IEICE TRANSACTIONS

on Communications

PAPER

On-Off Power Control with Low Complexity in D2D Underlaid Cellular Networks*

Tae-Won BAN[†a)]**, *Member* and Bang Chul JUNG**[††b)]**, *Nonmember***

SUMMARY We consider a device-to-device (D2D) underlaid cellular network where D2D communications are allowed to share the same radio spectrum with cellular uplink communications for improving spectral efficiency. However, to protect the cellular uplink communications, the interference level received at a base station (BS) from the D2D communications needs to be carefully maintained below a certain threshold, and thus the BS coordinates the transmit power of the D2D links. In this paper, we investigate *on-off power control* for the D2D links, which is known as a simple but effective technique due to its low signaling overhead. We first investigate the optimal on-off power control algorithm to maximize the sum-rate of the D2D links, while satisfying the interference constraint imposed by the BS. The computational complexity of the optimal algorithm drastically increases with D2D link number. Thus, we also propose an on-off power control algorithm to significantly reduce the computational complexity, compared to the optimal on-off power control algorithm. Extensive simulations validate that the proposed algorithm significantly reduces the computational complexity with a marginal sum-rate offset from the optimal algorithm.

key words: D2D communications, D2D underlaid cellular network, on-off power control, interference, computational complexity

1. Introduction

Mobile traffic has been continuously increasing and this trend is expected to continue. Especially, mobile video services have become widespread over recent years and it is expected that the mobile video traffic will capture about 80% of the total mobile traffic [1]. The quality of service (QoS) of the mobile video services is mainly determined by distance between transmitters and receivers as well as data transmission rate [2]–[6]. Wider channel bandwidth can easily increase data transmission rate but radio spectrum is a scare radio resource [7]. Although some advanced technologies such as multiple input and multiple out (MIMO) and small cell systems can efficiently use the limited radio spectrum by improving spectral efficiency [8], [9], it has

limitations in improving latency. Alternatively, device-to-device (D2D) communications have been attracting plenty of interest because they can improve both data transmission rate and latency simultaneously [10]–[13]. In particular, a D2D *underlaid* cellular network has received much attention from both industrial and academic communities because it can achieve much higher spectral efficiency by allowing the D2D communications to *share* the same spectrum with the conventional cellular communications.

One of the most challenging issues of D2D underlaid cellular networks is the *cross-interference* between cellular and D2D communications [14]–[24]. The cross-interference can be mitigated by three major types of solutions such as transmit mode selection [14]–[16], radio resource control or optimization for a given transmit mode [17]–[20], and power control [21]–[24]. In cellular-aided D2D networks, the data exchange between devices can be carried out in three different modes such as orthogonal mode (OM), non-orthogonal mode (NOM), and cellular mode (CM). In OM, D2D communications use dedicated resources orthogonal to cellular communications, while they share the same resources with cellular communications for higher spectral efficiency in NOM. In CM, the data exchange between devices is carried out via cellular infrastructure such as BS. [14] investigated a switching criterion between CM and NOM for D2D devices by considering network information such as link gains, noise levels, and signal-to-interference-ratio (SINR). The optimization among the three different modes was also investigated to maximize the sum-rate of the D2D underlaid cellular network [15], which was extended to multiple-input multiple-output (MIMO) environments [16]. [17]–[19] and [20] investigated the management or optimization of radio resource usage for NOMs and OM, respectively. On the other hand, several studies focused on another approach based on the concept of power control to resolve the cross-interference problem in cellular underlaid D2D networks [21]–[24]. [21] proposed a distributed power control scheme for D2D communications in NOM to minimize the consumption of power for a given sum-rate constraint. [22] investigated a centralized power allocation scheme by considering both transmission delay and the sum-rate of D2D communications in NOM. However, these power control schemes inevitably cause serious computational complexity to calculate transmit power levels and signaling overhead to notify D2D transmitters of the power levels because the transmit power levels are real positive continuous numbers. To reduce the complexity and signaling overhead, binary power control schemes were

investigated in [23], [24]. [23] proposed a binary power control scheme in NOM and analyzed the performance in terms of outage probability. [24] also proposed a binary power control scheme in a limited NOM with single D2D pair. Although binary power control schemes can greatly reduce complexity and signaling overhead compared to conventional power control schemes, they still require high complexity to select an optimal set of D2D transmitters for each power level because it is a combinatorial problem. In this paper, we thus propose a low-complexity on-off power control scheme. Contrary to conventional binary power control schemes, the proposed scheme has a linear complexity yielding near optimal sum-rates and can also guarantee the QoS of cellular communications by strictly controlling the total amount of interference caused by D2D communications to be less than I_{th}. We first investigate an optimal on-off power control scheme to guarantee the QoS of cellular communications. Then, we analyze the performance of the proposed low-complexity on-off power control scheme in terms of sum-rate as well as complexity, which are compared with those of the optimal on-off power control. To the best of our knowledge, the complexity of power control schemes has not been investigated in any previous research. The rest of this paper is organized as follows. In Sect. 2, system and channel models are described. In Sect. 3, the proposed on-off power control scheme is described. In Sect. 4, the performance of the proposed scheme is investigated in terms of average sum-rate and computational complexity. Finally, conclusions are drawn in Sect. 5.

2. System and Channel Models

Figure 1 depicts a D2D underlaid cellular network, which consists of a cellular BS, a cellular user equipment (UE), and N D2D pairs. It is assumed that the BS allocates each radio resource for cellular communications and then D2D communications reuse the same radio resource with the cellular communications to enhance spectral efficiency of the network. Uplink (spectral) resources are known to be more appropriate to be shared than downlink resources because of asymmetric traffic loads between uplink and downlink, and strong interference mitigation capability of the BS [18], [25]. All cellular and D2D UEs are assumed to associate with a single BS to exchange cellular data and control messages. Each D2D UE is assumed to be paired with its partner based on the proximity prior to D2D communications[†].

The channel coefficient between transmitter i and receiver j is denoted by h_{ij}, where $i, j \in \{1, 2, \cdots, N, c\}$. $i = c$ and $j = c$ denote the cellular UE and the BS, respectively. h_{ij} is assumed to follow i.i.d. $\mathcal{CN}(0, \lambda_{ij})$ for all i and j. The effect of path loss can be incorporated into λ_{ij}. We assume that the transmit power of all D2D devices and cellular UE

[†]It is assumed that the D2D pairing can be coordinated by the BS. However, the detailed procedure of the pairing is beyond the scope of this paper. Thus, we focus on the power control for given D2D pairs.
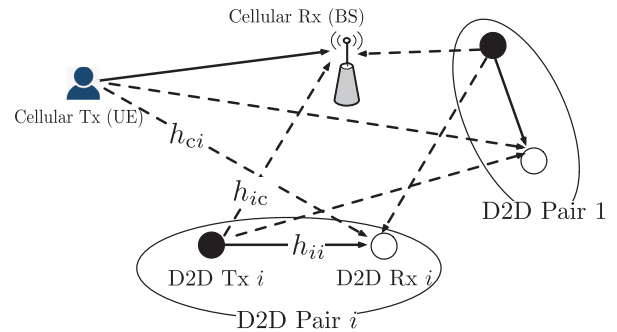

Fig. 1 D2D underlaid cellular network.

is set to P. The cellular UE is assumed to always transmit its data regardless of the presence of D2D transmission, while D2D transmissions are controlled by the BS. For on-off power control, the transmit power of the D2D transmitters is determined as 0 or P in a specific instance. Let N_0 denote the variance of thermal noise at D2D receivers. Then, the signal to noise plus interference ratio (SINR) at the i-th (D2D) receiver γ_i is given by

$$
\begin{aligned}
\gamma_i &= \frac{\mathbf{I}_i P |h_{ii}|^2}{\sum_{k=1, k \neq i}^{N} \mathbf{I}_k P |h_{ki}|^2 + P |h_{ci}|^2 + N_0} \\
&= \frac{\mathbf{I}_i \rho |h_{ii}|^2}{\sum_{k=1, k \neq i}^{N} \mathbf{I}_k \rho |h_{ki}|^2 + \rho |h_{ci}|^2 + 1},
\end{aligned}
\tag{1}
$$

where $\rho = P/N_0$ denotes the *transmit* signal-to-noise ratio (SNR), and $\mathbf{I}_i$ is an indicator function to indicate the activity of the D2D transmitter i. If the transmitter i is activated to transmit data, $\mathbf{I}_i = 1$. Otherwise, $\mathbf{I}_i = 0$. Let $\mathcal{I} \triangleq \{\mathbf{I}_1, \cdots, \mathbf{I}_N\}$. Then, the sum-rate of a D2D underlaid cellular network is defined as

$$
\mathsf{C}_{\text{D2D}} = \sum_{i=1}^{N} \log_2 (1 + \gamma_i).
\tag{2}
$$

The received interference at the cellular BS caused by D2D transmitters is given by $\sum_{i=1}^{N} \mathbf{I}_i P |h_{ic}|^2$, which is supposed to satisfy the following constraint

$$
\sum_{i=1}^{N} \mathbf{I}_i P |h_{ic}|^2 \leq I_{th}
\tag{3}
$$

to protect the cellular uplink communication. I_{th} denotes an interference threshold imposed by the cellular BS. Normalized by N_0, (3) can be rewritten by

$$
\sum_{i=1}^{N} \mathbf{I}_i \rho |h_{ic}|^2 \leq \frac{I_{th}}{N_0} \triangleq I'_{th}.
\tag{4}
$$

All channel gains among D2D UEs are assumed to be known to the BS by pilot signal exchange and feedback mechanism.

3. Proposed On-Off Power Control Algorithm

Satisfying the interference constraint in (4), the BS can determine the *optimal* $\mathcal{I}$ for maximizing the sum-rate in (2) as

Algorithm 1 Proposed On-Off Power Control Algorithm

1: Select D2D pairs satisfying $\rho|h_{ic}|^2 \leq I'_{\text{th}}$ and define them as an eligible set $\mathcal{E}$.
2: Sort the D2D pairs in $\mathcal{E}$ in a descending order according to $|h_{\hat{\mathcal{E}}(i)\hat{\mathcal{E}}(i)}|^2$ ($1 \leq i \leq |\mathcal{E}|$) and define it as $\hat{\mathcal{E}}$.
3: $n = 0$;
4: **for** $k = 1$ to $|\hat{\mathcal{E}}|$ **do**
5:    **if** $\sum_{i=1}^{k} \rho|h_{\hat{\mathcal{E}}(i)c}|^2 > I'_{\text{th}}$ **then**
6:       Break;
7:    **else**
8:       $C_{\text{prop}}(k) = \sum_{i=1}^{k} \log_2 \left(1 + \frac{\rho|h_{\hat{\mathcal{E}}(i)\hat{\mathcal{E}}(i)}|^2}{\sum_{j=1,j\neq i}^{k} \rho|h_{\hat{\mathcal{E}}(j)\hat{\mathcal{E}}(i)}|^2 + \rho|h_{c\hat{\mathcal{E}}(i)}|^2 + 1} \right)$;
9:       n^{++};
10:   **end if**
11: **end for**
12: $n^* = \underset{1\leq i \leq n}{\arg\max} \ C_{\text{prop}}(i)$;

follows:

$$\mathcal{I}^* = \underset{\mathcal{I}}{\arg\max} \quad \sum_{i=1}^{N} \log_2 (1 + \gamma_i)$$
$$\text{subject to} \quad \sum_{i=1}^{N} \mathbf{I}_i \rho |h_{ic}|^2 \leq I'_{\text{th}} \tag{5}$$

Note that $\mathcal{I}^*$ consists of N binary numbers and it can be obtained by an exhaustive searching algorithm. Thus, the computational complexity at the BS increases exponentially as N increases although it significantly reduces the signaling overhead compared with the conventional power control algorithms.

Hence, we propose a simple but effective on-off power control algorithm with low (computational) complexity, as summarized in Algorithm 1. In the proposed algorithm, the BS constructs a candidate set $\mathcal{E}$ which consists of D2D pairs satisfying the interference constraint as follows:

$$\mathcal{E} \triangleq \left\{ i | \rho|h_{ic}|^2 \leq I'_{\text{th}}, 1 \leq i \leq N \right\}$$
$$= \left\{ i | |h_{ic}|^2 \leq \frac{I'_{\text{th}}}{\rho}, 1 \leq i \leq N \right\} \tag{6}$$

Then, the BS sorts the D2D pairs included in the candidate set in a descending order according to the channel gain between D2D transmitter and D2D receiver. $\hat{\mathcal{E}}$ denotes the sorted candidate set. Thus,

$$|h_{\hat{\mathcal{E}}(1)\hat{\mathcal{E}}(1)}|^2 \geq \cdots \geq |h_{\hat{\mathcal{E}}(|\mathcal{E}|)\hat{\mathcal{E}}(|\mathcal{E}|)}|^2, \tag{7}$$

where $\hat{\mathcal{E}}(k)$ and $|\mathcal{E}|$ denote the k-th element of $\hat{\mathcal{E}}$ and the cardinality of $\mathcal{E}$, respectively, and $|\mathcal{E}| = |\hat{\mathcal{E}}|$. The BS checks if the interference constraint in (4) is satisfied by increasing the number of active D2D pairs one by one from $\hat{\mathcal{E}}(1)$ to $\hat{\mathcal{E}}(|\mathcal{E}|)$. When the interference constraint is violated, the BS terminates the iteration. The number of executed iterations before the termination is denoted by n. Finally, the BS determines the optimal value n^* maximizing $C_{\text{prop}}(i)$ for $1 \leq i \leq n$, and the index set of the D2D pairs allowed to transmit data is determined as $\mathcal{I}^*_{\text{prop}} \triangleq \{\hat{\mathcal{E}}(1), \cdots, \hat{\mathcal{E}}(n^*)\}$.

For a given $\mathcal{E}$, the optimal algorithm based on exhaustive searching and the proposed algorithm require $(2^{|\mathcal{E}|} - 1)$ and $|\mathcal{E}|$ iterations, respectively. Thus, the complexity ratio of

the optimal algorithm to the proposed algorithm η is defined as

$$\eta \triangleq \begin{cases} \text{Not defined}, & \text{if } |\mathcal{E}| = 0 \\ \frac{2^{|\mathcal{E}|}-1}{|\mathcal{E}|} & \text{otherwise} . \end{cases} \tag{8}$$

$\mathbb{E}[\eta]$ can be calculated as

$$\mathbb{E}[\eta] = \sum_{n=1}^{N} \frac{2^n - 1}{n} \times \Pr\left[|\mathcal{E}| = n \mid |\mathcal{E}| \neq 0\right]$$
$$= \sum_{n=1}^{N} \frac{2^n - 1}{n} \times \frac{\Pr\left[(|\mathcal{E}| = n)\&(|\mathcal{E}| \neq 0)\right]}{\Pr[|\mathcal{E}| \neq 0]}$$
$$= \sum_{n=1}^{N} \frac{2^n - 1}{n} \times \frac{\Pr\left[|\mathcal{E}| = n\right]}{\Pr[|\mathcal{E}| \neq 0]}$$
$$= \sum_{n=1}^{N} \frac{2^n - 1}{n} \times \frac{\Pr[|\mathcal{E}| = n]}{1 - \Pr[|\mathcal{E}| = 0]}, \tag{9}$$

where $\Pr[|\mathcal{E}| = n]$ denotes the probability that the cardinality of $\mathcal{E}$ is n and the averaging is carried out based on a condition of $|\mathcal{E}| \neq 0$ because η can be only defined for $|\mathcal{E}| \neq 0$.

4. Numerical Results

In this section, the performance of the proposed on-off power control algorithm is investigated in terms of average sum-rate and computational complexity, and compared with those of the optimal on-off power control algorithm. Figure 2 shows the average sum-rate performance and the computational complexity of the proposed algorithm and optimal algorithm for varying SNR values. For numerical simplicity, we assume that all wireless channels are i.i.d. and $\lambda_{ij} = 1 \ \forall \ i, j$. Thus, $|h_{ij}|^2$ is exponentially distributed with a unit mean. A D2D pair can satisfy the constraint given in (6) with the probability of $\left(1 - e^{-\frac{I'_{\text{th}}}{\rho}}\right)$, while it can not satisfy the constraint with the probability of $e^{-\frac{I'_{\text{th}}}{\rho}}$. The event that $(|\mathcal{E}| = n)$ has $\binom{N}{n}$ cases. For each case, n D2D pairs satisfy the constraint while $(N - n)$ D2D pairs do not satisfy the constraint. Thus, $\Pr[|\mathcal{E}| = n]$ can be determined as

$$\Pr[|\mathcal{E}| = n] = \binom{N}{n} \left(1 - e^{-\frac{I'_{\text{th}}}{\rho}}\right)^n \left(e^{-\frac{I'_{\text{th}}}{\rho}}\right)^{N-n}. \tag{10}$$

Substituting (10) into (9), we obtain (11).

$_pF_q\left(a_1, \cdots, a_p; b_1, \cdots, b_q; z\right)$ in (11) denotes the generalized hypergeometric function[†].

In addition, to quantify the performance degradation of the ON-OFF power control approach, we also analyse the average sum-rate of another approach using continuous transmit power. In the continuous transmit power scheme, each D2D transmitter can adjust its transmit power so that

---

[†] $_pF_q\left(a_1, \cdots, a_p; b_1, \cdots, b_q; z\right) \triangleq \sum_{n=0}^{\infty} \frac{a_1^{(n)} \cdots a_p^{(n)}}{b_1^{(n)} \cdots b_q^{(n)}} \frac{z^n}{n!}$, where $x^{(n)} = x(x+1) \cdots (x+n-1)$.

$$\mathbb{E}[\eta] = \sum_{n=1}^{N} \frac{2^n - 1}{n} \times \frac{\binom{N}{n}\left(1 - e^{-\frac{I_{th}}{\rho}}\right)^n \left(e^{-\frac{I_{th}}{\rho}}\right)^{N-n}}{1 - e^{-\frac{N I_{th}}{\rho}}}$$

$$= \frac{N e^{-\frac{N I_{th}}{\rho^d}}\left(e^{\frac{I_{th}}{\rho^d}} - 1\right)}{1 - e^{-\frac{N I_{th}}{\rho^d}}} \times \left[2 \, _3F_2\left(1, 1, -N + 1; 2, 2; -2 e^{\frac{I_{th}}{\rho^d}} + 2\right) - \,_3F_2\left(1, 1, -N + 1; 2, 2; -e^{\frac{I_{th}}{\rho^d}} + 1\right) \right]. \qquad (11)$$
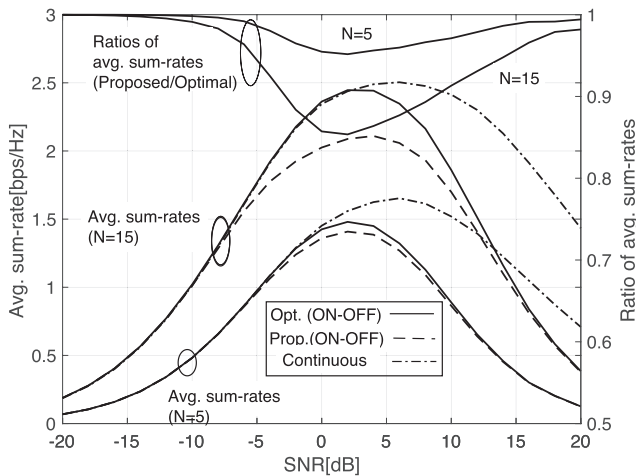
(a) Average sum-rate of the proposed on-off power control algorithm for varying SNR values.
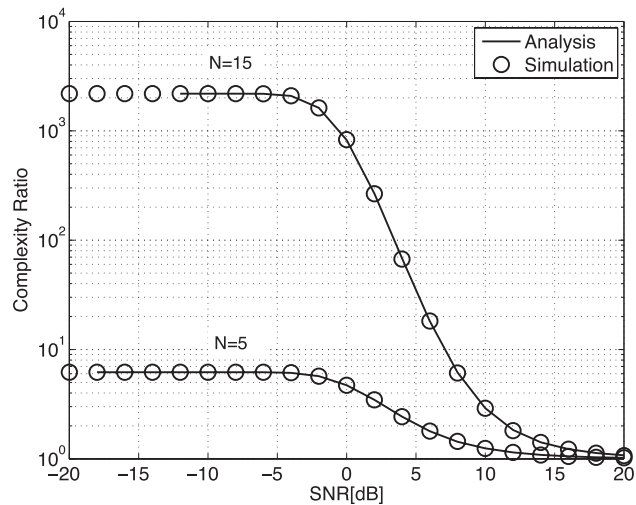
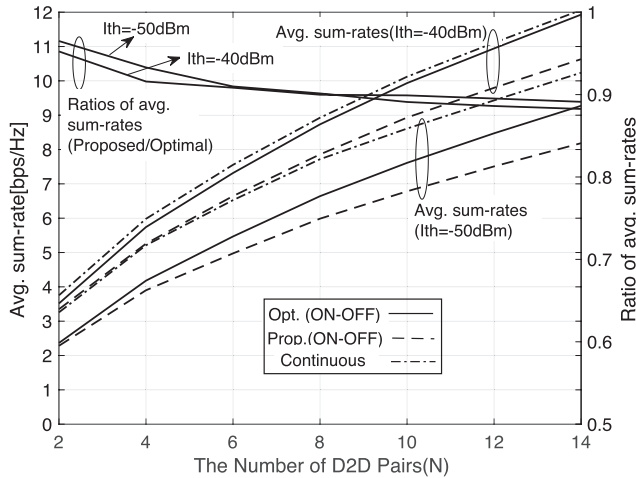(b) Complexity ratio of the optimal algorithm to the proposed algorithm for varying SNR values.

Fig. 2 Performance of the optimal algorithm and the proposed algorithm for varying SNR values when wireless channels are i.i.d. and $I'_{th} = 3$ dB.

the interference constraint can be always satisfied regardless of channel coefficients. The transmit power of each D2D transmitter i in the continuous transmit power scheme can be determined by

$$p_i = \begin{cases} P, & \text{if } P|h_{ic}|^2 \le I_{th} \\ \frac{I_{th}}{|h_{ic}|^2}, & \text{if } P|h_{ic}|^2 > I_{th} \end{cases}$$

$$= \min\left(P, \frac{I_{th}}{|h_{ic}|^2}\right). \qquad (12)$$

It is assumed that $I'_{th} = 3$ dB and $N = 5$ or 15. First of all, the proposed algorithm achieves similar sum-rate to that of the optimal algorithm over SNR values especially when N is small. In particular, the proposed algorithm yields near optimal performance in low and high SNR regimes. The sum-rate increases as SNR increases in low-SNR regime, while it decreases as SNR increases in high-SNR regime. The number of D2D pairs satisfying the interference constraint decreases as SNR increases in high-SNR regime, which reduces multi-user diversity gain in high-SNR regime. Interestingly, there exists an optimal SNR value that achieves the maximum average sum-rate for given N and I'_{th} in Fig. 2(a) and thus the average sum-rates of both proposed and optimal algorithms become concave functions according to SNR. The average complexity ratio derived in (11) is shown in Fig. 2(b), and the mathematical analysis is also validated by Monte-Carlo simulations. It is shown that the proposed algorithm has significantly lower computational complexity than the optimal algorithm, especially when N is large or SNR is low. For example, when SNR=-5 dB and $N = 15$, the complexity of the optimal algorithm is approximately 2×10^3 higher than the proposed algorithm, while the proposed algorithm achieves 98% sum-rate of the optimal algorithm. It is also shown that the on-off power control scheme causes the performance degradation compared with the continuous transmit power scheme. However, the continuous transmit power scheme inevitably causes extra overhead for signalling power values. In addition, the performance gap between two approaches almost disappears for low SNR values.

Figure 3 shows the sum-rate performance and the computational complexity of the proposed algorithm and the optimal algorithm for various numbers of D2D pairs N in the network when the wireless channels are non-i.i.d. and $I_{th} = -40$ dBm or -50 dBm. The D2D pairs ($2N$ D2D UEs) are assumed to be distributed uniformly within a circle with radius R. The average channel gain λ_{ij} is determined by $\min(1, d_{ij}^{-\alpha})$, where $d_{ij}(0 \le d_{ij} \le 2R)$ and α denote the distance between transmitter i and receiver j and a path loss exponent, respectively. It is assumed that $R = 100$ m, $\alpha = 4$, the transmit power of D2D UEs is equal to 23 dBm, the noise spectral density is equal to -174 dBm/Hz, and channel band-

(a) Average sum-rate of the proposed on-off power control algorithm for varying SNR values.
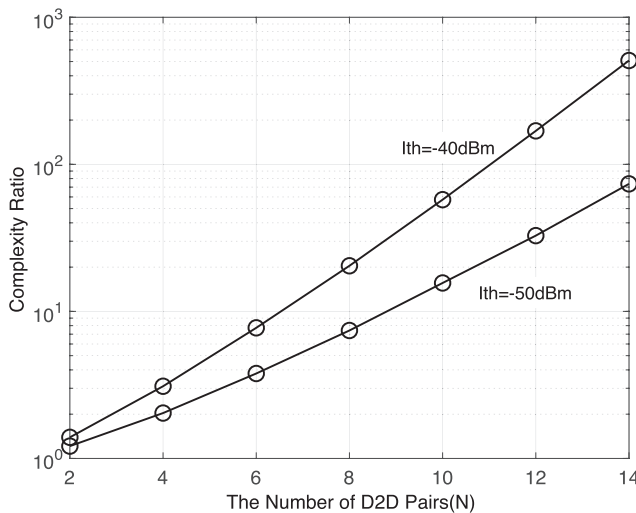
(b) Complexity ratio of the optimal algorithm to the proposed algorithm for varying number of D2D pairs in the network.

Fig. 3   Performance of the optimal and the proposed algorithms for varying N when wireless channels are non-i.i.d.

width is 10 MHz. As shown in Fig. 3(a), the proposed algorithm yields nearly the optimal average sum-rate especially when N is small or I_{th} is low. Although the optimal algorithm outperforms the proposed algorithm as N or I_{th} increases, the gap is marginal. For the proposed scheme with $N = 14$, we can achieve approximately 89% and 88% of the optimal average sum-rate when $I_{th} = -40$ dBm and -50 dBm, respectively. Note that Fig. 3(a) also shows the sum-rate ratio of the proposed scheme to the optimal scheme in the right vertical axis. Figure 3(b) shows the complexity ratio of the optimal algorithm to the proposed algorithm according to the number of D2D pairs in the network. Obviously, the complexity ratio increases as N or I_{th} increases because the number of D2D pairs allowed to transmit data increases as N or I_{th} increases. In addition, the performance gap between two approaches is marginal in non-i.i.d. environments.

5. Conclusions

We studied a cellular underlaid D2D network, where D2D communications share a radio spectrum with conventional cellular uplink communications for higher spectral efficiency. Thus, the D2D communications should be carefully regulated to protect the quality of the cellular uplink communications. For secure communications of the D2D underlaid cellular uplink, we considered an on-off power control scheme with low signaling overhead. We first investigated an optimal on-off power control scheme and proposed a suboptimal on-off power control scheme which can dramatically reduce computational complexity compared to the optimal scheme. Our analyses and simulations confirmed that the proposed scheme can achieve near optimal average sum-rate in low or high SNR regimes, while significantly reducing the excessive computational complexity of the optimal scheme. The practicality and effectiveness of the proposed scheme was also verified in a practical environment with non-i.i.d. channels.

References

[1] Cisco, Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2016-2021, Whitepaper, 2017 [Online]. Available: https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/mobile-white-paper-c11-520862.html

[2] G. Caire, The Role of Caching in 5G Wireless Networks, invited talk in IEEE ICC 2013.

[3] X. Cai, S. Zhang, and Y. Zhang, "Economic analysis of cache location in mobile network," Proc. IEEE WCNC, pp.1243–1248, Shanghai, China, April 2013.

[4] X. Wang, M. Chen, T. Taleb, A. Ksentini, and V.C.M. Leung, "Cache in the air: Exploiting content caching and delivery techniques for 5G systems," IEEE Commun. Mag., vol.52, no.2, pp.131–139, Feb. 2014.

[5] D. Giordano, S. Traverso1, L. Grimaudo, M. Mellia, E. Baralis, A. Tongaonkar, and S. Saha, "YouLighter: A cognitive approach to unveil YouTube CDN and changes," IEEE Trans. Cogn. Commun. Netw., vol.1, no.2, pp.161–174, June 2015.

[6] J. Son, Content networking trends: OTT, Global CDN and Operator, [Online]. Available: http://www.netmanias.com/en/post/reports/6015/cdn-google-netflix-ott-transparent-cache-youtube/2013-content-networking-trends-ott-global-cdn-and-operator-cdn

[7] FCC, Online Table of Frequency Allocations, 2017 [Online]. Available: https://transition.fcc.gov/oet/spectrum/table/fcctable.pdf

[8] E.G. Larsson, O. Edfors, F. Tufvesson, and T.L. Marzetta, "Massive MIMO for next generation wireless systems," IEEE Commun. Mag., vol.52, no.2, pp.186–195, Feb. 2014.

[9] H.H. Yang and T.Q.S. Quek, Massive MIMO Meets Small Cell: Backhaul and Cooperation, Springer, 2017.

[10] A. Asadi, Q. Wang, and V. Mancuso, "A survey on device-to-device communication in cellular networks," IEEE Commun. Surveys Tuts., vol.16, no.4, pp.1801–1819, Fourthquarter 2014.

[11] J. Liu, N. Kato, J. Ma, and N. Kadowaki, "Device-to-device communication in LTE-advanced networks: A survey," IEEE Commun. Surveys Tuts., vol.17, no.4, pp.1923–1940, Fourthquarter 2015.

[12] S. Swain, N. Mishra, S. Rath, and B.P.S. Sahoo, "Spectrum sharing for D2D communication in 5G cellular networks: An auction-based model," 2016 IEEE Annual India Conference (INDICON), Bangalore, 2016.

[13] 3GPP TR 22.803 v12.2.0, Feasibility study for Proximity Services (ProSe) (Release 12).

[14] S. Hakola, T. Chen, J. Lehtomaki, and T. Koskela, "Device-to-device (D2D) communication in cellular network - Performance analysis of optimum and practical communication mode selection," IEEE Wireless Communications and Networking Conference (WCNC), pp.1–6, April 2010.

[15] C.-H. Yu, K. Doppler, C. Ribeiro, and O. Tirkkonen, "Resource sharing optimization for device-to-device communication underlaying cellular networks," IEEE Trans. Wireless Commun., vol.10, no.8, pp.2752–2763, Aug. 2011.

[16] A. Morattab, Z. Dziong, K. Sohraby, and M. Islam, "An optimal MIMO mode selection method for D2D transmission in cellular networks," IEEE 11th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), pp.392–398, Oct. 2015.

[17] A. Al-Rimawi and D. Dardari, "Analytical modeling of D2D communications over cellular networks," IEEE International Conference on Communications (ICC), pp.2117–2122, June 2015.

[18] J. Wang, D. Zhu, C. Zhao, J.C. F. Li, and M. Lei, "Resource sharing of underlaying device-to-device and uplink cellular communications," IEEE Commun. Lett., vol.17, no.6, pp.1148–1151, June 2013.

[19] R. Zhang, X. Cheng, L. Yang, and B. Jiao, "Interference graph-based resource allocation (InGRA) for D2D communications underlaying cellular networks," IEEE Trans. Veh. Technol., vol.64, no.8, pp.3844–3850, Aug. 2015.

[20] H. Sun, M. Wildemeersch, M. Sheng, and T. Quek, "D2D enhanced heterogeneous cellular networks with dynamic TDD," IEEE Trans, Wireless Commun., vol.14, no.8, pp.4204–4218, Aug. 2015.

[21] G. Fodor and N. Reider, "A distributed power control scheme for cellular network assisted D2D communications," IEEE Global Telecommunications Conference (GLOBECOM), pp.1–6, Dec. 2011.

[22] W. Cheng, X. Zhang, and H. Zhang, "Optimal power allocation with statistical QoS provisioning for D2D and cellular communications over underlaying wireless networks," IEEE J. Sel. Areas Commun., vol.34, no.1, pp.151–162, Jan. 2016.

[23] N. Lee, X. Lin, J. Andrews, and R. Heath, "Power control for D2D underlaid cellular networks: Modeling, algorithms, and analysis," IEEE J. Sel. Areas Commun., vol.33, no.1, pp.1–13, Jan. 2015.

[24] J.M.B. da Silva and G. Fodor, "A binary power control scheme for D2D communications," IEEE Wireless Commun. Lett., vol.4, no.6, pp.669–672, Dec. 2015.

[25] 3GPP R1-141387, Frame Structure for D2D-Enabled LTE Carriers.

Bang Chul Jung received the B.S. degree in Electronics Engineering from Ajou University, Suwon, Korea, in 2002 and the M.S. and Ph.D. degrees in Electrical & Computer Engineering from Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea, in 2004 and 2008, respectively. He was a senior researcher/research professor with KAIST Institute for Information Technology Convergence, Daejeon, Korea, from January 2009 to February 2010. He is now an associate professor of Department of Electronics Engineering, Chungnam National University, Korea. Dr. Jung was the recipient of the 5th IEEE Communication Society Asia-Pacific Outstanding Young Researcher Award in 2011. His research interests include wireless communications, statistical signal processing, information theory, compressed sensing, interference management, MIMO, multiple access techniques, and radio resource management.

Tae-Won Ban received his B.S. and M.S. degrees in the Department of Electronic Engineering, Kyungpook National University, Korea, in 1998 and 2000, respectively, and the Ph.D. degree in the Department of Electrical and Electronic Engineering, Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea, in 2010. He was researcher and network engineer in Korea Telecom (KT) from 2000 to 2012. In KT, he researched 3G WCDMA, LTE, and Femto systems. He was also responsible for traffic engineering and spectrum strategy. Now, he is an associate professor of Department of Information and Communication Engineering, Gyeongsang National University, Korea. His current research interests include OFDM, MIMO, radio resource management for mobile communication systems, cognitive radio, and relay systems.