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On the Link Scheduling for Cellular-Aided Device-to-Device Networks

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***Abstract*—We consider a cellular-aided *inband overlay* device-to-device (D2D) network, where a base station (BS) and all devices share a frequency band for their communications, but the BS allocates dedicated radio resources to D2D direct communications to avoid the mutual interference between D2D and cellular communications. We first mathematically formulate the optimal sum rate of the D2D network, and provide closed-form approximations of the average sum rate for low and high signal-to-noise ratio (SNR) regimes. Furthermore, we propose two practical D2D link scheduling algorithms: centralized and distributed. The centralized algorithm reduces the computational complexity at the BS, and its performance is shown to be optimal since the SNR of D2D links tends to be either zero or infinity. The distributed algorithm significantly reduces the signaling overhead caused by channel state information feedback from devices to the BS, and the performance loss of the distributed algorithm is marginal compared with that of the centralized algorithm, particularly when the number of D2D pairs is small.**

***Index Terms*—Cellular networks, device-to-device (D2D) direct communications, interference management, link scheduling, overlay D2D networks.**

I. INTRODUCTION

Recently, cellular-aided device-to-device (D2D) direct communication has been attracting much interest due to the following promising benefits. First, the D2D direct communication extends the coverage of cellular networks without adding infrastructure, such as base stations (BSs) and repeaters [1]. Thus, the Federal Communications Commission has specified a requirement that public safety networks should support the D2D direct communication and has selected the Long-Term Evolution (LTE) standard as a public safety network [2]. Second, the D2D direct communication provides data services with a higher data rate, lower delay, and lower power consumption than conventional cellular communications [3]. Third, it improves spectral efficiency by increasing the spatial reuse gain, allowing simultaneous transmissions of multiple D2D communication pairs within the coverage of cellular networks. Motivated by these advantages of D2D direct communication, the Third-Generation Partnership Project (3GPP) started to standardize the D2D direct communication, which is called proximity-based services (ProSe) [4].

On the other hand, many academic studies have been carried out on the D2D communication based on underlay [5]–[8] and overlay

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Manuscript received October 2, 2014; revised August 14, 2015 and November 23, 2015; accepted January 11, 2016. Date of publication January 19, 2016; date of current version November 10, 2016. This work was supported by the Institute for Information and Communications Technology Promotion, Ministry of Science, ICT and Future Planning of Korea through the ICT R&D Program under Grant B0101-15-1272 (Development of Device Collaborative Giga-Level Smart Cloudlet Technology). The review of this paper was coordinated by Dr. I. Krikidis. *(Corresponding author: Bang Chul Jung.)*

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Digital Object Identifier 10.1109/TVT.2016.2519461

strategies [9], [10]. Underlay D2D communication shares the radio resources of the cellular network; thus, interference may occur between the D2D and cellular communication links. In the overlay strategy, the radio resources occupied by D2D communications are not used for cellular communications. An optimal communication mode selection at devices between cellular and D2D communications was proposed [5]. Several resource-sharing techniques, including frequency resource and power allocation, were proposed, considering the interference among D2D communication links and cellular communication links [6]–[8]. Contrary to the studies on the underlay D2D communication strategies, a resource-allocation technique for overlay D2D communications was proposed, which is called FlashLinQ [9]. In the FlashLinQ scheme, the D2D communication link with high priority is always scheduled, whereas the links with low priority are scheduled only when they do not cause excessive damage to the high-priority link. However, the optimality of its achievable performance was not fully investigated. An analytical assessment of cellular-aided inband overlay D2D communications was carried out based on stochastic geometry, and it was also shown that coordinated scheduling of D2D transmissions by cellular infrastructure can enhance system performance both in terms of average user rate and maximum allowable D2D link distance [10]. A new frame structure for LTE-based inband overlay D2D communications was proposed [11], and the coexistence and multiplexing between D2D and cellular communications were investigated in [12] and [13], respectively. Although the underlay D2D is a promising technology, the overall network performance can seriously deteriorate, and the quality of service of cellular communications cannot be guaranteed if interference mitigation schemes are not adequately adopted [5]. The interference mitigation schemes include mode selection, power control, multiple-input–multiple-output schemes, etc. Unfortunately, most of these interference mitigation schemes are not feasible for D2D communications because of mobility of devices and the heavy burden of signaling between D2D and cellular networks [14]. Motivated by this practical problem, in this paper, we consider the overlay-based cellular D2D to completely protect the cellular communication.

First, we mathematically formulate the achievable sum rate of an overlay D2D network, and provide *closed-form approximations* of the average sum rate for low and high signal-to-noise ratio (SNR) regimes. Furthermore, we propose two practical D2D link scheduling algorithms: a centralized scheme that reduces the computational complexity at a BS and a distributed scheme that reduces the signaling overhead from devices to a BS. The centralized scheme is shown to achieve the optimal sum rate for low- and high-SNR regimes. To the best of our knowledge, no such study has been conducted so far. The remainder of this paper is organized as follows. In Section II, system model is described. In Section III, the performance of cellular-aided D2D optimal scheduling algorithm is investigated in terms of average sum rate. In Section IV, centralized and distributed D2D scheduling algorithms are proposed. Our numerical results are shown in Section V, and conclusions are drawn in Section VI.

II. SYSTEM MODEL

We deal with a cellular-aided *inband overlay* D2D communication network [15], where all devices are associated with a BS for cellular data services and the BS controls all D2D communications occurring within its coverage in terms of pairing and scheduling. Although all devices share the same frequency band for the cellular data services, some radio resources in the frequency band are dedicated to the D2D communications to avoid the interference between the cellular and D2D communication links. Although the D2D communications can share either the uplink or downlink frequency band of a cellular network, uplink is more likely to be shared than downlink [7], [16]. Thus, the reference signals of the cellular uplink can also be used for channel estimation in the D2D communications.

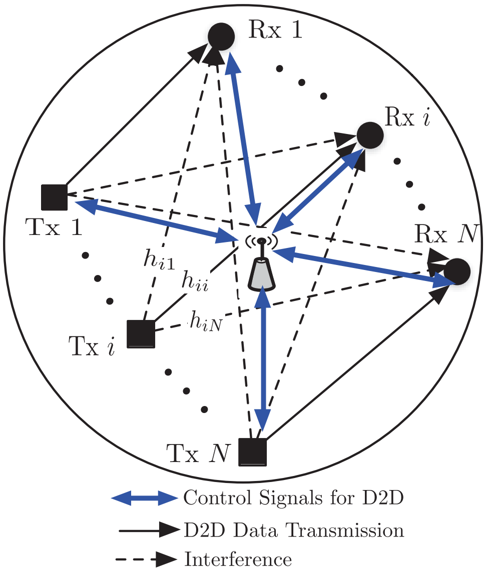

Fig. 1. Cellular-aided inband overlay D2D communication network.

Fig. 1 shows the system model considered in this paper. We assume that there exist N D2D pairs in a cell.[1] Let the channel coefficient between transmitter i and receiver j be h_{ij}, which is complex normally distributed with zero mean and variance λ_{ij}. We assume a block fading where each channel coefficient remains fixed but independently changes over transmission blocks. The effect of path loss can be incorporated into the variance λ_{ij} for mathematical simplicity. All D2D receivers are assumed to estimate all channel coefficients from transmitters through reference signals.

We define a decimal number $d(0 \leq d \leq 2^N - 1)$ with corresponding N binary digits and then the ith binary digit, $b_i(d)$ $(1 \leq i \leq N)$, is defined as

$$b_i(d) = \begin{cases} 1, & \text{if transmitter } i \text{ is allowed to transmit} \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

which can explicitly represent the activeness of D2D pair i and is determined by a link scheduling algorithm. For a given d, $\mathbf{1}(d) \triangleq \sum_{i=1}^{N} b_i(d)$ denotes the number of D2D pairs to transmit data simultaneously and the signal-to-noise-plus-interference ratio (SINR) at the D2D receiver i, γ_i^d, is expressed as

$$\begin{aligned} \gamma_i^d &= \frac{b_i(d) P |h_{ii}|^2}{\sum_{k=1,k\neq i}^{N} b_k(d) P |h_{ki}|^2 + N_0} \\ &= \frac{b_i(d) \rho |h_{ii}|^2}{\sum_{k=1,k\neq i}^{N} b_k(d) \rho |h_{ki}|^2 + 1} \end{aligned} \tag{2}$$

where P and N_0 denote the transmit power of D2D transmitters and the thermal noise variance at D2D receivers, respectively. ρ defined as P/N_0 denotes the *transmit* signal-power-to-noise-power ratio of D2D

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[1] We assume that all D2D devices have been associated with their partners based on the user's requirement, proximity, and channel quality, etc., prior to D2D communications. Thus, the pairing issue is beyond the scope of this paper.

devices and hereafter is referred to as SNR without loss of generality. In addition, it is assumed that all devices have an identical SNR.

The sum rate of the D2D network for the given d is represented as

$$C^d = \sum_{i=1}^{N} \log_2 \left(1 + \gamma_i^d\right). \tag{3}$$

III. SUM-RATE ANALYSIS OF DEVICE-TO-DEVICE NETWORK

A. Optimal Sum Rate

If the channel gains from all transmitters to receivers can be estimated by the receivers and the receivers feed them to a BS, the BS can determine the optimal D2D pair set in terms of sum rate for data transmission. The optimal sum rate is given by

$$C_{\text{opt}} = \max_{1 \le d \le 2^N - 1} C^d \tag{4}$$

where the number of transmitting devices can vary from 1 to N, and the solution can be obtained only by an exhaustive searching algorithm due to the nonconvexity of the objective function.

B. Sum-Rate Approximations

Although the closed-form solution of (4) cannot be obtained, it can be approximated for asymptotically low and high SNR[2] regimes, and the corresponding optimal average sum rates can be obtained.

If ρ is asymptotically low, the sum rate in (3) can be approximated by

$$C^d = \sum_{i=1}^{N} \log_2 \left(1 + \frac{b_i(d)\rho|h_{ii}|^2}{\sum_{k=1,k\neq i}^{N} b_k(d)\rho|h_{ki}|^2 + 1}\right) \tag{5}$$

$$\approx \sum_{i=1}^{N} \log_2 \left(1 + b_i(d)\rho|h_{ii}|^2\right) \tag{6}$$

where (6) is valid because the interference $\sum_{k=1,k\neq i}^{N} b_k(d)\rho|h_{ki}|^2$ becomes negligible, compared with 1, as $\rho \to 0$, and (6) can be maximized when $b_i(d) = 1\ \forall i$. Thus, if we allow all D2D pairs to transmit data $(b_i(d) = 1\ \forall i)$, we can achieve the optimal sum rate defined by

$$C_{\text{opt}}^{\text{low}} \triangleq \sum_{i=1}^{N} \log_2 \left(1 + \rho|h_{ii}|^2\right). \tag{7}$$

If ρ is asymptotically high and multiple D2D pairs transmit data $(\mathbf{1}(d) \ge 2)$, the corresponding sum rate, $C^{d,\mathbf{1}(d)\ge 2}$, can be approximated by

$$C^{d,\mathbf{1}(d)\ge 2} \approx \sum_{i=1}^{N} \log_2 \left(1 + \frac{b_i(d)\rho|h_{ii}|^2}{\sum_{k=1,k\neq i}^{N} b_k(d)\rho|h_{ki}|^2}\right) \tag{8}$$

$$= \sum_{i=1}^{N} \log_2 \left(1 + \frac{b_i(d)|h_{ii}|^2}{\sum_{k=1,k\neq i}^{N} b_k(d)|h_{ki}|^2}\right). \tag{9}$$

On the other hand, if an arbitrary D2D transmitter i transmits data alone ($\mathbf{1}(d) = 1$ and $b_i(d) = 1$, there exists no interference, and the corresponding data rate $C^{d,\mathbf{1}(d)=1}$ is given by

$$C^{d,\mathbf{1}(d)=1} = \log_2 \left(1 + \rho|h_{ii}|^2\right). \tag{10}$$

$C^{d,\mathbf{1}(d)=1}$ in (10) tends to be larger than $C^{d,\mathbf{1}(d)\ge 2}$ in (9) because $C^{d,\mathbf{1}(d)=1}$ becomes infinity as ρ goes to infinity, whereas $C^{d,\mathbf{1}(d)\ge 2}$ in (9) becomes constant for given channel gains. When $\sum_{k=1,k\neq i}^{N} b_k(d)|h_{ki}|^2$ in (9) becomes zero, $C^{d,\mathbf{1}(d)\ge 2}$ also becomes infinity. However, the probability of this event is equal to zero. Thus, we should allow only one D2D pair to transmit data for higher sum rate. Finally, if we select the D2D pair s with the highest channel gain as follows:

$$s = \arg\max_{1 \le i \le N} |h_{ii}|^2 \tag{11}$$

then we can achieve the optimal data rate given by

$$\begin{aligned} C_{\text{opt}}^{\text{high}} &\triangleq \log_2 \left(1 + \rho|h_{ss}|^2\right) \\ &\approx \log_2 \left(\rho|h_{ss}|^2\right). \end{aligned} \tag{12}$$

In addition, if we assume that all channels are identically and independently distributed (i.i.d.) and have unit variance, i.e., $\lambda_{ij} = 1$ for all i and j values, (7) and (12) can be simply averaged as

$$\mathbb{E}\left[C_{\text{opt}}^{\text{low}}\right] = N \cdot \mathbb{E}\left[\log_2 \left(1 + \rho|h_{ii}|^2\right)\right] = \frac{N e^{\frac{1}{\rho}} E_1\left(\frac{1}{\rho}\right)}{\ln(2)} \tag{13}$$

$$\begin{aligned} \mathbb{E}\left[C_{\text{opt}}^{\text{high}}\right] &= \mathbb{E}\left[\log_2 \left(1 + \rho \cdot \max_{1 \le i \le N} |h_{ii}|^2\right)\right] \\ &\approx \mathbb{E}\left[\log_2 \left(\rho \cdot \max_{1 \le i \le N} |h_{ii}|^2\right)\right] \\ &= \frac{N}{\rho} \int_0^\infty \log_2(x) e^{-\frac{x}{\rho}} \left(1 - e^{-\frac{x}{\rho}}\right)^{N-1} dx \\ &= \frac{N}{\rho} \int_0^\infty \log_2(x) e^{-\frac{x}{\rho}} \sum_{k=0}^{N-1} \binom{N-1}{k} (-1)^k e^{-\frac{kx}{\rho}} dx \\ &= \frac{N}{\rho} \sum_{k=0}^{N-1} \binom{N-1}{k} (-1)^k \int_0^\infty \log_2(x) e^{-\frac{(k+1)x}{\rho}} dx \\ &= \frac{N}{\ln 2} \sum_{k=0}^{N-1} \binom{N-1}{k} (-1)^{k+1} \frac{\eta - \ln(\rho) + \ln(k+1)}{k+1} \\ &= \log_2(\rho) - \frac{\eta}{\ln 2} + \frac{N}{\ln 2} \sum_{k=0}^{N-1} \binom{N-1}{k} \frac{(-1)^{k+1} \ln(k+1)}{k+1} \end{aligned} \tag{14}$$

where $E_1(\cdot)$ denotes an exponential integral function [17], and η denotes the Euler–Mascheroni constant ($\eta \approx 0.5772$).

IV. PROPOSED LINK-SCHEDULING ALGORITHMS

A. BS-Assisted Centralized Scheduling

The optimal D2D link scheduling described in (3) and (4) demands exhaustive searching to determine the set of transmitting devices; thus, it involves tremendous computation complexity at the BS. The number of iterations required to find the optimal set of D2D pairs to transmit is given by $(2^N - 1)$, and it exponentially grows as N increases. Here, we thus propose a BS-assisted centralized scheduling algorithm to reduce the computational complexity at the BS. First, N D2D pairs are sorted in descending order according to $|h_{ii}|^2$ $(1 \le i \le N)$. The sorted D2D pairs are identified by $\hat{i}$. The BS carries out up to N iterations to determine the set of D2D pairs to transmit data. In the kth iteration $(1 \le k \le N)$, the BS computes SINRs for D2D pairs from $\hat{1}$ to $\hat{k}$ and the corresponding sum rate. If the sum rate is reduced compared with the previous iteration, then the algorithm is terminated while allowing the D2D pairs from $\hat{1}$ to $\widehat{k-1}$ to transmit data. Otherwise, the algorithm proceeds to the next iteration. The proposed scheme is described in more detail in **Algorithm 1**, where $C_{\text{prop-c}}^{k}$ and $C_{\text{prop-c}}^{*}$ denote the achievable sum rates of the proposed centralized algorithm after the kth iteration and after the termination of iterations,

---

[2] Asymptotically low SNR denotes that SNR goes to zero, whereas asymptotically high SNR denotes that SNR goes to ∞.

respectively. $\gamma_{\hat{i}}$, denoting the SINR received at the $\hat{i}$th receiver with the proposed algorithm, is given by

$$\gamma_{\hat{i}} = \begin{cases} \rho|h_{\hat{1}\hat{1}}|^2, & \text{if } k = 1 \\ \frac{\rho|h_{\hat{i}\hat{i}}|^2}{\sum_{j=1, j\neq i}^{k} \rho|h_{\hat{j}\hat{i}}|^2 + 1}, & \text{if } k > 1. \end{cases} \tag{15}$$

Note that the maximal number of iterations required in the proposed scheduling algorithm is equal to N, which is much smaller than $(2^N - 1)$, particularly for large N. Furthermore, we will show that the average number of iterations required in the proposed algorithm becomes much smaller than N as ρ increases through simulations.

The centralized scheme may cause much feedback overhead, although it significantly reduces the computational complexity. In wireless networks, in general, more robust modulation and coding schemes are used for the feedback signals than data signals because feedback errors may seriously degrade performances of the network [18]. Hence, many studies in wireless network have assumed that the feedback signal is error free. In this paper, we also assume that the feedback information is transmitted without errors. The feedback signals can be transmitted to base station via dedicated frequency band separated from data signal, and the period of the feedback signals may depend on the coherence time of wireless channels or the trade-off between the feedback overhead and the performance.

Algorithm 1 BS-Assisted Centralized Scheduling

```
Sort $|h_{ii}|^2$ in descending order such that
    $|h_{\hat{1}\hat{1}}|^2 \geq |h_{\hat{2}\hat{2}}|^2 \geq \cdots \geq |h_{\hat{N}\hat{N}}|^2$
Initialize: $C^0_{\mathrm{prop-c}} = 0$
for $k = 1$ to $N$ do
    for $i = 1$ to $k$ do
        Compute SINR for $\hat{i}$th device, $\gamma_{\hat{i}}$
    end for
    Compute the achievable sum-rate of the selected $k$ D2D pairs from $\hat{1}$ to $\hat{k}$, $C^k_{\mathrm{prop-c}}$
        $C^k_{\mathrm{prop-c}} = \sum_{\hat{i}=1}^{k} \log_2(1 + \gamma_{\hat{i}})$
    if $C^k_{\mathrm{prop-c}} < C^{k-1}_{\mathrm{prop-c}}$ then
        break
    else
        $t = k$
    end if
end for
D2D pair set is determined as $\{\hat{1}, \ldots, \hat{t}\}$ and $C^*_{\mathrm{prop-c}} = C^t_{\mathrm{prop-c}}$
```

Theorem 1: When ρ is asymptotically low or high, the proposed centralized scheduling algorithm achieves $C^{\mathrm{low}}_{\mathrm{opt}}$ or $C^{\mathrm{high}}_{\mathrm{opt}}$, respectively.

Proof: The sum rates in the kth iteration of the proposed centralized scheduling algorithm for $k = 1$ and $k \geq 2$ can be obtained, respectively, by

$$C^{k=1}_{\mathrm{prop-c}} = \log_2\left(1 + \rho|h_{\hat{1}\hat{1}}|^2\right) \tag{16}$$

$$C^{k\geq 2}_{\mathrm{prop-c}} = \sum_{\hat{i}=1}^{k} \log_2(1 + \gamma_{\hat{i}}). \tag{17}$$

When ρ is asymptotically low, $C^{k\geq 2}_{\mathrm{prop-c}}$ in (17) can be approximated by

$$C^{k\geq 2}_{\mathrm{prop-c}} \approx \sum_{\hat{i}=1}^{k} \log_2\left(1 + \rho|h_{\hat{i}\hat{i}}|^2\right). \tag{18}$$

Based on (16) and (18), $C^k_{\mathrm{prop-c}}$ monotonically increases for k. Thus, the proposed algorithm terminates at $k = N$ without an intermediate break, while yielding

$$\begin{aligned} C^*_{\mathrm{prop-c}} &= C^N_{\mathrm{prop-c}} \\ &= C^{\mathrm{low}}_{\mathrm{opt}}. \end{aligned} \tag{19}$$

On the other hand, when ρ is asymptotically high, $C^{k\geq 2}_{\mathrm{prop-c}}$ in (17) can be approximated by

$$C^{k\geq 2}_{\mathrm{prop-c}} \approx \sum_{\hat{i}=1}^{k} \log_2\left(1 + \frac{|h_{\hat{i}\hat{i}}|^2}{\sum_{j=1, j\neq i}^{k} |h_{\hat{j}\hat{i}}|^2}\right) \tag{20}$$

and thus $C^{k=2}_{\mathrm{prop-c}}$ can be approximated by

$$C^{k=2}_{\mathrm{prop-c}} \approx \log_2\left(1 + \frac{|h_{\hat{1}\hat{1}}|^2}{|h_{\hat{2}\hat{1}}|^2}\right) + \log_2\left(1 + \frac{|h_{\hat{2}\hat{2}}|^2}{|h_{\hat{1}\hat{2}}|^2}\right). \tag{21}$$

$C^{k=1}_{\mathrm{prop-c}}$ in (16) is larger than $C^{k=2}_{\mathrm{prop-c}}$ in (21) with a high probability because $C^{k=1}_{\mathrm{prop-c}}$ becomes also infinity as ρ goes to infinity, whereas $C^{k=2}_{\mathrm{prop-c}}$ remains constant; thus, the proposed algorithm always terminates at $k = 2 (t = 1)$, while yielding

$$\begin{aligned} C^*_{\mathrm{prop-c}} &= C^1_{\mathrm{prop-c}} \\ &= C^{\mathrm{high}}_{\mathrm{opt}}. \end{aligned} \tag{22}$$

Equations (19) and (22) complete the proof. ■

Remark 1: In the proposed BS-assisted centralized scheduling algorithm, all D2D pairs are selected when SNR asymptotically tends to zero, but a single D2D pair with the highest received SNR is selected when SNR asymptotically tends to infinity.

B. Fully Distributed Scheduling

Although the proposed centralized scheduling algorithm in Section IV-A can reduce the computational complexity at the BS by avoiding the exhaustive search, it still requires significant feedback overhead from the devices to the BS in order to compute $\gamma_{\hat{i}}$ $(1 \leq \hat{i} \leq N)$ at the BS. Hence, we also propose a fully distributed D2D link-scheduling algorithm that does not require any feedback.

Transmitter i measures an instantaneous channel gain from its receiver i, h_{ii}, and starts a timer that is inversely proportional to $|h_{ii}|^2$ as in [19]. If we define $s = \arg\max_{1\leq i\leq N} |h_{ii}|^2$, the timer of the transmitter s will expire first. The transmitter s has a priority to transmit data and transmits a short *indicator* packet to its receiver. While waiting for their timers to expire, all transmitters stay in the listening mode. As soon as they receive the *indicator* packet from the transmitter s, they stop their timers. The receiver s then responds to the *indicator* packet by sending the *acknowledgement* packet. $(N - 1)$ transmitters, except for the transmitter s can measure channels from the receiver s by listening for the *acknowledgement* packet. If the transmitter $i (1 \leq i \leq N, i \neq s)$ satisfies the following criterion:

$$\frac{|h_{ii}|^2}{|h_{is}|^2} \geq \delta \tag{23}$$

then it is allowed to transmit data at the same time with the transmitter s. δ denotes a predetermined threshold that is assumed to be sent by BS. The sum rate of the D2D network may vary according to δ; thus, δ needs to be carefully chosen.

As for the implementation of the fully distributed algorithm in practice, the time-varying nature of wireless channels may affect the performance of the proposed algorithm. If we know the coherence time of the wireless channel, then it is possible to design for each timer of D2D devices expire within the coherence time. To be specific, the range of timer value becomes set by particular parameters (i.e., $T_{\min}$

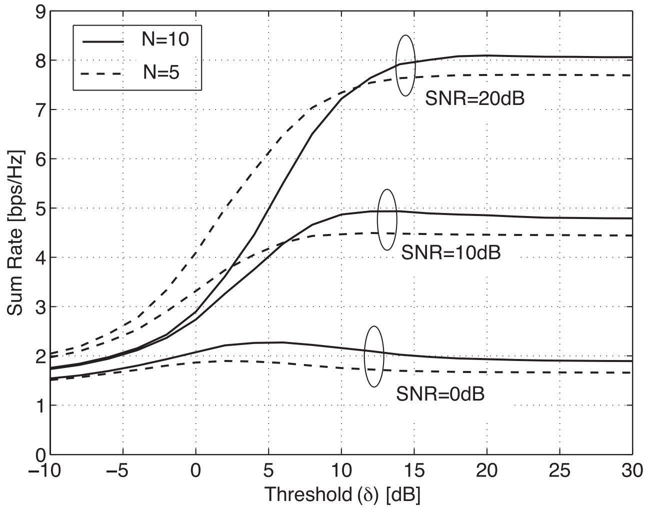

Fig. 2. Average sum rates of the distributed D2D link-scheduling algorithm according to δ for i.i.d. channels when $N = 5$, 10, and SNR = 0, 10, 20 dB.

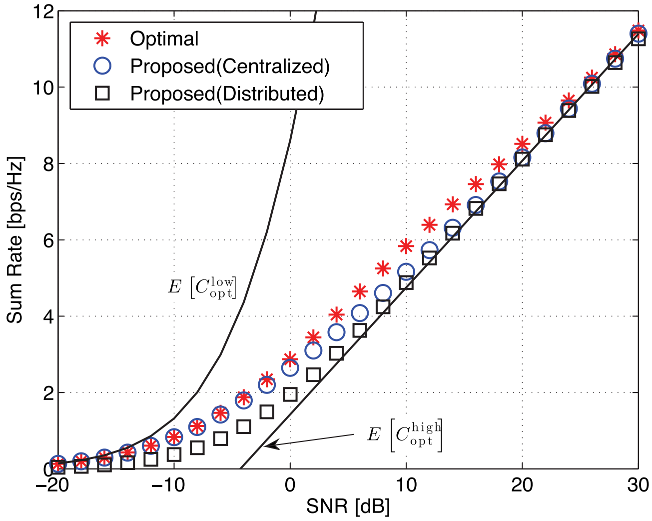

Fig. 3. Average sum rates of the proposed D2D link scheduling algorithms according to ρ for i.i.d. channels when $N = 10$ and $\delta = 20$ dB.

and $T_{\max}$), although the value varies according to channel gain $|h_{ii}|^2$. For example, let the timer value for a given $|h_{ii}|^2$ be

$$T_{\min}\left(1-e^{-|h_{ii}|^2}\right)+T_{\max}e^{-|h_{ii}|^2}. \tag{24}$$

Then, $|h_{ii}|^2 \to 0$, the timer goes to $T_{\max}$. As $|h_{ii}|^2 \to \infty$, the timer goes to $T_{\min}$. Thus, we can adaptively design for the timer to expire within the coherence time of the wireless channel and the effect of time-varying channel on the performance of the distributed link-scheduling algorithm can be resolved.

V. NUMERICAL RESULTS

Fig. 2 shows the sum rates of the distributed D2D link scheduling algorithm for varying δ. It is assumed that channels are i.i.d., $N = 5$ or 10, and SNR = 0, 10, or 20 dB. It is shown that the sum rate of the proposed distributed D2D link-scheduling algorithm is affected by δ. As N or SNR increases, the interference among D2D pairs also increases; thus, the optimal value of δ tends to increase to reduce the number of D2D pairs transmitting data simultaneously. Although the sum rate of the distributed algorithm can be enhanced by optimizing δ according to channel gains and SNR values, δ is set to a constant 20 dB for simplification in this paper.

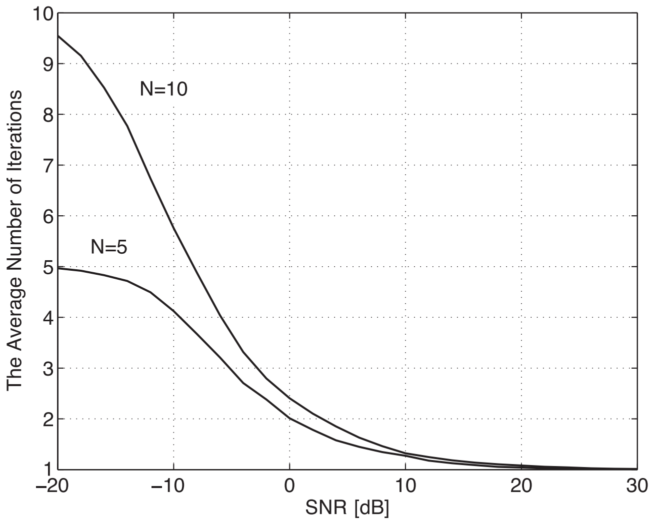

Fig. 4. Average number of iterations required in the proposed centralized D2D link-scheduling algorithm for i.i.d. channels.

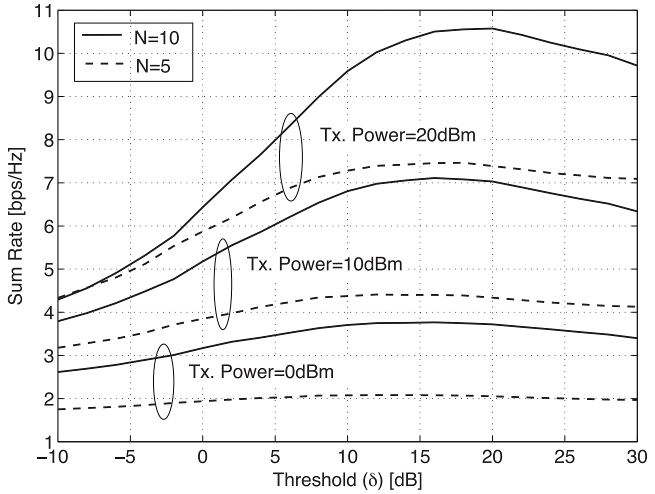

Fig. 5. Average sum rates of the distributed D2D link scheduling algorithm according to δ for non-i.i.d. channels when $N = 5$, 10, $R = 200$ m, and transmit power = 0, 10, 20 dBm.

Fig. 3 shows the average sum rates of the proposed D2D link scheduling algorithms for varying the SNR values when all channel gains are i.i.d. The channel gains have unit variance, $N = 10$, and $\delta = 20$ dB. The optimal sum rate obtained by exhaustive searching is also shown for comparison. The sum-rate approximations in (13) and (14) match well with the simulation results when SNR is low or high. It is observed that the proposed BS-assisted centralized D2D link scheduling algorithm achieves a near-optimal performance, regardless of the SNR values. Furthermore, the proposed fully distributed D2D link-scheduling algorithm also achieves a near-optimal performance when SNR is asymptotically low or high.

Fig. 4 shows the average number of iterations required in the proposed centralized D2D link-scheduling algorithm for i.i.d. channels. Note that the number of iterations decreases as SNR increases; thus, the proposed algorithm operates with a significantly reduced complexity at BS.

Along with the i.i.d. channels, we also consider non-i.i.d. channels to verify the feasibility of the proposed schemes in practical cellular networks. N D2D pairs ($2N$ nodes) are uniformly distributed within

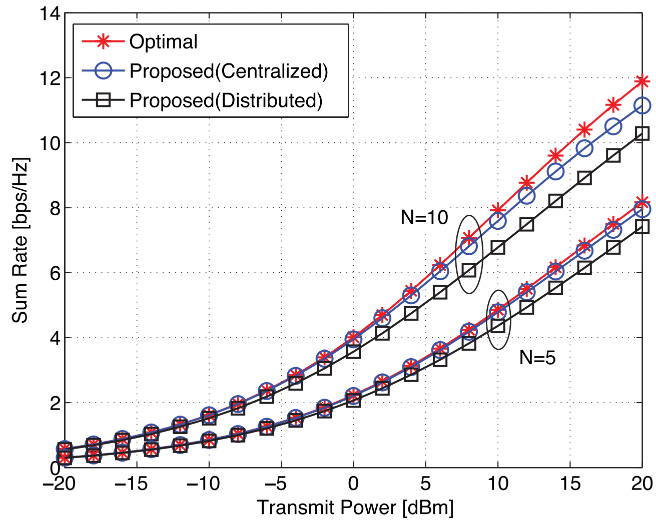

Fig. 6. Average sum rates for non-i.i.d. channels according to transmit power when $N = 5$, 10, $R = 200$ m, and $\delta = 20$ dB.

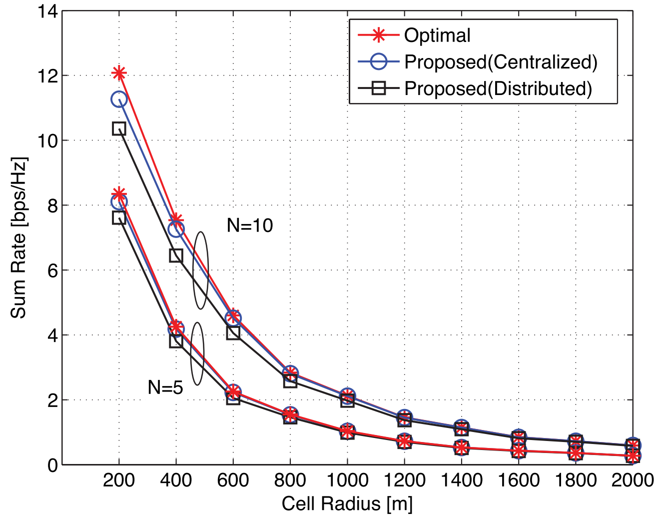

Fig. 7. Average sum rates for non-i.i.d. channels according to cell radius, when $N = 5$, 10, $\delta = 20$ dB, and transmit power = 20 dBm.

a circle with a radius R. λ_{ij} is determined by $(\max(\alpha, \alpha r_{ij}^{\beta}))^{-1}$, where $\alpha, r_{ij} (0 \le d_{ij} \le 2R)$, and β denote the minimum coupling loss between two nodes, the distance between transmitter i and receiver j, and the path-loss exponent, respectively. It is assumed that $\alpha = 40$ dB, $\beta = 4$, the channel bandwidth is 10 MHz, and the noise spectral density is -174 dBm/Hz. Fig. 5 shows the effect of δ on the proposed distributed algorithm in the non-i.i.d. channels. $R = 200$ m, $N = 5$ or 10, and transmit power = 0, 10, or 20 dBm. Similarly as in the i.i.d. channels, the optimal value of δ tends to increase as N or transmit power increases.

Fig. 6 shows the average sum rates of D2D link-scheduling algorithms for the non-i.i.d. channels. $N = 5$ or 10, $R = 200$ m, and the transmit power of D2D nodes varies from -20 to 20 dBm. It is observed that the average sum rate of the proposed D2D link-scheduling algorithms approaches that of the optimal scheme even in the non-i.i.d. practical channels. Finally, Fig. 7 shows the effect of cell radius R on average sum rates of the D2D link-scheduling algorithms. $N = 5$ or 10, $\delta = 20$ dB, and the transmit power of D2D nodes is 20 dBm. As R increases, the average sum rates for all algorithms tend to decrease because the average distance between D2D transmitter and receiver tends to increase. Furthermore, the performance gap between the proposed algorithms and the optimal algorithm becomes negligible.

VI. CONCLUSION

In this paper, we investigated a scheduling problem for a cellular-aided inband overlay D2D network. First, we analyzed the optimal average sum rate of D2D scheduling based on an exhaustive searching algorithm and derived the approximated closed-form solutions for the optimal average sum rate in low- and high-SNR regions. In addition, we proposed a suboptimal D2D scheduling scheme to reduce the computational complexity in the BS and a distributed D2D scheduling scheme to remove the channel feedback overhead. It was shown that the suboptimal scheme can achieve a near-optimal sum rate with significantly reduced computational complexity, and it can achieve the optimal sum rate when SNR is asymptotically low or high. In addition, the performance gap between the centralized and distributed D2D scheduling schemes is marginal, particularly for small N value. Finally, both the suboptimal and distributed schemes can achieve performance comparable to the optimal scheme even in non-i.i.d. channels.

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