Adaptive Resource Allocation for Device-to-Device Aided Cellular Systems

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Abstract. Resource allocation in device-to-device (D2D) aided cellular systems, in which the proximity users are allowed to communicate directly with each other without relying on the intervention of base stations (BSs), is investigated. A new uplink resource allocation policy is proposed for enabling the D2D user equipments (DUEs) to reuse the licensed spectrum, provided that the minimum signal-to-interference (SIR) requirement of conventional cellular user equipments (CUEs) is satisfied. Furthermore, the proposed resource-allocation problem can be formulated as "maximizing the number of simultaneously activated D2D pairs subject to the SIR constraints at both CUEs and DUEs". Numerical results relying on system-level simulation show that the proposed scheme is capable of substantially improving both the D2D-access probability and the network throughput without sacrificing the performance of conventional CUEs.

Keywords: Device-to-device · D2D-access probability
Network throughput

1 Introduction

With the rapid development of wireless communication techniques as well as the rapid popularity of smart terminals (e.g. ipad and iphone), the existing cellular networks are becoming increasingly difficult to meet the customers' exponentially growing data traffic demand [1–3]. Therefore, both wireless spectrum efficiency and network capacity need to be further enhanced [4–6]. Meanwhile, the base stations (BSs) may often operate at an overloaded state due to the existing BS-centric architecture of wireless access network (WAN), consequently resulting in a serious load imbalance over the whole WAN.

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Device-to-Device (D2D) communication technology is regarded as one of the effective ways [7–9] for addressing the above-mentioned issues mainly based on the following benefits. On the one hand, proximity communication is capable of offering a higher channel quality between proximity-communication peers, corresponding to a higher channel capacity [10] as well as a lower power consumption [11]. On the other hand, a much lower delay than in conventional cellular communications can be guaranteed by implementing the scheme of direct transmission between users [12]. Furthermore, through reusing the licensed spectrum of conventional cellular user equipments (CUEs), the spectral efficiency of wireless networks can be substantially improved by activating D2D links [13,14].

However, activating the D2D links may impose a severe interference on the conventional CUEs, thus significantly eroding the performance of the latter [15]. To achieve a better overall system performance while guaranteeing the minimum Quality of Service (QoS) requirement of CUEs, an appropriate interference management technique (e.g., in terms of resource allocation, mode selection and power control) must be implemented in the activated D2D user equipments (DUEs).

Up to now, interference-management technologies for D2D aided cellular system have been widely studied in both academy and industry [15,16]. To coordinate the interference among CUEs and DUEs, the authors in [17] proposed a new technique for optimizing the sum data rate relying on power control schemes of different modes. Subject to a sum-rate constraint, a distributed power control algorithm relying on small-scale path losses has been proposed in [18] for minimizing the overall power consumption. Furthermore, a resource allocation scheme, in which the local awareness of the interference between CUEs and DUEs can be generated at the BSs, is proposed for minimizing the interference imposed on the CUEs [19]. In order to better combine the advantages of resource allocation and power control techniques, a jointly resource allocation and power control scheme has been proposed in [20] for maximizing the energy-efficiency (EE) of D2D aided underlaying cellular networks. In addition, a joint scheme by considering mode selection, channel assignment and power control simultaneously in D2D communications has been proposed in [21] for optimizing the overall system throughput while guaranteeing the SIR of both CUEs and DUEs.

Despite all this, most of the above-mentioned literatures mainly considered a relatively simple system model (e.g. comprising only a single CUE as well as D2D pair), in which the licensed spectrum of the objective CUE can be reused by at most one D2D pair. In this paper, resource allocation in D2D aided heterogeneous cellular systems is investigated by proposing a heuristic resource allocation algorithm for maximizing the number of simultaneously activated D2D pairs. The main contributions of this paper are reflected as follows:

1. The main objective of this paper is to maximize the number of simultaneously activated D2D pairs, while guaranteeing the minimum SIR of both CUEs and DUEs. Furthermore, a framework of resource allocation for D2D aided heterogeneous cellular systems is proposed, in which the licensed spectrum of a single CUE is allowed to be reused by more than one D2D pair.

2. Unlike [22], in the proposed system model, we assume that there exists an interference limited area (ILA) either for BSs or for D2D receivers, inside which the licensed spectrum is prohibited to be reused by DUEs.
3. By performing system-level simulations, it demonstrates that a significant performance improvement in terms of both the D2D access probability and the overall network throughput can be obtained, while without significantly sacrificing the performance of conventional CUEs.

The remainder of this paper is organized as follows. Section 2 gives out the system model. The proposed resource allocation strategy is discussed in Sect. 3, followed by evaluating the performance of the proposed algorithm using simulations in Sect. 4. Finally, Sect. 5 concludes this paper.

2 System Model

In this section, system model for the proposed D2D aided heterogeneous networks is first proposed, followed by analyzing the link SIR.

2.1 System Model for D2D Aided Heterogeneous Networks

In this paper, without loss of generality, licensed spectrum allocated to CUEs is allowed to be fully reused by DUEs, in which scenario a total of N_c CUEs are assumed to coexist with N_d D2D pairs. Meanwhile, multiple D2D pairs are allowed to reuse the licensed spectrum of a single CUE. However, an orthogonal spectrum is assumed to be allocated to an adjacent cell in order to avoid the inter-cell interference, and a fully-loaded spectrum allocation scenario with uplink resource sharing is considered in the proposed system model. Furthermore, To mitigate the D2D-induced interference inside a given cellular coverage, a circle guard zone, namely the ILA, is pre-set for both BSs and D2D receivers, inside which area the licensed spectrum is not prohibited to be reused by DUEs. In the following, the radius of the ILA is denoted by d.

2.2 SIR Analysis for Cellular and D2D Links

In this paper, without loss of generality, a typical Urban Micro (UMi) scenario is considered in the proposed system model. The performance erosion is assumed to be mainly induced by the impact of propagation and shadowing effects of wireless channels. Meanwhile, both the antenna gains of devices (i.e. including both BSs and CUEs/DUEs) and the feeder loss are taken into account. For convenience, we use $\mathcal{C} = \{1, 2, ..., N_c\}$ and $\mathcal{D} = \{1, 2, ..., N_d\}$ to denote the index sets of active CUEs and candidate D2D pairs, respectively, with N_c and N_d denoting the maximum number of CUEs and candidate D2D pairs, respectively. Furthermore, $\phi_i \subseteq \mathcal{D}$ is used to denote the set of admitted D2D pairs (i.e. the activated DUE pairs), which will reuse the spectrum allocated to the i-th CUE. In addition, parameters C_i and D_j are used to denote the i-th CUE and j-th D2D pair, respectively.

The Received SIR of the typical CUE-BS (i.e., C_i-BS) and D2D (i.e., D_j) links can be respectively represented as

$$\gamma_i^c = \frac{P_i^c g_{i,B}}{N_0 + \sum\limits_{j \in \phi_i} P_j^d g_{j,B}}, \tag{1a}$$

$$\gamma_j^d = \frac{P_j^d g_j}{N_0 + \sum\limits_{k \in \phi_i \setminus j} P_k^d g_{k,j} + P_i^c g_{i,j}}, \tag{1b}$$

where P_i^c and P_j^d stand for the transmit power of C_i and j-th D2D transmitter, respectively. Without loss of generality, we assume that $P_i^c = P_j^d = P_0$. Furthermore, $g_{i,B}$ denotes the channel gain between C_i and the corresponding BS, and $g_{j,B}$ denotes the channel gain between the j-th D2D transmitter and the associated BS. Thus, g_j can be used to denote the corresponding channel gain of D_j, with $g_{i,j}$ standing for the channel gain between C_i and the j-th D2D receiver. Finally, N_0 is used to denote the power of thermal noise. The sum throughput of the proposed D2D aided cellular systems can be expressed as

$$R_{\text{sum}} = \sum_{i \in \mathcal{C}} \left(\log\left(1 + \gamma_i^c\right) + \sum_{j \in \phi_i} \log\left(1 + \gamma_j^d\right) \right). \tag{2}$$

3 Resource Allocation Strategy for D2D Aided Cellular Systems

It has been shown that the activated D2D links may impose a severe interference on the CUEs and the interference induced by either CUEs or the geographically close-by D2D transmitters may also significantly erode the quality of a given activated D2D link during the uplink transmission periods. To mitigate the D2D-induced interference, a resource allocation strategy aiming at maximizing the number of simultaneously activated D2D pairs is proposed. For convenience of analysis, we can form a frequency reuse set comprising the objective CUE and its co-spectrum DUEs, provided that the minimum QoS (or in other words, minimum SIR) requirement of each user in this set can be guaranteed. Based on the above-mentioned principle, a resource-allocation framework can thus be formulated as:

$$\textbf{P1:} \quad \max_{\phi_1, \phi_2, \ldots, \phi_{N_c}} T_D \tag{3}$$

$$\text{s.t.} \quad T_D = \sum_{i \in \mathcal{C}} |\phi_i|, \tag{3a}$$

$$T_D \leq N_d, \tag{3b}$$

$$\gamma_i^c \geq \gamma_{\min}^c, \forall i \in \mathcal{C}, \tag{3c}$$

$$\gamma_j^d \geq \gamma_{\min}^d, \forall j \in \mathcal{D}, \tag{3d}$$

$$\phi_p \cap \phi_q = \varnothing, \forall p, q \in \mathcal{C} \& p \neq q, \tag{3e}$$

$$d_{j,B} > d, d_{t,j} > d, \forall t \in \mathcal{C}||\mathcal{D} \setminus j, \forall j \in \mathcal{D}, \tag{3f}$$

where T_D denotes the total number of admitted D2D pairs in the whole system, ϕ_i represents the set of admitted D2D pairs reusing the spectrum of C_i, $\gamma_{\min}^c$ and $\gamma_{\min}^d$ stand for the minimum SIR requirement of C_i and D_j, respectively. $d_{j,B}$ denotes the distance between j-th D2D transmitter and BS, $d_{t,j}$ denotes the distance between interference transmitter (i.e. CUE or other D2D transmitter) and j-th D2D receiver. Furthermore, (3e) ensures that any single D2D pair can reuse the spectrum of one and only one CUE. In addition, (3f) is used to limit the D2D-induced interference imposed on both BSs and D2D receivers (i.e. corresponding to formulating the function of ILA).

According to (3c) and (3d), the maximum number of simultaneously activated D2D pairs can be expressed as

- when $\gamma_i^c \geq \gamma_{\min}^c, |\phi_i| \leqslant \frac{P_i^c g_{i,B}}{\gamma_{\min}^c \overline{I_i^c}} - \frac{N_0}{\overline{I_i^c}}$,
- when $\gamma_j^d \geq \gamma_{\min}^d, |\phi_i| \leqslant \frac{P_j^d g_j}{\gamma_{\min}^d \overline{I_j^d}} - \frac{N_0}{\overline{I_j^d}}$,

thus

$$|\phi_i| \leq \min\left(\frac{P_i^c g_{i,B}}{\gamma_{\min}^c \overline{I_i^c}} - \frac{N_0}{\overline{I_i^c}}, \frac{P_j^d g_j}{\gamma_{\min}^d \overline{I_j^d}} - \frac{N_0}{\overline{I_j^d}}\right), \tag{4}$$

where $\overline{I_i^c}$ and $\overline{I_j^d}$ denote the average interference ($\overline{I}$) imposed on C_i and D_j receivers, respectively. Since $I_i^c = P_j^d g_{j,B}$, and $I_j^d = P_t g_{t,j}, t \in \mathcal{C}||\mathcal{D} \setminus j$, we can identify the minimum-maximum value of $|\phi_i|$ when $g_{j,B} = g_{t,j} = g_{max}$, corresponding to the highest average interference level. From the definition of ILA, we can readily conclude that the maximum interference level may happen at the ILA boundary of the typical receivers, in which case the distance between the objective receivers and the interfering terminals would be very short. Therefore, the minimum-maximum value of any spectrum reuse set associated with the activated D2D pairs can be identified. When $\overline{I_i^c} = \overline{I_j^d} = \overline{I_{max}}$ satisfies, the minimum-maximum value can be expressed as

$$|\phi_i| = \begin{cases} \frac{g_{i,B}}{\gamma_{min}^c g_{\max}} - \frac{N_0}{P_0 g_{\max}}, & \frac{g_{i,B}}{\gamma_{\min}^c} \leqslant \frac{g_j}{\gamma_{\min}^d}, \\ \frac{g_j}{\gamma_{min}^d g_{\max}} - \frac{N_0}{P_0 g_{\max}}, & \text{otherwise.} \end{cases} \tag{5}$$

From (5), it is shown that the interference tolerance (IT)[1] of CUE is smaller than that of DUE, if $\frac{g_{i,B}}{\gamma_{\min}^c} \leqslant \frac{g_j}{\gamma_{\min}^d}$ is satisfied. Accordingly, the condition

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[1] In this paper, the IT of a user is defined as $\text{IT}_k = |\phi_k|\overline{I}$, where $k = i, j$.

$g_{i,B} > \gamma^c_{min} g_{j,B}$ can be adopted as a criterion for identifying the candidate D2D pairs that can be activated in order to improve the D2D access ratio, while guaranteeing the SIR requirements of both CUEs and DUEs. Similarly, we can also employ the condition $g_j > \gamma^d_{\min} g_{t,j}$ as a criterion for improving the D2D access ratio in the presence of $\frac{g_{i,B}}{\gamma^c_{\min}} > \frac{g_j}{\gamma^d_{\min}}$.

In summary, the D2D pairs having a better channel gain (i.e. g_j) will receive a higher activating priority, and the D2D access probability can be maximized by fully exploiting the channel gains of each candidate D2D pair, together with the inter-D2D-interference considered, as expressed as

$$\begin{cases} g_{i,B} > \gamma^c_{\min} g_{j,B}, & \frac{g_{i,B}}{\gamma^c_{\min}} \leqslant \frac{g_j}{\gamma^d_{\min}}, \\ g_j > \gamma^d_{\min} g_{t,j}, & \text{otherwise.} \end{cases} \tag{6}$$

From the above-mentioned analysis, the optimal conditions/constraints for improving the sum throughput of the proposed D2D aided cellular systems under the criteria of maximizing the activated D2D pairs can be derived as follows. Obviously, the sum throughput R_c in the traditional cellular network (i.e. without considering D2D communications) can be expressed as

$$R_c = \sum_{i \in \mathcal{C}} \left(\log \left(1 + \xi^c_i \right) \right), \tag{7}$$

where $\xi^c_i = \frac{P^c_i g_{i,B}}{N_0}$. As compared to (4), the throughput gain brought about by employing D2D mode can be expressed as

$$\begin{aligned} R^G &= R_{\text{sum}} - R_c \\ &= \sum_{i \in \mathcal{C}} \left(\log \left(\frac{\left(1 + \gamma^c_i\right) \prod\limits_{j \in \phi_i} \left(1 + \gamma^d_j\right)}{1 + \xi^c_i} \right) \right), \end{aligned} \tag{8}$$

leading to

$$\begin{cases} R^G \geq \sum\limits_{i \in \mathcal{C}} \left(\log \left(\frac{1 + \gamma^c_i + \sum\limits_{j \in \phi_i} \gamma^d_j}{1 + \xi^c_i} \right) \right), \\ R^G \leq \sum\limits_{i \in \mathcal{C}} \left(\log \left(\frac{\varUpsilon}{1 + \xi^c_i} \right) \right), \end{cases} \tag{9}$$

where

$$\varUpsilon = 1 + \left(\gamma^c_i + \sum_{j \in \phi_i} \gamma^d_j \right) + \frac{C^1_{m-1}}{2} \left(\gamma^c_i + \sum_{j \in \phi_i} \gamma^d_j \right)^2 + \cdots + \frac{C^{m-1}_{m-1}}{m} \left(\gamma^c_i + \sum_{j \in \phi_i} \gamma^d_j \right)^m, \tag{10}$$

with m denoting the size of spectrum reuse set. For conventional cellular systems, as a benchmark, it is easy to derive $R_{\text{sum}} = R_c$. However, for D2D aided cellular networks, it is shown that $R_{\text{sum}} > R_c$ can be met if $\gamma^c_i + \sum\limits_{j \in \phi_i} \gamma^d_j > \xi^c_i$ is satisfied.

Evidently, the sum throughput of the proposed D2D aided cellular systems (i.e. $\gamma_i^c + \sum\limits_{j\in\phi_i} \gamma_j^d$) relying on the criteria of maximizing the number of simultaneously activated D2D pairs.

To maximize the number of simultaneously activated D2D pairs, we can readily make the following approximations, i.e. $\gamma_i^c \approx \gamma_{\min}^c$ and $\gamma_j^d \approx \gamma_{\min}^d$, thus leading to $\gamma_i^c + \sum\limits_{j\in\phi_i} \gamma_j^d = \gamma_{\min}^c + \sum\limits_{j\in\phi_i} \gamma_{\min}^d$. Without loss of generality, the maximum interference imposed on BS and D2D receivers can be denoted by $I_{\max}^c$ and $I_{\max}^d$, respectively. For any C_i sharing its spectrum with D2D pairs and inducing interferences $I_i^c = \sum\limits_{j\in\phi_i} P_j^d g_{j,B} = I_{\max}^c$ and $I_j^d = \sum\limits_{t\in\phi_i\setminus j||C_i} P_t g_{t,j} = I_{\max}^d$, the performance gain in terms of SIR can be expressed as

$$\begin{aligned}\gamma_{i,j}^G &= \gamma_i^c + \sum_{j\in\phi_i} \gamma_j^d - \xi_i^c \\ &= \frac{N_0 \varDelta_1 + I_{\max}^c \varDelta_2}{\left(N_0 + I_{\max}^d\right)\left(N_0 + I_{\max}^c\right)},\end{aligned} \tag{11}$$

where

$$\begin{cases}\varDelta_1 = \sum\limits_{j\in\phi_i} N_0 P_0 g_j - I_{\max}^c P_0 g_{i,B}, \\ \varDelta_2 = \sum\limits_{j\in\phi_i} N_0 P_0 g_j - I_{\max}^d P_0 g_{i,B},\end{cases} \tag{12}$$

Evidently, $\gamma_{i,j}^G > 0$ (i.e. $R_{i,j}^G > 0$) holds if $\varDelta_1 > 0$ and $\varDelta_2 > 0$ are satisfied simultaneously, thus leading to

$$N_0 g_j > \max\left(p_j^d g_{j,B} g_{i,B}, p_t g_{t,j} g_{i,B}\right), \tag{13}$$

Consequently, **P1** can be heuristically rewritten as

$$\textbf{P2:} \quad \max_{\phi_1,\phi_2,\ldots,\phi_{N_c}} T_D \tag{14}$$

$$\text{s.t.} \quad \text{(3a)}-\text{(3f)},$$

$$g_{i,B} > \gamma_{\min}^c g_{j,B}, \text{if } \frac{g_{i,B}}{\gamma_{\min}^c} \leqslant \frac{g_j}{\gamma_{\min}^d}, \tag{14a}$$

$$g_j > \gamma_{\min}^d g_{t,j}, \quad \text{if } \frac{g_{i,B}}{\gamma_{\min}^c} > \frac{g_j}{\gamma_{\min}^d}, \tag{14b}$$

$$N_0 g_j > \begin{cases} p_j^d g_{j,B} g_{i,B}, \text{if } g_{j,B} > g_{t,j}, \\ p_t g_{t,j} g_{i,B}, \text{ if } g_{j,B} \le g_{t,j}, \end{cases} \tag{14c}$$

where $i \in \mathcal{C}$, $j \in \mathcal{D}$ and $t \in \mathcal{C}||\mathcal{D} \setminus j$.

4 Numerical Analysis

In this section, numerical analysis for the proposed algorithm is performed relying on the proposed channel model to explore the attainable benefits brought about by the proposed algorithm. We consider a wrap-around system configuration comprising 19 sites (i.e. each comprising 3 cells). Without loss of generality, the minimum UE-to-BS distance is assumed to be 10 m, and the maximum distance between a pair of D2D peers is 50 m. In addition, the transmit power of BS and CUEs assumed to be 42 dBm and 24 dBm, respectively. Finally, the noise power spectrum density is assumed to be −174 dBm/Hz. The detailed parameter settings, which come from the standard [23], are elaborated on in Table 1.

Table 1. Parameter settings of the proposed system-level simulation

Parameters	Settings
Scenario environment	UMi
System bandwidth	10 MHz (TDD)
Carrier frequency	2.5 GHz
The min-distance of UE to BS	10 m
Antenna model of Macro BS	$A(\theta) = -\min\left[12(\frac{\theta}{\theta_{3\,\mathrm{dB}}})^2, A_m\right]$ $A_e(\phi) = -\min\left[12(\frac{\phi-\phi_{tilt}}{\phi_{3\,\mathrm{dB}}})^2, A_m\right]$ $-\min\left[-(A(\theta) + A_e(\phi)), A_m\right]$ $A_m = 20\,\mathrm{dB}$ $\theta_{3\,\mathrm{dB}} = 70$, $\phi_{tilt} = 15$ $-180 \le \theta \le 180$, $-90 \le \phi \le 90$
Antenna model of UE	Omnidirectional
Traffic pattern	Full buffer
BS height	10 m
UE height	1.5 m
BSNoiseFigure	5 dB
UENoiseFigure	7 dB
BS transmit power	42 dBm
UE transmit power	24 dBm
Power level of thermal noise	−174 dBm/Hz

In Fig. 1, the performance of random spectrum allocation and proposed resource allocation algorithms in terms of the maximum number of simultaneously activated D2D pairs is performed by considering variant η values, with a single CUE considered. It is shown that the number of simultaneously activated D2D pairs decreases as η increases, because the interference tolerance of CUE decreases as the SIR threshold increases, thus requiring fewer D2D pairs to be activated simultaneously so as to impose a lower interference on CUE (i.e. to guarantee the minimum SIR requirement of the CUE). Anyway, the proposed algorithm is shown to always outperform the conventional random spectrum allocation scheme in terms of throughput, because the former is capable of coordinating the interference between CUEs and D2D pairs and optimizing the spectrum reuse set adaptively according to the instantaneous channel condition.

In Fig. 2, the impacts of ILA radius and CUE-SIR threshold on the number of simultaneously activated D2D pairs in a single-cellular scenario is investigated. It is shown that the access probability of the proposed algorithm is a monotonically decreasing function of η, because the interference tolerance of DUEs decreases as η increases. Meanwhile, it is also shown that the performance of proposed algorithm increases first, and then decreases as d increases. We can explain this observation as follows: when ILA radius is small, the interference imposed on signal receiver from one interference transmitter is more intensive compared with signal receiver power when the distance of interference link is bigger than D2D links. But when ILA radius is beyond the distance of D2D links, the probability of candidate D2D pairs access to network declines with the increase of d, as a result, the admitted D2D pairs decreases.

Figure 3 demonstrates the impact of ILA on the throughput as a function of η. Evidently, the throughput is a monotonically decreasing function of η, because the number of simultaneously activated D2D pairs decreases as the SIR threshold increases. Meanwhile, the performance of the proposed algorithm is also shown to increase firstly, and then decreases as d increases. This is because the interference is much more intensive when $d < 50$ (i.e. the maximum allowable distance of D2D links) compared with receiver signal power, and fewer D2D pairs can access to the network while guaranteeing the requirement of ILA radius, if ILA radius is beyond the distance of D2D links. Consequently, the sum throughput decreases.

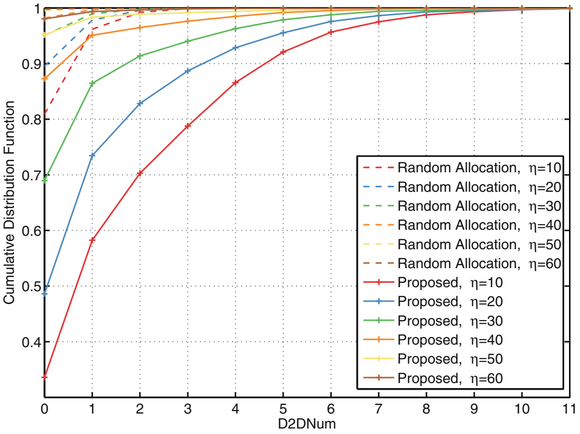

Fig. 1. Performance comparison of the proposed algorithm and the conventional random spectrum allocation scheme in terms of the maximum number of simultaneously activated D2D pairs for variant SIR thresholds, with a single CUE considered, where $N_c = 50$, $N_d = 300$ and $d = 50$.

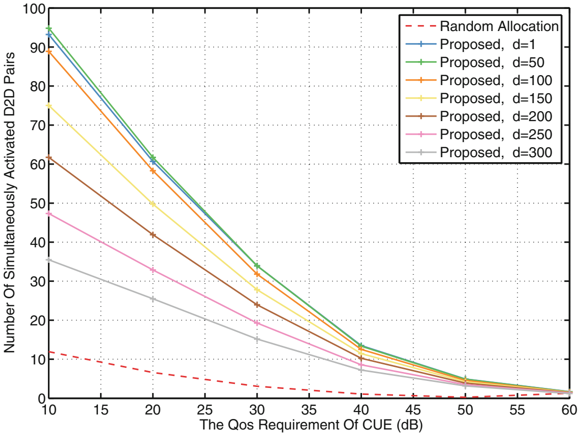

Fig. 2. The maximum number of simultaneously activated D2D pairs in the proposed system under different settings of SIR threshold, with a BS, where $N_c = 50, N_d = 300$.

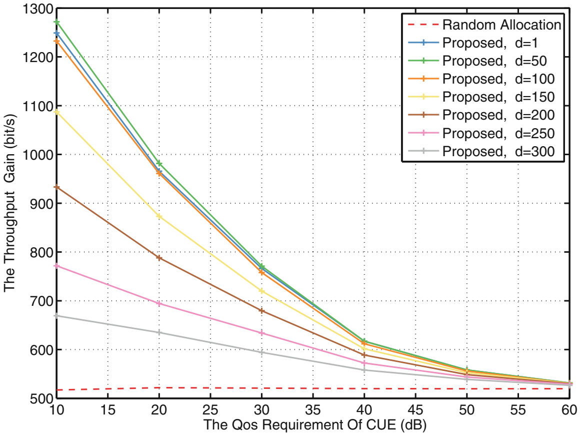

Fig. 3. Performance comparison of the proposed algorithm and the conventional random spectrum allocation scheme in terms of the sum throughput gain for variant radius of ILA, where $N_c = 50$ and $N_d = 300$.

5 Conclusions

In this paper, the problem of adaptive spectrum allocation was formulated as the maximization of the number of simultaneously activated D2D pairs in scenario of D2D reusing the uplink licensed spectrum, with a fully loaded cellular network considered. To maximize the number of simultaneously activated D2D pairs without eroding the SIRs of both CUEs and DUEs, a greedy heuristic algorithm was also implemented for finding the objective spectrum-reuse set. Numerical results showed that the proposed algorithm is capable of improving both the D2D-access probability and the sum throughput of the whole system. It was shown that the proposed algorithm is capable of increasing the admitted D2D pairs and sum throughput by about 800% and 80% as compared to the conventional random spectrum allocation algorithm when η=20 dB and $d = 50$.

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References

1. Zhang, Z., Long, K., Wang, J., Dressler, F.: On swarm intelligence inspired self-organized networking: its bionic mechanisms, designing principles and optimization approaches. IEEE Commun. Surv. Tutor. **16**(1), 513–537 (2014)
2. Zhang, Z., Long, K., Wang, J.: Self-organization paradigms and optimization approaches for cognitive radio technologies: a survey. IEEE Wirel. Commun. Mag. **20**(2), 36–42 (2013)
3. Dahlman, E., Parkvall, S., Skold, J.: 4G: LTE/LTE-Advanced for Mobile Broadband. Academic Press, Oxford (2013)
4. Zhang, Z., Chai, X., Long, K., Vasilakos, A.V., Hanzo, L.: Full duplex techniques for 5G networks: self-interference cancellation, protocol design, and relay selection. IEEE Commun. Mag. **53**(5), 128–137 (2015)
5. Zhang, Z., Long, K., Vasilakos, A.V., Hanzo, L.: Full-duplex wireless communications: challenges, solutions and future research directions. Proc. IEEE **104**(7), 1369–1409 (2016)
6. Wang, G., Liu, Q., He, R., Gao, F., Tellambura, C.: Acquisition of channel state information in heterogeneous cloud radio access networks: challenges and research directions. IEEE Wirel. Commun. **22**(3), 100–107 (2015)
7. Xiao, H., Ouyang, S.: Power allocation for a hybrid decodeamplify forward cooperative communication system with two sourcedestination pairs under outage probability constraint. IEEE Syst. J. **9**(3), 797–804 (2015)
8. Wang, G., Gao, F., Tellambura, C.: Ambient backscatter communication systems: detection and performance analysis. IEEE Trans. Commun. **64**, 4836–4846 (2016)
9. Zhang, H., Jiang, C., Mao, X., Chen, H.-H.: Interference-limit resource optimization in cognitive femtocells with fairness and imperfect spectrum sensing. IEEE Trans. Veh. Technol. **65**(3), 1761–1771 (2016)
10. Jnis, P., Yu, C.-H., Doppler, K., Ribeiro, C., Wijting, C., Hugl, K., Tirkkonen, O., Koivunen, V.: Device-to-device communication underlaying cellular communications systems. Int. J. Commun. Netw. Syst. Sci. **2**(3), 169 (2009)
11. Zhang, G., Yang, K., Liu, P., Du, Y.: Using full duplex relaying in device-to-device (D2D) based wireless multicast services: a two-user case. Sci. Chin. Inf. Sci. **58**(8), 1–7 (2015)
12. Ferrus, R., Sallent, O., Baldini, G., Goratti, L.: Lte: the technology driver for future public safety communications. IEEE Commun. Mag. **51**(10), 154–161 (2013)
13. Zhang, G., Liu, P., Yang, K., Du, Y., Hu, Y.: Orthogonal resource sharing scheme for device-to-device communication overlaying cellular networks: a cooperative relay based approach. Sci. China Inf. Sci. **58**(10), 1–9 (2015)

14. Zhang, H., Jiang, C., Beaulieu, N.C., Chu, X., Wen, X., Tao, M.: Resource allocation in spectrum-sharing OFDMA femtocells with heterogeneous services. IEEE Trans. Commun. **62**(7), 2366–2377 (2014)
15. Chai, X., Liu, T., Xing, C., Xiao, H., Zhang, Z.: Throughput improvement in cellular networks via full-duplex based device-to- device communications. IEEE Access **4**, 7645–7657 (2016)
16. Sun, J., Liu, T., Wang, X., Xing, C., Xiao, H., Vasilakos, A.V., Zhang, Z.: Optimal mode selection with uplink data rate maximization for D2D-aided underlaying cellular networks. IEEE Access **4**, 8844–8856 (2016)
17. Yu, C.-H., Tirkkonen, O., Doppler, K., Ribeiro, C.: Power optimization of device-to-device communication underlaying cellular communication. In: 2009 IEEE International Conference on Communications, pp. 1–5. IEEE (2009)
18. Fodor, G., Reider, N.: A distributed power control scheme for cellular network assisted D2D communications. In: 2011 IEEE Global Telecommunications Conference (GLOBECOM 2011), pp. 1–6. IEEE (2011)
19. Janis, P., Koivunen, V., Ribeiro, C., Korhonen, J., Doppler, K., Hugl, K., Interference-aware resource allocation for device-to-device radio under- laying cellular networks. In: IEEE 69th Vehicular Technology Conference: VTC Spring 2009, pp. 1–5. IEEE (2009)
20. Jiang, Y., Liu, Q., Zheng, F., Gao, X., You, X.: Energy efficient joint resource allocation and power control for D2D communications (2016)
21. Yu, G., Xu, L., Feng, D., Yin, R., Li, G.Y., Jiang, Y.: Joint mode selection and resource allocation for device-to-device communications. IEEE Trans. Commun. **62**(11), 3814–3824 (2014)
22. Min, H., Lee, J., Park, S., Hong, D.: Capacity enhancement using an interference limited area for device-to-device uplink underlaying cellular networks. IEEE Trans. Wirel. Commun. **10**(12), 3995–4000 (2011)
23. M Series: Guidelines for evaluation of radio interface technologies for IMT-advanced (2009)