Cognitive Spectrum Access in Device-to-Device (D2D)-Enabled Cellular Networks

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***Abstract*—Cognitive spectrum access (CSA) in in-band D2D-enabled cellular networks is a potential feature that can promote efficient resource utilization and interference management among co-existing cellular and D2D users. In this article, we first outline the challenges in resource allocation posed by the coexistence of cellular and D2D users. Next, we provide a qualitative overview of the existing resource allocation and interference management policies for in-band D2D-enabled cellular networks. We then demonstrate how cognition along with limited information exchange between D2D users and the core network can be used to mitigate interference and enhance spectral efficiency of both cellular and D2D users. In particular, we propose a CSA scheme that exploits channel sensing and interference-aware decision making at the D2D terminals. This CSA scheme at the D2D terminals is complemented by a D2D-aware channel access method at the cellular BSs. The performance gains of the proposed CSA scheme are characterized in terms of channel access probability for a typical D2D transmitter and spectral efficiencies for both cellular and D2D transmissions. Finally, potential research issues that require further investigation are highlighted.**

***Index Terms*—D2D communication, cognitive cellular networks, resource allocation, spectrum access probability, spectral efficiency.**

I. Introduction

Device-to-device (D2D) communication enables nearby wireless devices to exploit their proximity and communicate directly with each other bypassing their corresponding cellular base stations (BSs) [1], [2]. By enabling single-hop communication instead of dual-hop uplink (UL) and downlink (DL) communication, D2D communication improves the radio resource utilization at the BSs and enhances the latency, spectral efficiency, and power consumption of D2D transmitters (TXs). Also, it offloads traffic from the cellular BSs and thus reduces congestion on radio resources used by the cellular user equipments (CUEs). Potential commercial applications of D2D communication include localized social networking and data transfer, home automation, and commerce and advertising. Public safety is another application where a local connectivity can be ensured in the absence of BSs or hazards at BSs.

Since D2D transmissions typically occur in proximity, the D2D terminals are expected to discover their peers (or communicating partners), select spectrum, schedule transmissions, and perform power control while avoiding interference from/to cellular transmissions in a smart manner. For instance, a D2D user can perform licensed spectrum sensing (similar to a cognitive radio) to detect the idleness of a given channel. Moreover, the D2D user can sense the surrounding environment to obtain required channel state information (CSI), interference, mobility, and other information related to nearby wireless devices. Exploiting cognition in D2D communication thus empowers the D2D users to make autonomous decisions and adjust their transmit power, operating frequency, and spectrum access policy opportunistically. Consequently, cognitive spectrum access (CSA) in D2D networks paves the way to develop distributed resource management solutions with reduced signaling overhead and complexity [3].

While cognition at D2D terminals can effectively reduce the control signaling overheads, it may not be efficient in terms of overall performance. To overcome this, limited exchange of control information from cellular BSs seems inevitable for a successful integration of D2D communication in the emerging cellular standards. In general, the D2D sessions can be managed either centrally by the BSs (referred to as network-controlled D2D) or distributively by the D2D pairs themselves. Further, distributed solutions can be implemented either with no information exchange (referred to as D2D-unaware networks) or with limited information exchange from BSs (referred to as D2D-aware networks) [4].

This article first overviews the different scenarios of D2D communication in cellular networks from an implementation perspective. Then the challenges related to resource allocation and interference management in D2D-enabled cellular networks are discussed followed by a qualitative overview of the existing centralized and distributed resource allocation approaches. A CSA scheme is then proposed to demonstrate the impact of cognition and prioritized spectrum access in D2D-enabled cellular networks. The performance gains of CSA scheme are then analyzed quantitatively. Finally, several potential directions for future research are outlined.

II. D2D-Enabled LTE/LTE-A Networks

The Third Generation Partnership Project (3GPP) targets D2D communication in Long-Term Evolution (LTE) Release 12 to provide new commercial or public safety proximity services (ProSe) [5]. In general, D2D communications can be enabled in a cellular network in three possible ways, i.e., *D2D-unaware* transmissions, *D2D-aware* transmissions, and *network-controlled D2D* transmissions.

In *D2D-unaware* transmissions, the D2D users can exchange control and data packets between each other with no intervention from the eNB (i.e., BS). The eNB does not have any supervision over the radio resources used by the D2D pairs (e.g., power control and spectrum allocation) as shown in Fig. 1(a). To be specific, coordination between D2D and cellular transmissions is not possible in this scenario. Note that the D2D users can use the PC5 interface which is defined by the

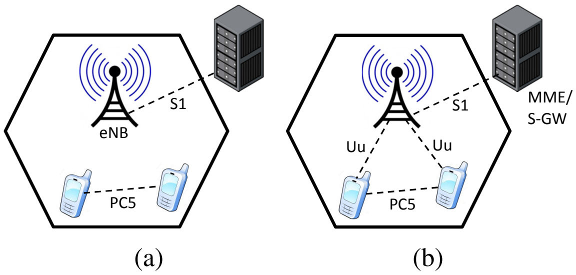

Fig. 1. Architecture of D2D-unaware and D2D-aware LTE cellular networks.

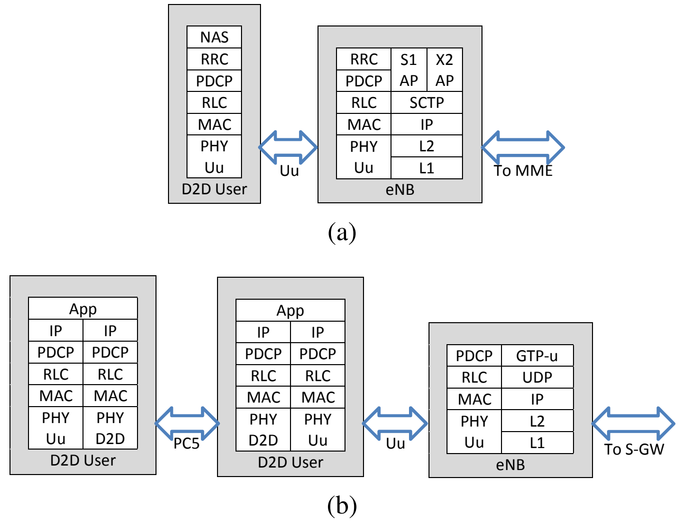

Fig. 2. Protocol stacks for D2D-enabled LTE networks: (a) control plane (b) user plane.

LTE standard for discovery and direct communication between D2D users. On the other hand, in *D2D-aware* transmissions, a D2D pair can perform limited information exchange with the core network through the eNB using the LTE-Uu (i.e., cellular link) interface. In this case, the core network can perform limited supervision of D2D transmissions for better coordination with the concurrent cellular transmissions. Nonetheless, this supervision should be limited in terms of information exchange and signaling overheads. The D2D users can possibly decide their mode of operation (i.e., D2D or cellular mode) and the radio resources for data transmission using the PC5 interface (as shown in Fig. 1(b)).

In *network-controlled D2D* transmissions, an eNB fully controls the radio resources management of all cellular and D2D users in a cell. The network architecture in this case is similar to the one shown in Fig. 1(b) but with full control exercised by the eNB. This scenario enables the network to make perfect coordination between cellular and D2D users which may require large amount of information exchange and signaling overheads. Moreover, a D2D pair cannot establish a communication link without initiating a request and the approval of request from eNB.

The aforementioned scenarios offer trade-offs in terms of performance and complexity of implementation. The D2D-aware transmissions can however provide more flexibility in terms of signaling overheads and performance by allowing the BSs to have minimal control of D2D sessions, i.e., through limited information exchange. These scenarios also differ in the control and data protocol stacks. Fig. 2 shows the control and data protocol stacks for the network-controlled D2D-enabled LTE/LTE-A cellular networks. It can be seen in Fig. 2(a) that the LTE control plane is reused for the D2D control plane over the LTE-Uu interface where there is no control signaling between D2D users. On the other hand, the D2D user plane in Fig. 2(b) reuses the LTE data protocol stack with the introduction of the PC5 interface. The same protocol stacks in Fig. 2 can be used for D2D-aware deployment with minimal use of LTE-Uu interface. Finally, for the D2D-unaware cellular networks, the D2D users do not interact with the radio access network; hence, data and control signaling are performed over the PC5 interface between each D2D pair.

III. Fundamental Challenges of Resource Allocation in D2D-Enabled Cellular Networks

For in-band D2D communication (i.e., where the same radio resources are used for both cellular and D2D communication), the primary resource allocation challenges include interference management among co-existing CUEs and D2D users, development of low-complexity centralized or semi-distributed spectrum access and interference mitigation techniques with minimal signaling overheads, and the notion of priority for the resource management of D2D and CUEs. These challenges are elaborated below.

A. Resource Allocation

Network-controlled D2D architecture (as illustrated in Section II) considers centralized resource allocation where the BS in a cell allocates resources to both CUEs and D2D users to improve its own utility. However, the centralized approaches may incur high computational and signaling complexities. For instance, the BS may need to be totally aware of the interference status at various D2D pairs or the channel information between a D2D pair for efficient spectrum allocation. In contrast, distributed resource allocation methods could be simpler. For example, local sensing can be used at the D2D terminals to sense the network environment and adaptively utilize the radio resources. The local sensing will enable the D2D terminals to measure the harmful interference (e.g., from CUEs and BSs, respectively, when uplink and downlink resources are used) and utilize this information to improve the spectral efficiency of D2D transmission. Another approach could be to exploit message passing [6]. This message passing approach requires exchange of local information among neighbors. However, in a densely deployed multi-tier network, the signaling overhead can become very high. As such, exploiting cognition at D2D terminals with limited information exchange with the BSs can be useful in such scenarios.

B. Prioritization of Cellular and D2D Users

In D2D-enabled cellular networks, typically, CUEs are offered a higher priority compared to D2D users. For example, a typical assumption in most of the existing literature is that

D2D users can communicate only if they do not cause excessive interference to the CUEs. Since D2D communication aims at offloading traffic from cellular BSs in a distributed manner, it is crucial to add some notion of priority for D2D users in such a way that the performance of CUEs is not affected. For instance, to facilitate D2D communication, a few channels may not be assigned to the CUEs (i.e., allocated for D2D communication only) until the traffic load of CUEs becomes high enough to require those channels. This information can be transmitted by the BSs to the D2D pairs. The need of semi-distributed solutions (or D2D-aware networking) is thus evident.

C. Cognitive Spectrum Access

Spectrum sharing between CUEs and D2D pairs allows higher spectrum reuse. However, it may lead to severe cross-tier interference at D2D links when they coexist with CUEs and other tiers such as the small cell tier in a multi-tier cellular network. On the other hand, static spectrum splitting among different tiers eliminates cross-tier interference but still could significantly degrade spectral efficiency depending on the number of D2D terminals and the proportion of available spectrum for them. For this reason, cognitive spectrum access methods with limited control of BSs are crucial that can potentially adapt to the traffic load intensities of CUEs and D2D pairs.

D. D2D-Aware Scheduling in High Traffic Load

For high intensity of CUEs, prioritizing spectrum for D2D transmissions will not work. As such, simple D2D-aware scheduling techniques need be developed that allocates resources to D2D users in an opportunistic manner while providing fairness among CUEs and D2Ds. In this regard, D2D terminals can exploit cognition to sense user activity in a set of channels and then inform the BS about their most favorable channel. The BS then allocates the channels considering the overall intensity of D2D pairs and CUEs, and informs the D2D users about the spectrum allocation.

E. Management of Cross-tier and Inter-D2D Interferences

The introduction of D2D communication in cellular networks is challenging for both D2D and CUEs due to the cross-tier interference resulting from the concurrent cellular and D2D transmissions. This issue is more challenging in multi-tier networks in which low power small cells are densely deployed over existing single-tier networks (as will be in the emerging 5G cellular wireless networks) [7]. These small cells result in additional cross-tier interference on top of that from the CUEs. Efficient interference management techniques (e.g., power control, spectrum allocation, multiple antenna beamforming, etc.) will be therefore essential. Furthermore, the interference incurred at a D2D receiver from neighboring D2D transmitters (referred to as *inter-D2D interference*) also needs to be mitigated through proper user pairing and frequency assignment techniques.

IV. The State-of-the-Art Resource Allocation Methods for In-Band D2D-Enabled Cellular Networks

This section overviews the existing research studies that deal with centralized and distributed resource allocation of D2D-enabled cellular networks. A qualitative summary of the state-of-the-art approaches is provided in Table I. In particular, Table I summarizes the relevant research studies on resource alloction (RA) in D2D-enabled cellular networks where all D2D pairs and CUEs share the same radio spectrum. For each article, the main objective and the considered assumptions are highlighted. Also, a comparative analysis is performed in terms of signaling overhead, UL and DL applicability, and priority settings of CUEs and D2D pairs.

A. Centralized Approaches

In [8], a near-optimal greedy resource allocation scheme is proposed for a single-cell scenario with multiple underlaying D2D pairs. The duration of simultaneous D2D transmissions is minimized while meeting cross-tier interference thresholds, signal-to-interference-plus-noise ratio (SINR) for D2D links, and maximum power constraints. The problem is formulated as a mixed integer programming (MIP) and a column generation-based method is proposed to obtain a low-complexity centralized solution where cellular links are given higher priority.

In [9], the authors consider a single-cell uplink network where multiple CUEs and one D2D pair can share the same radio spectrum. In this paper, the cross-tier interference caused be cellular transmissions is managed to improve the overall network throughput where the interference from D2D transmissions is ignored assuming that a power control method is in place. The interference management scheme does not allow CUEs to coexist with the D2D pair in the same spectrum resource if the resulting interference-to-signal-ratio (ISR) at the D2D receiver becomes higher than a predefined threshold.

A sum-rate maximization problem is formulated with both D2D and CUEs considering D2D-enabled uplink MIMO cellular networks [10]. Optimal resource allocations are obtained by using a pure random search. Moreover, a non-cooperative resource allocation game for the joint channel allocation, power control, and precoding of the D2D users is formulated. The feasibility and existence of the pure strategy Nash equilibrium are then established by developing a self-optimizing algorithm. Finally, a distributed resource allocation algorithm based on best response dynamic is proposed.

B. Distributed Approaches

In [6], a distributed resource allocation scheme is proposed to maximize network sum-rate while satisfying the data rate requirements for CUEs and D2D users considering a multi-user and multi-relay network. A message passing technique is used where each user sends and receives information messages to/from the relay node in an iterative manner with the goal of achieving an optimal allocation. The authors in [11] propose a distributed CSA policy in which D2D users can opportunistically share the UL spectrum resources with the

TABLE I
EXISTING LITERATURE ON IN-BAND D2D-ENABLED CELLULAR NETWORKS

Approach	Article	Objective and assumptions	Overhead	Spectrum	User priority
Centralized	[8]	- RA for spectrum utilization maximization - Single cell and multiple D2D pairs - MIP solved by a column generation-based method	Medium	DL/UL	Cellular
	[9]	- Interference management to enhance overall data rate - Single cell and one D2D pair, multiple CUEs - Scheme to control interference limited area is proposed	Low	UL	D2D
	[10]	- Network rate maximization with target rate constraints for both D2D and CUEs - Single cell with multiple CUEs and D2D pairs - Non-cooperative RA game is solved by self-optimization algorithm	High	UL	Both
Distributed	[6]	- Subcarrier and power allocation for two-hop rate maximization - Relay-assisted cellular network - Signaling overhead due to messages between relay and CUEs. - Message passing approach	Low	UL	Both
	[11]	- Opportunistic spectrum access protocol with minimal SINR degradation of CUEs - Statistical estimates of the channel gains - Network information in the discovery packet	Medium	UL	Cellular
	[12]	- RA for D2D mode selection optimization and utility maximization - Utility of secondary users in D2D mode and total secondary users - Evolutionary game model	Medium	DL/UL	Cellular
	[14]	- Maximize D2D rate under CUEs' interference constraints - Overhead due to price broadcast at each channel - BS requires CSI of cellular links - D2D TX requires CSI of the D2D link and its link to the BS. - Stackelberg game	Low	UL	Cellular
	[15]	- Network utility maximization with pricing - Near optimal solution - CSI of both D2D and CUEs required at BS - Reverse iterative combinatorial auction method	Medium	DL	N/A

CUEs. In order to limit the degradation of SINR of cellular links, each D2D user is assumed to perform power control to limit the level of cross-tier interference. Then, the D2D user determines if the link should be established in a single- or multi-hop manner. A random access technique is used to mitigate inter-D2D interference by allowing only one D2D pair to access the spectrum at a time.

In [12], an efficient resource allocation method is proposed for a cognitive cellular network with D2D communication. While a secondary user may operate either in a cellular mode or a D2D mode, the theory of evolutionary game is used to model the behavior of such users. The proposed solution attempts to optimize the mode selection criterion with a set of utilities considering the data rate, transmit power, and cross-tier interference. The application of several game models in the distributed resource allocation of D2D-enabled cellular networks is discussed in [13]. For D2D communication, non-cooperative and auction game models are suggested as the most suitable option to solve the resource allocation problems.

An iterative two-stage pricing-based algorithm is proposed in [14] in which the BSs send a pricing signal depending on the gap between the aggregate interference from D2D links and a predefined interference tolerance level. Next, each D2D link independently maximizes its utility consisting of a reward equal to its expected rate and a penalty proportional to the interference caused by this link to the BS, as measured by the pricing signal. In [15], a reverse iterative combinatorial auction method is used to optimize the system sum utility. A non-monotonic descending price auction algorithm is proposed to maximize the utility function that accounts for the channel gain from D2D and the costs for the system. The scheme is cheat-proof and converges in a finite number of iteration rounds.

While the centralized or near-optimal solutions leverage on significant network information, they are not scalable for dense networks with large number of BSs, CUEs, and D2D users. On the other hand, the distributed solutions mainly require high signaling overheads to allow some coordination between BSs and D2D users. As such, the need of exploiting cognition at D2D terminals for automated channel sensing and decision making is evident.

V. COGNITIVE SPECTRUM ACCESS FOR D2D-AWARE CELLULAR NETWORKS

CSA in D2D-enabled cellular networks can be realized by enabling channel sensing and interference-aware decisions at the D2D terminals distributively. To enhance the performance of CSA, a prioritized channel access policy for D2D transmissions is also used at the BSs which offers limited network control. To evaluate the performance of the proposed solution, we characterize (i) channel access probability (CAP) of a D2D TX and (ii) spectral efficiency for both cellular and D2D transmissions.

A. Cognition at D2D Devices

A cognitive D2D user is capable of sensing the received interference level on a given transmission channel. With this knowledge, a D2D user can make an intelligent decision about utilizing a given channel while avoiding interference from nearby cellular transmissions (in UL or DL). Since RXs are highly vulnerable to nearby interferers, we exploit cognition at the D2D RXs. That is, the D2D TX sends a RTS (ready-to-send) request to its intended receiver over PC5 interface. Then, on a given channel, if the maximum received interference from any neighboring TX is sensed to be lower than a predefined sensing threshold γ, a D2D RX sends a CTS (clear-to-send) signal over the PC5 interface to its corresponding TX to use this specific channel. Otherwise, the D2D TX remains silent.

Cognition at the D2D RXs provides a protection region around each D2D RX in which a D2D communication link cannot be established if there is at least one TX (i.e., CUE in uplink or BS in the downlink) using the same channel inside this region. In general, the protection region around each D2D RX has a random shape due to the randomness in channel conditions and transmit power. As an example, for channel gain h and an interferer at a distance r with transmit power P, the decision is taken by comparing the received interference power Phr^{-4} (assuming that the path-loss exponent for radio propagation is 4) to the sensing threshold γ. If $r > (\frac{Ph}{\gamma})^{\frac{1}{4}}$, this means that the interferer is outside the protection region and the D2D TX can thus transmit; otherwise, the D2D TX remains silent. Note also that, decreasing γ provides more protection to the D2D RXs by decreasing the aggregate interference; however, it reduces the channel access probability for the D2D transmitters. Therefore, γ is an important network design parameter.

Although CSA protects the D2D RXs from excessive cross-tier interference, the inter-D2D interference is still an issue when the D2D TXs in close proximity transmit on the same channel at the same time. Thus, to avoid inter-D2D interference, we assume that, after sensing a free channel, each D2D RX sets a random back-off timer after which the D2D TX can use the channel if the channel is still available. This means that the D2D TX corresponding to the D2D RX with the shortest back-off duration will access the free channel alone, thus avoiding any possible nearby D2D interferer.

B. Spectrum Access Policy Adopted by BSs

In a D2D-enabled cellular network, the spectrum access policy at the cellular BS commonly defines how the BS assigns spectrum to serve both the CUEs for DL and/or UL transmissions. In the sequel, we consider the two following spectrum access techniques: (i) D2D-unaware spectrum access (DUSA); (ii) D2D-aware spectrum access (DASA), as described below. The first policy is the baseline scenario in which BSs assign different frequencies to its users without considering the D2D transmissions. On the other hand, the second policy is a conservative policy in which the BSs avoid causing interference to the D2D transmissions, whenever possible.

- *DUSA policy:* a BS can utilize any channel to serve any CUE based only on its scheduling policy whereas each D2D pair selects a random channel to perform CSA.
- *DASA policy:* a BS firstly assigns one of the channels (say c_d) for D2D transmissions and exchanges the ID of this channel with the D2D users in its coverage area over the LTE-Uu interface. Once the D2D users are informed of the D2D channel, they are responsible for initiating the communication session by exchanging control and data signals over PC5 interface with no further supervision from the BS. This channel is not exclusive for D2D users and can be used for cellular transmissions based on the following policy: the BS schedules CUEs in any of its available channels except c_d as long as the number of CUEs N_u is less than the total number of available channels C. Thus, c_d is guaranteed to be the least congested channel. That is, the D2D transmissions can fully exploit the channel c_d when $N_u < C$. When $N_u \geq C$, a CUE and a D2D user will compete for c_d. In this case, the CUE is granted the channel since it normally has more priority than D2D users. Note that this policy also helps to minimize cross-tier interference on cellular links which use the channels other than channel c_d.

The main difference between DUSA and DASA is that the latter policy exploits the situations, where the cellular network is not heavily loaded, by scheduling the CUEs on channels other than c_d. If the network is overloaded, i.e., $N_u \geq C$, both the schemes will offer similar performance. Hence, they differ in the order in which channels are selected by the BS to schedule its users. Note that the CUEs have more priority than the D2D users in both the schemes. A similar concept can be exploited in the presence of small cells in the network where the small cells follow the same policy to avoid occupying c_d whenever possible.

Using the DASA policy with CSA (referred to as the DASA-CSA policy), the interference at D2D RXs can be further minimized while improving the overall spectral efficiency of D2D transmissions. To compare the performances of DASA and DUSA policies, we calculate the probability for a D2D pair to find a free channel to establish a communication link. The *channel access probability (CAP)* in a given cell is directly related to N_u. Users are uniformly distributed and N_u is modeled by a Poisson random variable with mean $\frac{\sqrt{3}}{2}\mathcal{U}d^2$, where $\mathcal{U}$ is the spatial intensity of CUEs and d is the inter-BS distance. This expression is derived by using the area of the hexagonal cell $A = \frac{\sqrt{3}}{2}d^2$ and the statistical properties of the PPPs. Note that, while the number of channels assigned by a BS depends on N_u within its coverage area, the order in which the channels are used by this BS varies according to the adopted spectrum access policy.

To cope with the dynamics of spectrum access in a D2D-enabled cellular network with the DASA-CSA policy, the D2D user can exchange other information such as the spectrum sensing range (or equivalently, the spectrum sensing threshold) for the cognitive D2D transmitters, with the BS over the PC5 interface. This is in addition to the information about the designated non-exclusive channels for D2D transmissions. These parameters can be estimated based on statistical averaging over the different spatial distributions of D2D users and CUEs.

VI. Performance Evaluation Results

To show the reliability of the proposed schemes, we compare the four possible scenarios, namely, DUSA-only without CSA, DASA-only without CSA, DUSA-CSA, and DASA-CSA, in terms of CAP and spectral efficiency. The results

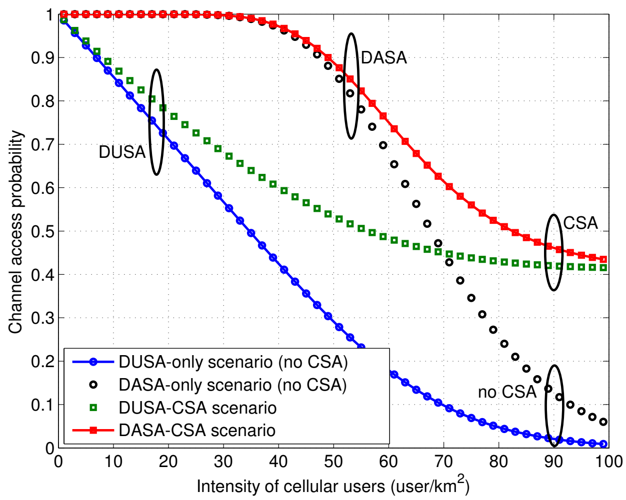

Fig. 3. Channel access probability for a D2D TX vs. spatial intensity of cellular users for DUSA and DASA policies (with and without cognition).

are shown in Fig. 3 which shows the effect of increasing the spatial intensity of CUEs on the CAP for a D2D TX. Note that the CAP for the DASA-CSA scenario is equivalent to the probability that the number of CUEs served by a BS is at most $C-1$, i.e.,

$$\text{CAP of DASA-CSA} = \sum_{n=0}^{C-1} \mathbb{P}\{N_u = n\},$$

where $\mathbb{P}\{N_u = n\}$ is the probability mass function of N_u which is a function of the spatial intensities of BSs and CUEs and the user association policy.

On the other hand, for the DUSA-CSA scenario, the CAP is obtained using the fact that each BS assigns all channels to different users with the same probability, i.e.,

$$\text{CAP of DUSA-CSA} = \sum_{n=0}^{C-1} \left(1 - \frac{n}{C}\right) \mathbb{P}\{N_u = n\}.$$

In this comparison, the network has a total of 15 channels where the inter-site distance is 500 m according to the 3GPP evaluation methodology.

Impact of cognition (CSA vs. no-CSA): It can be seen in Fig. 3 that exploiting cognition in D2D transmissions can highly improve the CAP for a D2D TX for both DUSA and DASA scenarios. Note that, cognition is more advantageous in dense networks due to significant interference. For example, with the DUSA policy, the improvement in CAP due to cognition is only 3% (i.e., from 0.85 to 0.87) when the density of CUEs is 10 CUEs/km^2 compared to 85% (i.e., from 0.29 to 0.53) when the density of CUEs is 50 users/km^2. This result suggests that CSA is not crucial when the number of CUEs is low since not all radio resources are used by the macro-tier and the D2D TXs have a good chance of finding free channels. On the other hand, for dense networks, CSA is crucial to avoid the nearby interferers and increase the efficiency of using the available resources.

Impact of D2D-awareness (DUSA vs. DASA): Fig. 3 also quantifies the performance gain of DASA over the DUSA policy for both scenarios (i.e., with and without CSA). The figure shows that, as the density of CUEs increases, CAP degrades for both DUSA and DASA. For example, increasing the CUEs in the DUSA-only scenario from 10 to 50 users/km^2 degrades CAP by a factor of 3 (i.e., from 0.85 to 0.29). Most importantly, it can be seen that, with and without cognition, the DASA scenario offers better performance for all network parameters when compared to the DUSA scenario. For instance, in the D2D-aware scenario, with a 5 times increase in the intensity of CUEs, the CAP becomes 0.87 compared to only 0.29 in the D2D-unaware scenario. In addition, we can see that the gains of DASA become more evident in dense networks (i.e., the CAP decreases significantly). Note that, this improvement comes at the expense of making other channels more congested for the CUEs. However, in the worst case, when all BSs have more users than the available channels, both the access policies offer similar performance.

Gain of proposed framework (DASA-CSA vs. DUSA-only): It can be seen from Fig. 3 that there is a value for the spatial intensity of CUEs below which the gain of prioritized spectrum access is higher than that of CSA. After this point, using CSA is more beneficial. Therefore, combining both the schemes will offer a better performance for high and low spatial intensities. Fig. 3 shows that the scenario in which both cognition and prioritized techniques are combined (i.e., DASA-CSA) gives a superior performance when compared to the baseline scenario (DUSA-CSA) for all values of $\mathcal{U}$. For instance, in the scenario with 70 CUEs/km^2, DASA-CSA offers a 525% improvement in performance in terms of CAP for D2D TXs.

Furthermore, Fig. 4 illustrates the gain in spectral efficiency (SE) when combing cognition and prioritization in D2D-enabled networks. In this context, the spectral efficiency is defined as number of successfully transmitted bits per unit time per Hz where the data is considered successfully transmitted when the received signal-to-interference-plus-noise ratio (SINR) is higher than a predefined threshold τ. The following remarks can be made.

- The spectral efficiency for both cellular and D2D users degrade with increasing $\mathcal{U}$. This is intuitive due to the increase in both cross-tier and co-tier interference levels.
- The DASA-CSA policy can provide higher data rates for D2D transmissions compared to DUSA-only scenario especially for dense cellular networks. For example, the DUSA-only scenario cannot support an SE of 1 bps/Hz for D2D transmissions when the number of CUEs is higher than 13 users/km^2 while the DASA-CSA scenario provides the same SE with minimal coordination for CUE intensity up to 63 CUEs/km^2.
- The proposed DASA-CSA scheme does not impact the performance of CUEs where the gap between the SE of transmission by cellular users in this scenario and the scenario with no D2D network is negligible.
- While the SE of CUEs is higher than that of the D2D users in DUSA-only scenario due to the cross-tier interference, the opposite happens in the DASA-CSA scenario since the D2D

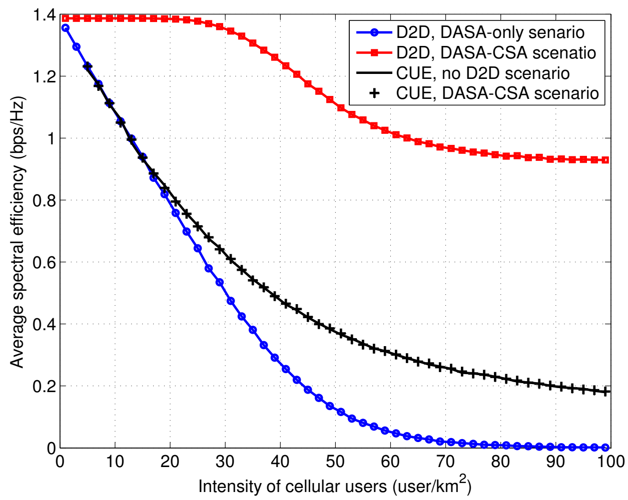

Fig. 4. Spectral efficiency of transmission in D2D links vs. spatial intensity of cellular users for DUSA and DASA policies (with and without cognition).

users almost operate in an interference-free environment using their cognition capabilities.

VII. Open Research Issues

The performance of cognitive spectrum access in D2D-enabled cellular networks can be further improved (e.g., in terms of both spectrum efficiency and energy efficiency) by using more advanced resource allocation methods as well emerging communication techniques such as full-duplexing, and also radio frequency (RF) energy harvesting techniques. In this context, several research directions are outlined below.

1) Traffic load-aware spectrum selection: Due to highly asymmetric UL and DL data traffic in cellular networks, spectrum selection for D2D transmission needs to be adaptive to the traffic load. Traffic load-aware channel selection has a direct impact on the interference, spectral efficiency, as well receiver complexity.

2) Optimal spectrum allocation for prioritized D2D channels: Since the proposed CSA scheme along with BS-awareness of D2D communication allocates part of the spectrum for D2D transmissions, an important question is: how to optimally decide the proportion of prioritized resources for D2D transmissions? Given the intensity of D2D and CUEs, the proportion of prioritized spectrum needs be decided in a dynamic fashion.

3) Admission control to manage inter-D2D interference: The performance gains of D2D transmissions highly depend on the intensity of D2D pairs on a given channel and their distances from each other. Efficient D2D admission control algorithms need to be developed that maximize the overall utility of both the CUEs and the D2D users. For instance, exploiting D2D communications for cell-edge users or deeply faded users may be more beneficial to provide fair network connectivity. Thus, D2D admission control needs to be triggered in an opportunistic manner and the transmission of D2D users can be switched through the BS when communication using the direct D2D links is no longer beneficial.

4) Exploiting full-duplex transmissions: While D2D links are typically exploited for half-duplex data transmissions, they may be used for interference mitigation or channel selection if exploited in full-duplex mode. For instance, a cognitive D2D transmitter when operating in full-duplex mode, can hear interference signals and can provide information about the interference to its intended receiver along with the data packets. In a similar way, a CUE receiving transmission in the DL can also exploit the D2D communication to forward interference knowledge to a nearby cognitive D2D user. This knowledge can help the D2D user in either interference cancellation or channel selection.

5) Cognitive spectrum access in presence of RF energy harvesting: Energy efficiency of D2D-enabled cellular networks can be highly improved using energy harvesting especially because direct D2D transmissions are for short distances. With cognitive spectrum access, a D2D user can harvest energy while performing spectrum sensing or waiting for a free channel. Then, the stored energy can be used later for data transmissions. Thus, resource allocation schemes need to be aware of the amount of energy available at the transmitter. Also, the durations of data transmission and energy harvesting will need to be optimized to maximize the system performance and reliability.

6) Combination of full-duplexing and energy harvesting: If a D2D transmitter is equipped with dual antennas, one for transmission and the other for reception, then the hybrid mode of information transmission and energy harvesting can be implemented using one antenna for each purpose. Unlike the information reception in traditional full-duplex mode, the self-interference from the transmission in full-duplex mode can be utilized for energy harvesting since decoding of the self-interference would not be required in this case. Therefore, adaptive (or cognitive) D2D can be used for this hybrid mode to further enhance the spectrum efficiency and the energy efficiency through energy harvesting in full-duplex mode, instead of the costly self-interference cancellation for information reception.

VIII. Conclusion

This article has focused on highlighting the key challenges in the resource allocation of in-band D2D enabled cellular networks. A qualitative overview of the existing research advancements related to centralized and distributed resource allocation techniques has been provided. Since centralized solutions generally incur high computation and signaling overheads, distributed or semi-distributed solutions which exploit cognition at the D2D terminals are promising. We have proposed a semi-distributed CSA solution in which cognition at the D2D terminals allows interference-aware decision making and limited control at the BSs helps the D2D users in selecting the spectrum band with the least interference. The performance of CSA scheme has been analyzed quantitatively in terms of channel access probability and spectral efficiency of transmission in cellular and D2D links. The performance of CSA in a D2D-enabled cellular network can be optimized through a proper choice of network design parameters such as the spatial intensity of BSs, the mode selection criteria, and the spectrum sensing threshold.

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