DYNAMIC SHARED SPECTRUM ALLOCATION FOR UNDERLAYING DEVICE-TO-DEVICE COMMUNICATIONS

Berna özbek, Mylene Pischella, and Didier Le Ruyet

ABSTRACT

This article provides an overview on spectrum sharing in D2D underlaying communications for 5G and beyond 5G applications. Various spectrum sharing algorithms are summarized within a framework of underlaying D2D communications in cellular networks to increase spectrum efficiency. Dynamic spectrum sharing algorithms in the frequency, power, and spatial dimensions are proposed for underlaying D2D communications with both single antenna and multiple antennas at the base station. Performance evaluations show the effectiveness of the proposed algorithms in terms of average data rate per D2D pair.

INTRODUCTION

The required data traffic is expected to significantly increase due to very high throughput services such as high definition (HD) video streaming, wireless cloud office, and augmented reality. In order to cope with these new traffic demands, cellular networks should dynamically allocate their radio resources as efficiently as possible. This can be achieved by performing direct communications between mobile users on top of the hierarchical architecture where mobile users can only be connected to the base station (BS). Therefore, device-to-device (D2D) communications can be established between two nearby mobile users that are directly exchanging data. Such direct communication has many advantages since it decreases latency, increases the data rate, and decreases power consumption due to low propagation loss. Moreover, the spectrum can be shared by several D2D pairs if they are far enough to assume that their mutual interference is negligible. Of course, not all mobile users may be involved in direct communication, and other users (referred to as cellular users in the remaining parts of the article) will still communicate with the BS. Spectrum sharing is allowed between cellular and D2D communications dynamically; however, adding D2D communications should not generate any regression of cellular transmissions. D2D communications are then underlaid in cellular transmissions.

Dynamic spectrum sharing in underlaying D2D communications raises many issues regarding how resources should be allocated to make the best use of the spectrum [1]. In multi-carrier transmissions such as Long Term Evolution (LTE), two types of algorithms can be used. In the first one, resource block (RB) allocation is separated from power control and performed just once; in the second one, the two steps are separated, but they are iterated to achieve better performances. In [2], the first type of algorithm was used with the additional constraint that only one D2D pair can be multiplexed per RB with a cellular user. The optimization objectives may be written to maximize the sum rate or the energy efficiency. Another constraint imposed, that each D2D pair is only allocated one RB, whereas several D2D pairs are multiplexed with a cellular user, was considered in [3, 4]. The multiplexing of D2D pairs with cellular users has been written as a graph-coloring problem in, for instance, [5, 6]. The second type of algorithm relies on iterative solutions [7] to maximize the weighted sum rate or to achieve proportional fairness.

In this article, we first provide an overview of D2D communications and of the different existing D2D transmission modes with a special emphasis on underlaying communications. Then we introduce the studied scenario. The different approaches for dynamic shared spectrum allocation in the frequency, power, and spatial dimensions are described. The novel spectrum sharing techniques are assessed with numerical results, and finally, some open issues are discussed.

D2D COMMUNICATIONS

OVERVIEW OF D2D COMMUNICATIONS

Current cellular networks are structured in a hierarchical way with a BS in each cell that controls all the users and through which all data traffic goes. Recently, D2D communications have been presented to offload the data traffic of BSs [1]. D2D communications provide a direct connection between two mobile users in proximity without the help of the BS. D2D communication is a promising solution to improve spectral efficiency by increasing high-rate local services, such as distributing large files between close wireless devices. Moreover, D2D communications offer a large panel of proximity services including online gaming, real-time social networking, communication in natural disaster, mobile advertising, and so on.

We can distinguish two types of D2D commu-

Digital Object Identifier:
10.1109/MWC.2017.1700064

Berna Özbek is with Izmir Institute of Technology; Mylene Pischella and Didier Le Ruyet are with CNAM-Paris.

nications. In D2D communications with operator controlled link establishment, the source and destination devices talk and exchange data with each other without the need for a BS. However, they are assisted by the operator for link establishment. On the other hand, in D2D communications with device controlled link establishment, the source and destination devices have direct communication with each other without any operator control. In this article, we mainly consider operator controlled link establishment. In both cases, the spectrum resources for D2D communications should be allocated in such a way as to ensure limited interference with other devices and maximize the overall spectrum efficiency. Besides, an important challenge of D2D communications is related to device discovery. The discovery can be processed by the BS, which will inform the devices about other devices in close proximity, or can be performed by the devices themselves through the use of beacons.

Two D2D communication modes to reuse cellular spectrum resources can be considered: overlay and underlay communications [2]. In overlay D2D communications, the operator allocates dedicated resources, such as frequency band, to D2D pairs and cellular users separately. This approach eliminates interference between the D2D and cellular links; however, it leads to low spectral efficiency. In underlay D2D communications, the cellular and D2D links use the same spectrum band. One major challenge is how to manage the interference caused by D2D links to cellular transmission and vice versa. This interference can be mitigated by introducing spectrum allocation and power control schemes, as developed in this article. Underlay communications imply a hierarchical allocation of the resources: cellular users have higher priority over D2D pairs. In this article, it is assumed that first the cellular users are dynamically allocated, and then a spectrum allocation for a D2D pair is performed.

D2D IN 3GPP LTE STANDARD

Since D2D communications will enhance the network in terms of both service delivery capability and efficiency, the Third Generation Partnership Project (3GPP) started to study D2D in 2010. Proximity Services (ProSe) are considered by the 3GPP with the goal to define D2D communications within LTE networks. The first study item was finished in early 2013 (Release 12) with the introduction of preliminary functionalities for D2D communications including network assistance for D2D discovery and communication The remaining ProSe features, including direct communication (one-to-one and one-to-many), mobile to network relays, and Evolved Packet Core (EPC) support for wireless local area network (WLAN) direct discovery and communication, were added in stage 2 (Release 14). Further research developments are under study in the context of fifth generation (5G) and beyond 5G (B5G) networks [9].

STUDIED SCENARIO

We assume that the D2D transmission utilizes uplink resources in order to limit interference. Indeed, when using downlink resources, the D2D transmitter may cause high interference to nearby cellular mobiles receiving downlink traffic. On the opposite side, if the D2D transmission utilizes uplink resources, the D2D receivers will experience interference from nearby cellular mobiles transmitting uplink traffic. In that case, the interference generated by the D2D transmitters to the BS can be controlled.

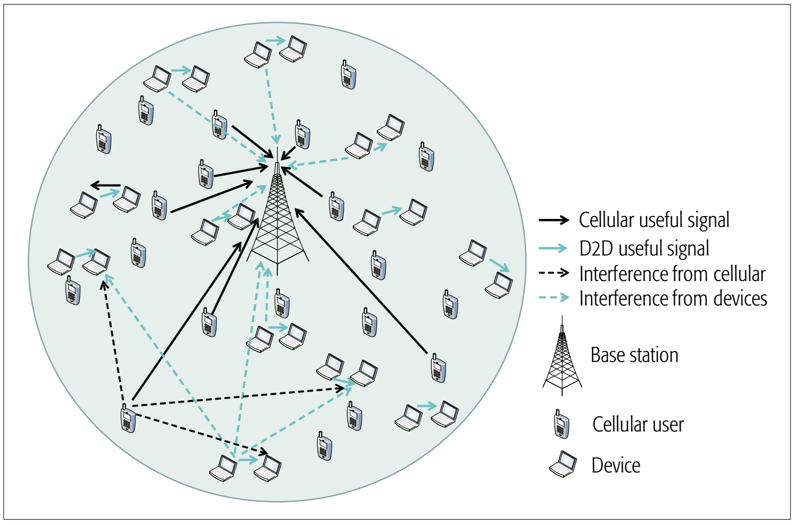

FIGURE 1. Underlaying D2D scenario.

We consider a scenario with K D2D pairs and C cellular users, as represented in Fig. 1. Multi-carrier transmission based on orthogonal frequency-division multiplexing (OFDM) is used. Adjacent subcarriers are grouped to form an RB, and the transmit power per RB as well as the total power per transmitter may be adapted. Frequency reuse is not allowed for cellular users, but several D2D pairs may reuse the same RB. They may also reuse the same RB as cellular users, as long as the interference that they generate at the BS remains under a threshold, which is denoted I_o. Under this constraint, the interference caused by D2D pairs on cellular communications is negligible, and D2D communications are underlaid in cellular communications. We consider both the case of single antenna and $N_r > 1$ antennas at the BS. All cellular users and D2D pairs have only one antenna.

The objective of the dynamic shared spectrum allocation considered in this article is to maximize the weighted sum data rate of the D2D pairs under two constraints: first, all cellular users must achieve signal-to-interference-plus-noise ratio (SINR) constraints per RB; second, the total interference caused by all D2D transmitters at the BS in each RB must be lower than the allowed interference level.

For resource allocation of the cellular users, the RBs are equally shared among the cellular users. and the cellular user that has the highest channel gain is allocated for each RB. After that, the power level of each cellular user is determined to achieve a given SINR by taking into account the maximum transmitted power and the channel gain of the allocated cellular user per RB with open loop power control. When the number of antennas at the BS is higher than one, the channel gain is determined considering the post-coding vector based on maximum ratio combining.

The spectrum sharing of D2D pairs is optimized by finding a set of D2D pairs generating low interference to each other in each RB. This problem is equivalent to a graph coloring problem [10], which can be solved with several levels of complexity, including weighted graphs [5] or using iterative branch-and-bound [6], among other possible techniques.

SPECTRUM ALLOCATION FOR UNDERLAYING D2D WITH A SINGLE ANTENNA

SHARED USE OF THE SPECTRUM THROUGH DISTANCE-BASED FREQUENCY REUSE

D2D pairs may be located anywhere in the cell. D2D pairs that are far enough may reuse the same frequency resources in order to increase the total throughput. It is possible to multiplex several D2D pairs on the same RB, and to multiplex them with a cellular user. In D2D underlay communications, we assume that resources are dynamically allocated to D2D pairs depending on their relative distance or channel gain between each other and their distance or channel gain to the BS. The spectrum sharing of D2D pairs is optimized by finding a set of D2D pairs generating low interference to each other in each RB. This problem is equivalent to a graph coloring problem [10], which can be solved with several levels of complexity, including weighted graphs [5] or using iterative branch-and-bound [6], among other possible techniques.

A low-complexity graph-based RB allocation for D2D pairs can be described as follows. D2D pairs k and l are forbidden to transmit in the same RB if the distance between the D2D transmitter of pair k and the D2D receiver of pair l, or the distance between the D2D transmitter of pair l and the D2D receiver of pair k is lower than a given threshold. The graph is represented by $\mathbf{G} = (\mathbf{V}, \mathbf{E})$, where the vertices $\mathbf{V}$ are all K D2D pairs, and the edges $\mathbf{E}$ are binary variables such that $E_{k,l} = 1$ if D2D pairs k and l are forbidden to transmit in the same RB, and it is equal to 0 otherwise. The first step of the algorithm consists of building the graph. Then several graph coloring techniques may be used to assign the vertices to colors so that if $E_{k,l} = 1$, vertices k and l are in different colors. Finally, the D2D pairs that belong to the same color are distant enough and can be multiplexed on the same RB. On the contrary, the D2D pairs in different colors must be allocated to orthogonal RBs.

We propose another solution that does not use graph coloring and is based not only on distance, but also on channel gains. It consists of determining the maximum number of multiplexed D2D pairs that can jointly achieve a high SINR. The SINR per RB n is defined as a function of the transmit power of all active devices among the K D2D pairs. The constraint that all active devices should achieve SINR higher than a given threshold, noted γ_{th}, is written as a set of K equations depending on the channel gains. The problem can be expressed in matrix notation as

$$(\mathbf{I}_K - \Phi)\,\mathbf{p} = \nu \qquad (1)$$

where $\mathbf{p}$ is the transmit power vector of all devices in RB n and $\mathbf{I}_K$ is the identity matrix of size K. Φ is a matrix containing the ratio of interfering D2D channel gains to direct D2D channel gains multiplied by the target SINR of each user, denoted as γ_k, corresponding to line k. Finally, ν is a vector that contains the product of the target SINR with the interference coming from the active cellular user in RB n plus the thermal noise per RB, and divided by the direct channel gain of D2D pair k. The target SINR is set to either $\gamma_k = \gamma_{\text{th}}$ if D2D pair k is active in the RB or $\gamma_k = 0$ if D2D pair k is inactive. A feasible positive power allocation exists if and only if the spectral radius of matrix Φ, denoted $\rho(\Phi)$, is strictly less than 1. Consequently, the proposed RB allocation algorithm consists of determining the largest subset of D2D pairs with $\gamma_k = \gamma_{\text{th}}$ such that the spectral radius of matrix Φ is lower than 1. However, computing the spectral radius for any subset of pairs is too complex, and it is preferable to use an upper bound on $\rho(\Phi)$. The spectral radius is upper bounded by any norm of matrix Φ. The infinity norm has the main advantage of leading to a distributed criterion, as was used in another context in [11]. Thanks to the infinity norm, we obtain the following algorithm: If a D2D pair k is such that the sum of all interfering channels at receiver k divided by the direct channel gain of D2D pair k is strictly less than the inverse of the target SINR, then transmitter k is active in RB N. Otherwise, D2D pair k is not allocated in this RB. This heuristic approach provides a feasible subset that is sub-optimal, but it still achieves good performance compared to graph-based allocations, as shown later by simulation results. Moreover, this heuristic approach has the same complexity as graph-based allocation.

SHARED USE OF THE SPECTRUM THROUGH POWER CONTROL

Spectrum sharing between devices is quite effective with the different techniques based on distances. However, these techniques do not take into account the fact that D2D communications should be underlaid in cellular communications. The interference received at the BS in each RB n is the sum of the interference generated by all the D2D pairs that are multiplexed in RB n. Consequently, in order to fulfill the BS interference constraint, some of the D2D pairs multiplexed in RB n must decrease their transmit power. This may particularly have an influence on the transmit power of devices that are close to the BS, since they generate more interference at the BS than the devices that are at the cell edge.

Power control can be used not only to fulfill the BS interference constraint, but also to mitigate the remaining interference among the D2D pairs that are allocated in the same RB. This may be extremely useful if the RB allocation has not been efficient, for instance, if the algorithms detailed in the previous section have not been used. However, even if they are used, power control can help achieve some specific resource allocation goals that can be mathematically expressed as optimization problems. For instance, a possible optimization objective may be written to maximize the weighted sum rate among all D2D pairs, taking into account all RBs; other possibilities are given to minimize the transmit power subject to a target data rate, or to maximize the energy efficiency. In [12], a power control algorithm was proposed to maximize the weighted sum rate of D2D pairs while fulfilling the interference constraint at the BS. This algorithm can be implemented in a distributed way, which is particularly interesting for dynamic allocation to rapidly react to the variations of the channels. One drawback of this algorithm can be that it requires all active D2D pairs to have high SINR. Consequently, an efficient RB allocation step similar to the ones previously presented should be used beforehand.

Therefore, the high SINR assumption holds, and the power control utility function is simplified to $U(p_{n,k}) = \alpha_k \log(\text{SINR}_{n,k})$ for each user k active in RB n where α_k is the weight of user k. Then the weighted sum rate, which is expressed by summing of the data rate of all D2D pairs based on their allocated RBs, is maximized under the constraints of the maximum transmit power per D2D pair and the maximum allowed interference per RB at the BS, I_0.

Nevertheless, power control may substantially decrease the transmit power of the D2D pairs that are close to the BS and lead to low data rates. In single-input single-output (SISO) transmission, the only means for these D2D pairs to reach very high data rates would be to transmit in RBs that are not currently occupied by cellular users, and where the BS interference constraint does not hold. But this may only happen if the number of cellular users is low or their data traffic is limited. In order to overcome this limitation, multiple antennas can be used at the BS in single-input multiple-output (SIMO) transmissions. Then the interference generated by the D2D transmitters close to the BS may be low thanks to spatial semi-orthogonality. The flow chart of the proposed spectrum sharing for SISO D2D communications is given in Fig. 2 with the blocks in darker green. The same flow chart is also used for the proposed spectrum sharing in SIMO D2D communications by adding the block in light green. This solution is explained in detail in the next section.

SPECTRUM ALLOCATION FOR UNDERLAYING D2D WITH MULTIPLE ANTENNAS

When multiple antennas are available at the BS, under the same target SINR, the transmitted powers of cellular users are decreased because of antenna gain at the BS. Consequently, the interference generated by cellular users to D2D receivers is also reduced. Since the interference caused by D2D transmitters at the BS is very critical for the cellular links, the D2D pairs that are near the BS have less chance to be allocated than D2D pairs far from the BS. In order to overcome this major problem, we can allow link establishment for D2D pairs close to the BS by taking into account the directivity properties of the multiple antennas at the BS. To do so, we propose to allow spectrum sharing through spatial orthogonality.

The proposed spectrum sharing algorithm for SIMO D2D communications is performing resource allocation for cell-center D2D pairs based on semi-orthogonality criterion and cell-edge D2D pairs based on multiplexing and then applying power allocation for all D2D pairs.

First, we separate all D2D pairs into two sets depending on their location in the cell. Let R be the cell radius and R_D a given distance to distinguish cell-edge and cell-center regions by $0 \leq R_D \leq R$. Then $\mathcal{S}_C$ is a cell-center D2D set that includes the D2D pairs in the area of $(0,1 - R_D)$, and $\mathcal{S}_E$ is the cell-edge D2D set that includes the D2D pairs in the area of (R_D, R).

Then, for each RB, one cell-center D2D pair that is semi-orthogonal to the previously allocated cellular user is selected. The semi-orthogonal-based spectrum sharing leads to selecting the cell-center D2D pair that causes the lowest interference at the BS [13]. Therefore, the channel between the D2D transmitter and the BS becomes as orthogonal as possible to the uplink channel of the allocated cellular user.

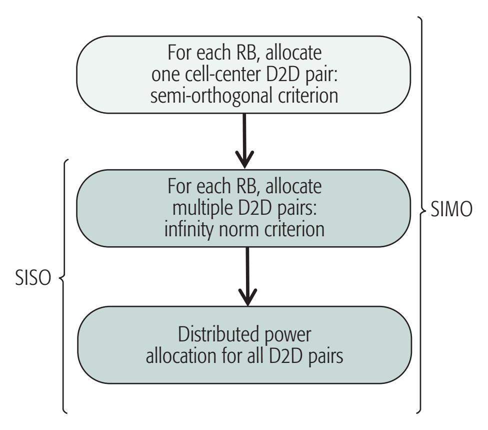

FIGURE 2. Flowchart of the proposed spectrum sharing for SISO/SIMO underlaying D2D.

In order to construct a feasible set of cell-center D2D pairs for spectrum sharing between cellular users and D2D pairs, we hold the following constraints for each RB:

- This set must contain only one cell-center D2D pair that is semi-orthogonal to the initially allocated cellular user as explained above.
- This set must not contain any other cell-center D2D pairs because the cumulative effect of interference at the BS is more severe than the interference caused by cell-edge D2D pairs.

As explained in the shared use of the spectrum through distance-based frequency reuse, we determine the largest set of cell-edge D2D pairs that can be multiplexed on the same RB without violating the infinity norm criterion by taking into account already chosen cell-center D2D pairs. Then the distributed power allocation algorithm for D2D pairs is performed as explained in the shared use of the spectrum through power control.

PERFORMANCE EVALUATION

In this section, we illustrate simulation results for different shared use of the spectrum for underlaying D2D communication in cellular networks. The simulation parameters are given in Table 1. All D2D pairs have the same weight, $1/K$. The target SINR at each RB for the cellular users and D2D pairs is chosen as 20 dB and 10 dB, respectively.

The simulation results for SISO D2D communications are illustrated in Fig. 3. The proposed SISO algorithm is compared to a frequency-division multiple access (FDMA) algorithm, where each RB is allocated to one D2D pair, and all D2D pairs obtain the same number of RBs with a random selection. There is no power control among D2D pairs, but the interference constraint at the BS is verified. The second algorithm uses graph-coloring (GBA) to allocate RBs and then uses the proposed power control algorithm. The average data rate with the proposed SISO algorithm is 42 to 84 percent higher than with GBA and 337 to 748 percent higher than with FDMA. In Fig. 4, the average data rate is increased between 7 and 12 percent by the proposed

The proposed spectrum sharing algorithm for SIMO D2D communications is performing resource allocation for cell-center D2D pairs based on semi-orthogonality criterion and cell-edge D2D pairs based on multiplexing and then applying power allocation for all D2D pairs.

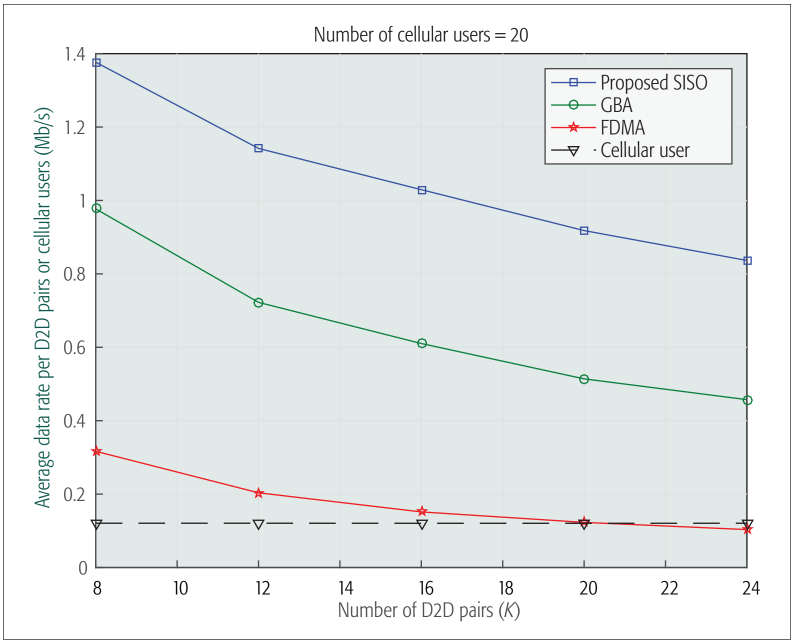

FIGURE 3. Average data rate per D2D pair or cellular user, SISO case.

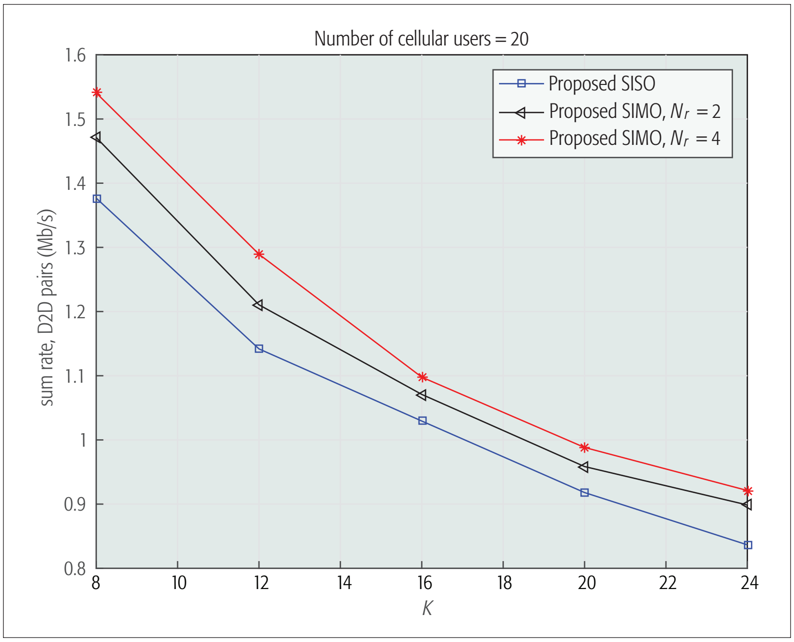

FIGURE 4. Average data rate per D2D pair, SIMO case.

Cell radius	500 m
Maximum distance for D2D pairs	50 m
Maximum distance for GBA	125 m
Maximum transmit power	21 dBm
Noise power spectral density	–174 dBm/Hz
Bandwidth	5 MHz
Fast Fourier Transform size	512
Number of RB	25
Number of cellular users	20
Number of D2D pairs	8 to 24
Path loss model to BS	$L_{dB} = 128.1 + 37.6 \log_{10}(d(km))$
Path loss model to devices	$L_{dB} = 140 + 36.8 \log_{10}(d(km))$
Shadowing at BS	$\sigma = 9$ dB
Shadowing at devices	$\sigma_d = 4$ dB
Multi-path fading for devices	Indoor channel-B model
Multi-path fading for cellular	Pedestrian-B model
Interference level at BS, I_0	Equal to the noise per RB

TABLE 1. Simulation parameters.

SIMO algorithm compared to the proposed SISO algorithm depending on the number of antennas at the BS and the number of D2D pairs in the cell coverage. Besides, thanks to the spectrum sharing with the proposed SIMO D2D algorithm, which gives an opportunity to the cell-center D2D pairs to obtain RBs under the semi-orthogonality criterion, the percentage of the D2D pairs that cannot establish a communication link is significantly reduced, as shown in Fig. 5.

CONCLUSION AND OPEN ISSUES

In this article, we have discussed the research aspects on dynamic shared spectrum allocation for D2D communications underlaying cellular networks. Topics addressed include spectrum sharing through distance-based frequency reuse, power control, and semi-orthogonality in the multi-antennas case for interference management. Performance evaluation for different shared spectrum allocation algorithms have been provided to illustrate the average data rate of D2D pairs and cellular users. There are several open issues for D2D communications in 5G and B5G networks. Enabling D2D communications over millimeter-wave (mmWave) communication is a promising technology to provide very high data rates. Since mmWave communication has a high propagation loss and operates through directional antennas, it causes relatively low multi-user interference. However, the interference management between D2D pairs and an mmWave BS through efficient spectrum sharing strategies is one of the future directions because of densely deployed mmWave BSs in 5G networks. Enabling D2D communications in massive multiple-input multiple-output (MIMO) in which a BS has a large antenna array can almost mitigate interference between D2D pairs and the BS. However, the multiuser transmission in massive MIMO may increase the interference between cellular users to D2D pairs, especially under imperfect channel state information at the receivers that perform interference cancellation. Future work may carry out spectrum sharing algorithms between D2D pairs and cellular users by taking into account imperfect channel conditions.

REFERENCES

[1] P. Mach, Z. Becvar, and T. Vanek, "In-band Device-to-Device Communication in OFDMA Cellular Networks: A Survey and Challenges," *IEEE Commun. Surveys & Tutorials*, vol. 17, no. 4, Oct. 2015, pp. 1885–1922.

[2] C. H. Hu *et al.*, "Resource Sharing Optimization for Device-to-Device Communication Underlaying Cellular Networks," *IEEE Trans. Wireless Commun.*, vol. 10, no. 8, Aug. 2011, pp. 2752–63.

[3] M. Hasan and E. Hossain, "Distributed Resource Allocation in D2D-Enabled Multi-Tier Cellular Networks: An Auction Approach," *Proc. IEEE ICC*, London, U.K., May 2015.

[4] R. Wang *et al.*, "QoS-Aware Channel Assignment for Weighted Sum-Rate Maximization in D2D Communications," *Proc. IEEE GLOBECOM*, San Diego, CA, Dec. 2015.

[5] R. Zhang *et al.*, "Interference Graph-Based Resource Allocation (InGRA) for D2D Communications Underlaying Cellular Networks," *IEEE Trans. Vehic. Tech.*, vol. 64, no. 8, Aug. 2015, pp. 3844–50.

[6] T. D. Hoang, L. B. Le, T. Le-Ngoc, "Resource Allocation for D2D Communication Underlaid Cellular Networks Using Graph-based Approach," *IEEE Trans. Wireless Commun.*, vol. 15, no. 10, Oct. 2016, pp. 7099–7113.

[7] T. D. Hoang, L. B. Le, and T. Le-Ngoc, "Power Allocation for D2D Communications under Proportional Fairness," *Proc. IEEE GLOBECOM*, Dec. 2014, Austin, TX.

[8] S. Mumtaz and J. Rodriguez, *Smart Device to Smart Device Communication*, Springer-Engineering Series Book, 2014.

[9] G. Fodor *et al.*, "An Overview of Device-to-Device Communications Technology Components in METIS," *IEEE Access*, vol. 4, June 2016, pp. 3288–99.

[10] X. Cai, J. Zheng, and Y. Zhang, "A Graph-Coloring Based Resource Allocation Algorithm for D2D Communication in Cellular Networks," *Proc. IEEE ICC*, London, U.K., May 2015.

[11] M. Pischella and J.-C. Belfiore, "Distributed Resource Allocation for Rate-Constrained Users in Multi-Cell OFDMA Networks," *IEEE Commun. Letters*, vol. 12, no. 4, Apr. 2008, pp. 250–52.

[12] M. Pischella, R. Zakaria, and D. Le Ruyet, "Resource Block Level Power Allocation in Asynchronous Multi-Carrier D2D Communications," *IEEE Commun. Letters*, vol. 21, no. 4, Apr. 2017, pp. 813–16.

[13] B. Özbek and D. Le Ruyet, *Feedback Strategies for Wireless Communication Systems*, Springer-Engineering Series Book, 2014.

BIOGRAPHIES

BERNA ÖZBEK (bernaozbek@iyte.edu.tr) has held an assistant professor position in the Electrical and Electronics Engineering Department of Izmir Institute of Technology, Turkey, since 2006. She graduated from the Electrical and Electronics Department of Dokuz Eylul University, Turkey, in 1994, and completed her M.Sc. and Ph.D. studies in 1999 and 2004, respectively. Afterwards, she worked as a postdoctoral researcher at Conservatoire National des Arts et Metiers (CNAM), Paris, France, in 2005. In 2010, she was awarded a Marie Curie Intra-European (EIF) Fellowship by the European Commission for two years at CNAM. She has managed one international and four national projects and served as a consultant for three Eureka-Celtic projects. Under her supervision, 11 Master's theses and two doctoral dissertations have been completed. She is an author of more than 70 peer-reviewed papers, one book, one book chapter, and two patents. Her research interests are interference management and limited feedback strategies in multi-user, multi-antenna, and multicarrier systems in device-to-device and heterogeneous wireless communications.

MYLENE PISCHELLA (mylene.pischella@cnam.fr) has been an associate professor in telecommunications at CNAM since 2010. She received a Master's degree in engineering in 2002 and a Ph.D. in communications and electronics in 2009, both from TELECOM ParisTech. From 2002 to 2009, she was a research engineer at Orange Labs, where she specialized in the optimization of cellular networks and contributed to several European collaborative projects. In 2009–2010, she was an assistant professor at ISEP, Paris, France. She is an author of more than 60 peer-reviewed papers, three books, one book chapter, and seven patents. Her research interests are resource allocation in wireless networks, including heterogeneous networks, device-to-device communications, multi-carrrier modulation, and cognitive, cooperative, and relaying networks.

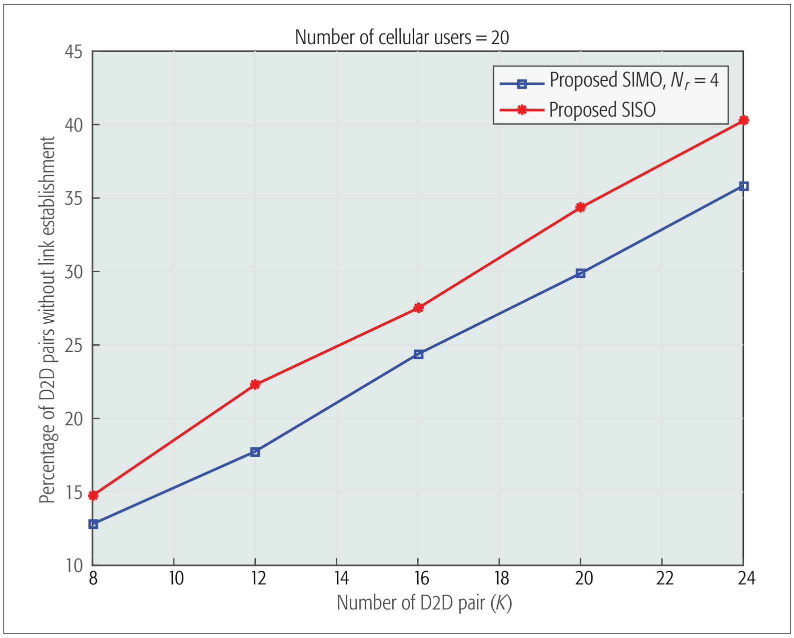

FIGURE 5. The percentage of D2D pairs without establishing a communication link.

DIDIER LE RUYET (didier.le_ruyet@cnam.fr) received his Engineering degree and Ph.D. from CNAM in 1994 and 2001, respectively. In 2009, he received the "Habilitation a diriger des recherches" from Paris XIII University. From 1988 to 1996 he was a senior member of technical staff at SAGEM Defence and Telecommunication, France. He joined CNAM in 1996 and has been a full professor in the CEDRIC research laboratory since 2010. He has published more than 150 papers in refereed journals and conference proceedings and nine books/book chapters in the area of communication. He has been involved in many national and European projects dealing with multicarrier transmission techniques and multi-antenna transmission. He has served as Technical Program Committee member for major IEEE conferences. His main research interests lie in the areas of digital communications and signal processing including channel coding, detection and estimation algorithms, filter-bank-based multi-carrier communication, and multi-antenna transmission.