Thus, at slot  $t$ , the sequence  $\mathbf{x}$  has  $\sum_{i=1}^t \mathbb{1}_{\emptyset}(s_i)$  elements less than  $\mathbf{y}$ , where  $\mathbb{1}_A(x)$  is the indicator function of the event A.

Building on the observations in § III-A, the probability that cellular mode is successful depends on the amount of ACKs that UE<sub>2</sub> sends, and the probability that D2D mode is successful depends on how often UE<sub>1</sub> correctly decodes the control signals from UE<sub>2</sub>. Thus, we set  $\mathbb{P}_{\text{cell}} = \text{Prob}(x_i = 1)$  and  $\mathbb{P}_{\text{d2d}} = \text{Prob}(y_i = 1)$ .

We seek for a decision rule that, on the basis of the smallest amount of observations possible, lets UE<sub>1</sub> decide whether  $\mathbb{P}_{\text{d2d}} > \mathbb{P}_{\text{cell}}$  or not. To this end, the sequential procedure proposed in [8] provides a useful tool for the case at hand. By recasting our problem as deciding which of two sequences of Bernoulli trials, observed at different rates, has the greatest success probability, the decision procedure becomes as follows. At time slot  $t$ , UE<sub>1</sub> computes the number of ACKs and undetected control signals collected up to that slot; that is,  $n_A(t) = \sum_{i=1}^t \mathbb{1}_A(s_i)$ , and  $n_{\emptyset}(t) = \sum_{i=1}^t \mathbb{1}_{\emptyset}(s_i)$ , respectively. Subsequently, UE<sub>1</sub> evaluates the function

$$\psi(t, n_A(t), n_{\emptyset}(t)) = 2 \frac{tn_A(t) - (t - n_{\emptyset}(t))^2}{2t - n_{\emptyset}(t)}. \quad (1)$$

Given a predefined positive constant  $B$ , at the first time slot  $T$  such that  $|\psi(T, n_A(T), n_{\emptyset}(T))| \geq B$ , UE<sub>1</sub> stops collecting UE<sub>2</sub> control signals. If  $\psi(T, n_A(T), n_{\emptyset}(T)) \geq B$  or  $\psi(T, n_A(T), n_{\emptyset}(T)) \leq -B$ , UE<sub>1</sub> infers that  $\mathbb{P}_{\text{cell}} > \mathbb{P}_{\text{d2d}}$  or  $\mathbb{P}_{\text{cell}} < \mathbb{P}_{\text{d2d}}$ , respectively. Note that the complexity of the proposed algorithm grows linearly with the chosen  $B^2$ .

This procedure is typically able to take the optimal decision quickly (using a few tens of observations). Longer observation sequences are required to make the decision when the two unknown probabilities are similar, and for large values of  $B$ . In particular, the error probability  $P_e$  of the procedure depends on the odds ratio  $\lambda$  of the two probabilities as follows:  $P_e \lesssim 1/(\lambda^B + 1)$  (see [8] for details). Moreover, the values of (1) for which no decision can be made lie in the *indecision interval*  $[-B, B]$ , which increases with  $B$ . Note that  $B$  is a chosen parameter and it does not depend on any factor, but its choice affects the probability of error, as discussed below.

<sup>2</sup>To compute (1), one needs  $T$  additions for computing the sums  $n_A(T)$  and  $n_{\emptyset}(T)$ , 5 multiplications and 2 additions. For  $T \approx 10B$ , as suggested in Fig. 2(a), and because for the comparison one needs 2 more additions, approximately  $10B + 9$  operations are needed.

## IV. NUMERICAL RESULTS

We consider a 7-cell network with the BSs placed at the center of their cells. In each cell, there are randomly placed cellular users assigned to different channels. For our purposes, we consider only the pairs assigned to the same channel in the seven cells. Powers are set as follows:  $P_0 = P_0^{\text{max}}/|\mathcal{F}|$ ;  $P_1 = \min\{P + \rho \cdot \bar{g}_{\text{PL}}, P^{\text{max}}\}$  dBm, where  $\bar{g}_{\text{PL}}$  is the uplink path loss and  $P = \rho(\gamma^{\text{d}} + P_{\text{IN}}) + (1 - \rho)P^{\text{max}}$ ;  $P_2 = \gamma^c \sigma^2 R^\alpha$ , where  $R$  is the cell radius. Table I lists the simulation parameters.

TABLE I  
SIMULATION PARAMETERS.

Parameter	Value	Parameter	Value
$P_0^{\text{max}}, P^{\text{max}}$	40 W, 250 mW	$\sigma^2$	-174 dBm/Hz
$\alpha$	4	$R$	500 m
$\rho$	0.8	$P_{\text{SuccessN}}$	-116 dBm
$ \mathcal{F} $	25	$\beta_{\text{SI}}$	-95 dB
$\gamma^c, \gamma^{\text{d}}$	0, 10 dB	$B$	4

First, we look at the performance of the proposed algorithm with respect to the design parameter  $B$ . We generate 1000 Monte Carlo simulations, each with a different triple of probabilities ( $\text{Prob}(s_i = \text{A}), \text{Prob}(s_i = \text{N}), \text{Prob}(s_i = \emptyset)$ ). By knowing the true probabilities  $\mathbb{P}_{\text{cell}}$  and  $\mathbb{P}_{\text{d2d}}$ , we can compare the optimal decision to the one selected with the proposed algorithm. Fig. 2 reports the achieved results. For different values of  $B$ , we look both at the average number  $\bar{T}$  of slots needed to make a decision (i.e., average number of samples in the sequence  $\mathbf{s}$ ) and at the probability of error  $P_e$ .

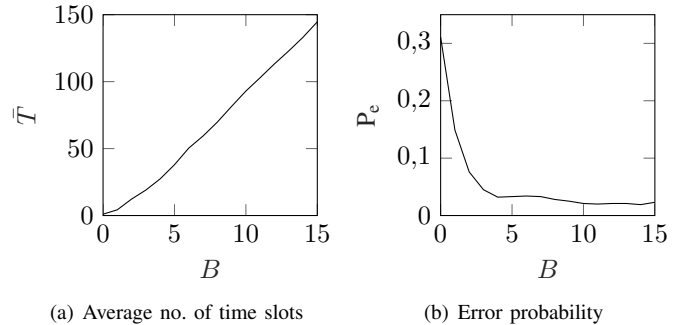


Fig. 2. For different values of  $B$ : (a) average number of observations needed for decision, and (b) probability of not choosing the best communication mode.

As aforementioned, when  $B$  increases, more observations are needed to select the communication mode, as shown in Fig. 2(a). On the other hand, because having more observations corresponds to more information available, the probability of error decreases with larger  $B$ . In particular, Fig. 2(b) shows that the probability of error goes down to 2% for  $B > 10$ . For large  $B$ , the algorithm may still be mistaken when  $\mathbb{P}_{\text{cell}} \approx \mathbb{P}_{\text{d2d}}$ , which is in line with the analysis in [8]. In fact, when the two probabilities are very similar an infinite number of samples might be required to make the correct decision. This does not represent an issue for the application considered in this work. In fact, when  $\mathbb{P}_{\text{cell}} \approx \mathbb{P}_{\text{d2d}}$ , transmitter UE<sub>1</sub> remains in the indecision state and continues communicating to UE<sub>2</sub> in cellular mode, but given that the performance of the two modes

are similar, there is no need to switch mode. As Fig. 2 shows,  $B = 4$  gives a good trade-off between the error probability ( $\approx 5\%$ ) and the time required for MS ( $\bar{T} \approx 25$ ).

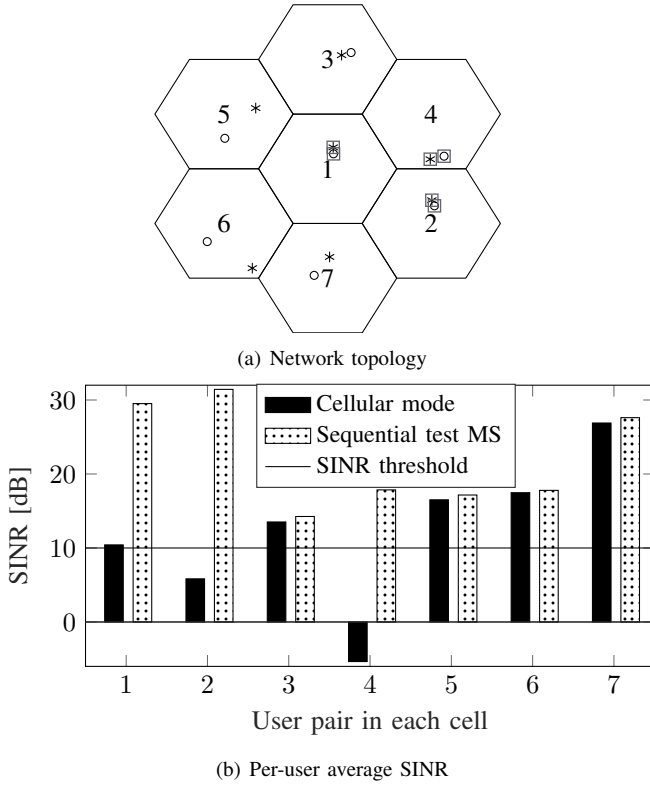


Fig. 3. (a) Network topology: asterisks and circles represent transmitters and receivers, respectively. Gray squares indicate users assigned to D2D mode. (b) Average SINR at the receivers with and without performing MS.

We now evaluate the performance of the proposed algorithm when applied to the simulated network with the user locations shown in Fig. 3(a). Specifically, we consider the case when all users are in cellular mode, and the case where MS is performed with the proposed algorithm. For the two cases, we compute and compare the average SINR of each receiver over 200 time slots. Fig. 3(b) shows the results. We can see that the IBFD operations strongly affect the MS decision and the achievable performance. In particular, when a mobile transmitter is very close to the BS, she perceives high intra-cell interference from the BS, because both the uplink and the downlink transmissions occur on the same channel. As a consequence, the mobile transmitter is not able to decode the overheard ACK/NACKs from the mobile receiver, and the user pair does not switch to D2D mode, even if the mobile transmitter and receiver are very close to each other. This situation is shown in Cell 3 in Fig. 3(a). This is not the case for the user pairs in Cell 1, 2, and 4. For them, the short distance between the users and the sufficiently large distance between each transmitter and the BS allow for D2D communication. Moreover, the results in Fig. 3(b) show that the pairs that switch to D2D mode increase their SINR considerably. This is mainly due to the elimination of the *UE-to-UE interference*, which is high when the transmitter and receiver are close to each other. We therefore conclude that, especially

in those cases, the D2D mode represents a good alternative to boost the communication performance. Furthermore, we see that when a user pair switches to D2D mode, the SINR of all users increases. This is because with D2D communications there are less transmissions in the shared channel compared with the cellular communications only, leading to a beneficial interference reduction in the entire network.

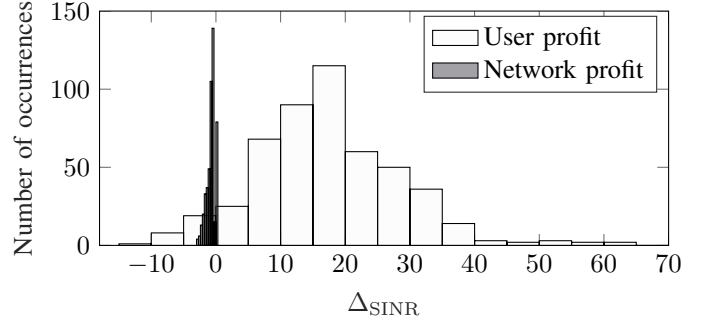


Fig. 4. Distribution of the user and network profit for 500 different scenarios.

To gain more insights into the benefits of the proposed MS algorithm, we define  $\gamma_j(\text{MS}_i)$  as the average SINR achieved by pair  $j$  in the network, when pair  $i$  is using the communication mode selected by our algorithm, and  $\gamma_j(\overline{\text{MS}}_i)$  as the average SINR achieved by pair  $j$  when pair  $i$  is not using the communication mode selected by our algorithm. The SINRs are averaged over 200 slots with different fading values. Then, we introduce the following two metrics: 1) **User profit**: for a given user pair  $i$ , it is defined as  $\Delta_{\text{SINR}_i} \triangleq \gamma_i(\text{MS}_i) - \gamma_i(\overline{\text{MS}}_i)$ . This metric measures the SINR gain/loss of pair  $i$  when using the communication mode chosen by our algorithm. Here, we consider  $i = 1$ , that is, the user pair in cell no.1 (see Fig. 3(a)). 2) **Network profit**: it is defined as  $\Delta_{\text{SINR}} \triangleq \min_{j \neq i} \{\gamma_j(\text{MS}_i) - \gamma_j(\overline{\text{MS}}_i)\}$ . This metric measures the maximum degradation of the SINR that pair  $i$  causes to the other pairs when using the communication mode chosen by our algorithm. Fig. 4 shows the results for 500 network topologies with randomly placed users in cells. From the two histograms, we draw the following conclusions. First, it is beneficial for a user pair to use the communication mode selected by our algorithm because the SINR increases in approximately 94.5% of the cases. Second, the greedy selection of the communication mode of each pair has small impact on the performance of the other users.

Finally, in Fig. 5 we compare the performance of the following MS approaches: i) **Cellular mode**: when all user pairs communicate via the BS; ii) **D2D mode**: when all user pairs communicate directly; iii) **Seq. test**: when the communication mode of each pair is selected with the proposed algorithm; iv) **Exh. search**: when we evaluate the performance of all combinations of MS for the seven user pairs (that is, we perform an exhaustive search), and select the one that boosts the users' SINR the most.

Fig. 5 shows the CDF of the SINR when considering 500 random network topologies. To reduce the edge effect, we

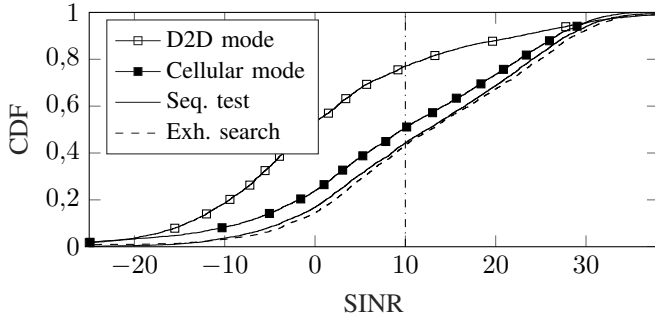


Fig. 5. CDF of the SINR achieved with different MS approaches.

show only the performance of user pair in cell no.1 (see the example topology in Fig. 3(a)). We can see that forcing the user pairs to transmit directly is the worst strategy, because of the potentially large distance between the transmitters and intended receivers. In fact, given that they are randomly placed within the cell area, their distance can even reach twice the cell radius. A proper selection of the communication mode of each user pair improves the performance otherwise achievable with the traditional communication in cellular mode. In particular, Fig. 5 shows that the CDF related to the proposed algorithm is shifted towards higher values of SINR than the CDF for the Cellular mode, with a reduction of the probability of outage by approximately 6%. It is remarkable that the performance of our proposed algorithm is close to the one achieved via exhaustive search, with the advantage that our scheme is fully distributed and does not require any knowledge about the statistics of the channel gains. Additionally, with the proposed algorithm the mobile transmitter decides whether to switch to D2D mode or not using, on average, only seven samples of the ACK/NACK information.

## V. CONCLUSION

We proposed a practical MS scheme for IBFD D2D networks, which uses the existing ACK/NACK signals to evaluate if D2D mode can increase the probability of successful communication between two users. Simulations showed that the D2D mode not only overcomes situations where the traditional cellular mode does not achieve the required SINR, it also reduces the overall interference in the system. Future research directions include considering bidirectional communications, and combining channel allocation strategies and advanced power control schemes to allow for resource reuse also within each cell.

## APPENDIX

### D2D POWER APPROXIMATION

The sets  $\mathcal{U}$  and  $\tilde{\mathcal{U}}$  denote the sets of nodes transmitting on the same channel as  $UE_1 - UE_2$ , before and after  $UE_1$  switches to D2D mode, respectively.  $UE_1$  decodes the control signals from  $UE_2$ , and  $UE_2$  decodes the D2D data from  $UE_1$  with the following success probabilities, respectively:

$$\mathbb{P}_c = 1 - \text{Prob}\left(g_{21} \leq \frac{\gamma^c}{P_2} \left( \sum_{\substack{i \in \mathcal{U} \\ i \neq 1,2}} P_i g_{i1} + \beta_{SI} P_1 + \sigma^2 \right)\right),$$

$$\mathbb{P}_d = 1 - \text{Prob}\left(g_{12} \leq \frac{\gamma^d}{\tilde{P}_1} \left( \sum_{\substack{j \in \tilde{\mathcal{U}} \\ j \neq 1,2}} \tilde{P}_j g_{j2} + \beta_{SI} \tilde{P}_2 + \sigma^2 \right)\right),$$

where we denote by  $\tilde{P}_j$  the transmit power of user  $j$  after the MS. The gains  $g_{ij}$  are independent exponentially distributed random variables with means  $\bar{g}_{ij}$ . Therefore,

$$\mathbb{P}_c = \prod_{\substack{i \in \mathcal{U} \\ i \neq 1,2}} \frac{\bar{g}_{21} P_2}{\bar{g}_{21} P_2 + \gamma^c P_i \bar{g}_{i1}} e^{-\frac{\gamma^c (\beta_{SI} P_1 + \sigma^2)}{\bar{g}_{21} P_2}},$$

$$\mathbb{P}_d = \prod_{\substack{j \in \tilde{\mathcal{U}} \\ j \neq 1,2}} \frac{\bar{g}_{12} \tilde{P}_1}{\bar{g}_{12} \tilde{P}_1 + \gamma^d \tilde{P}_j \bar{g}_{j2}} e^{-\frac{\gamma^d (\beta_{SI} \tilde{P}_2 + \sigma^2)}{\bar{g}_{12} \tilde{P}_1}}.$$

Note that  $\tilde{P}_2 = P_2$  because the control power is fixed, and  $\bar{g}_{12} = \bar{g}_{21}$  because they are deterministic quantities related to the physical distance between nodes 1 and 2. We want to determine  $\tilde{P}_1$  such that  $\mathbb{P}_d \geq \mathbb{P}_c$ , that is

$$e^{-\frac{\gamma^d (\beta_{SI} P_2 + \sigma^2)}{\bar{g}_{12} \tilde{P}_1} + \frac{\gamma^c (\beta_{SI} \tilde{P}_1 + \sigma^2)}{\bar{g}_{12} P_2}} \geq \frac{\prod_{\substack{i \in \mathcal{U} \\ i \neq 1,2}} \frac{1}{1 + \gamma^c \frac{P_i \bar{g}_{i1}}{P_2 \bar{g}_{12}}}}{\prod_{\substack{j \in \tilde{\mathcal{U}} \\ j \neq 1,2}} \frac{1}{1 + \gamma^d \frac{\tilde{P}_j \bar{g}_{j2}}{P_1 \bar{g}_{12}}}}. \quad (2)$$

Let us indicate with  $\Omega$  the ratio on the RHS in (2). Assuming the SI much higher than the noise, we rewrite (2) as

$$\gamma^c \tilde{P}_1 / P_2 - \gamma^d P_2 / \tilde{P}_1 \geq (\bar{g}_{12} / \beta_{SI}) \ln(\Omega). \quad (3)$$

The set  $\mathcal{U}$  includes the BS, which causes strong interference to  $UE_1$ , while the interfering nodes in  $\tilde{\mathcal{U}}$  are only those in the other cells. Considering that physically close cell-edge users in neighboring cells should not be assigned to the same channel, it is reasonable to assume that  $\Omega \leq 1$  and, thus, that the RHS of (3) is nonpositive. This observation allows us to find a power  $\tilde{P}_1$  that fulfills (3) without resorting any information on the channel gains, that is  $\tilde{P}_1 \geq \sqrt{\gamma^d / \gamma^c} P_2$ .

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