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Pilot reuse and power control of D2D underlaying massive MIMO systems for energy efficiency optimization

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Abstract It is predicted that there will be billions of machine type communication (MTC) devices to be deployed in near future. This will certainly cause severe access congestion and system overload which is one of the major challenges for the proper operation of 5G networks. Adopting device-to-device (D2D) communications into massive multiple-input multiple-output (MIMO) systems has been considered as a potential solution to alleviate the overload of MTC devices by offloading the MTC traffic onto D2D links. This work proposes a novel pilot reuse (PR) and power control (PC) for energy efficiency (EE) optimization of the uplink D2D underlaying massive MIMO cellular systems. Although the use of large scale antenna array at the base station (BS) can eliminate most of the D2D-to-Cellular interference, the Cellular-to-D2D interference and the channel estimation error caused by PR will remain significant. Motivated by this, and in order to reduce the channel estimation error, in this paper a novel heuristic PR optimum pilot reuse scheme is proposed for D2D transmitters (D2DTs) selection. By taking into account the interference among users as well as the overall power consumption, the overall system EE is maximized through power optimization while maintaining the quality-of-service (QoS) provisions for both cellular users (CUEs) and D2D pairs. The power optimization problem is modeled as a non-cooperative game and, as such, a distributed iterative power control algorithm which optimizes users' power sequentially is proposed. Various performance evaluation results obtained by means of computer simulations have shown that the proposed PR scheme and PC algorithm can significantly increase the overall system EE.

Keywords device-to-device (D2D), massive MIMO, energy efficiency (EE), pilot reuse (PR), power control (PC)

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1 Introduction

Accounting for the rapid growth of various Internet of Things (IoT) applications, machine type communication (MTC) has become an emerging technology for connecting generic machines to the Internet. Recent studies foresee that the number of connected MTC devices is expected to exceed 28 billion by

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2021 [1]. With such a huge number of devices being planned to be deployed in future 5G networks, the access congestion and system overload will become a major challenge which must be rather urgently dealt with. Therfore, some essential support should be provided for MTC in 5G networks.

Device-to-device (D2D) communication underlaying cellular networks is considered as one of the key technologies for 5G communication systems [2]. For this technology, D2D users (DUEs) directly communicate with each other by reusing the cellular users' (CUEs) resources [3]. Due to its short communication distance, it can naturally reduce the communication delay and the power consumption [4]. For MTC devices which are deployed in close proximity to the DUEs, the DUEs can act as the machine type gateways (MTG) and collect all the data from the MTC devices and relay them through D2D links [5, 6]. Furthermore, MTC devices communicating directly through a D2D connection has been considered as an important type of MTC architecture [7], since offloading MTC traffic onto D2D links can help to manage the spectrum access and reduce the power consumption of MTC devices. Another promising technology being recognized as one of the candidates for 5G systems is massive multiple-input multiple-output (MIMO) [2]. Compared to traditional wireless technologies, massive MIMO systems can greatly increase the network capacity and energy-efficiency (EE) by employing a large number of antennas at the base station (BS) [8–10]. The various MTC applications need more reliable cellular network to support the large number of MTC devices, and massive MIMO is capable to provide such support. It is noted that D2D in massive MIMO systems can provide better support for MTC and offer significantly higher EE [11]. As it will be explained in related work, although there exist numerous studies on D2D and massive MIMO, there are relatively few publications which consider both.

To fully explore the potential of MIMO systems, channel state information (CSI) should be known. Pilots assisted channel estimation is a choice for the uplink massive MIMO systems [12]. The length of orthogonal pilots is limited by the duration of channel coherent time. For D2D underlaying massive MIMO systems, if the D2DTs transmit orthogonal pilots together with CUEs, the pilot overhead will be very high. Another possibility is that the same orthogonal pilot sequences are reused among CUEs and D2D pairs, but this will incur channel estimation errors. Furthermore, co-channel interference (CCI) caused by resource sharing is also a serious problem for D2D communication underlaying massive MIMO systems. In contrast to D2D underlaying single-antenna cellular systems, although the large scale antenna array at the BS can effectively suppress D2D-to-Cellular interference in the uplink, Cellular-to-D2D interference not only remains present but also could become even worse [13]. In addition, power consumption is another hot topic in D2D communications since the battery life of mobile devices is always limited. Therefore, for heterogeneous networks, it is important to propose appropriate interference management and power control schemes which optimize the overall system EE, especially when introducing D2D communications into massive MIMO systems.

• Related work

Existing research on power optimization for D2D communications underlaying cellular networks mainly focuses on single-antenna BS scenarios [14–18], and few work considers the large-scale-antenna BS scenarios. For example, by considering channel estimation, Ref. [13] studied the interplay between massive MIMO and underlaid D2D networking and analyzed the spectral efficiency under both perfect and imperfect channel state information (CSI). However, all these works have assumed that the D2DTs transmit orthogonal pilots together with CUEs without taking into account the pilot overhead. If D2D pairs are introduced into massive MIMO systems, pilot reuse should be considered due to the limited length of pilots. Clearly, how to design appropriate pilot reuse schemes is still an open problem which needs to be further investigated.

Furthermore, most of the previous works on pilot reuse for massive MIMO have focused on the multi-cell scenarios, where CUEs in the same cell use orthogonal pilots and the same pilots are reused among CUEs in different cells [9, 19–22]. Besides, pilot reuse among intra-cell CUEs has been investigated in [23–25]. Recently, pilot reuse for D2D communications in massive MIMO systems is also frequently considered. For example, to reduce the large pilot overhead, the authors of [26] have proposed to reuse a set of orthogonal pilots among D2D pairs so that the length of pilots can be reduced and have formulated a power control problem of how to minimize the transmit power of D2D links. However, their work focuses only on investigating the D2D links without taking into account the analysis of the user-BS links. To further reduce the pilot overhead, Ref. [27] proposed a pilot scheduling scheme by allowing D2D users to reuse the pilots with cellular users. This work focused mainly on the analysis of the performance of the sum throughput without considering the power consumption and the possible impact from the channel estimation of D2D links.

Different from the aforementioned works, by jointly considering the pilot overhead and power consumption, in our current work we analyze the effect of pilot reuse and power control on EE optimization in uplink of D2D communications underlaying massive MIMO systems. In doing so, the uplink coherent time is divided into two phases: i) the channel estimation phase and ii) the data transmission phase. During the first phase, the D2D pairs reuse the orthogonal pilots of the CUEs, thus the pilot overhead can be significantly reduced compared to some other orthogonal training schemes. Aiming at reducing the channel estimation error and to improve the overall system EE, a low-complexity pilot reuse (PR) scheme is proposed. MMSE channel estimation scheme is employed to estimate the channels of both user-BS links and D2D links. In addition, in order to reduce the D2D-to-Cellular interference, the pilot powers of CUEs and D2DTs are set to be different according to the optimal power ratio found out through extensive simulation experiments. During the data transmission phase, a MMSE detector is employed at the BS to suppress the D2D-to-Cellular interference. With the goal of improving the overall system EE, a distributed power control algorithm based on noncooperative game is proposed. It is also shown that under the given quality-of-service (QoS) constraints for both CUEs and D2D pairs, a Nash equilibrium can be achieved after sufficient iterations. Intensive simulations are done to verify the performance of the proposed schemes, and results show that the overall system EE is notably enhanced.

The rest of the paper is organized as follows. In Section 2, the system model of D2D underlaying massive MIMO system is introduced. In Section 3, the heuristic pilot reuse (PR) scheme is presented. In Section 4, the distributed power control (PC) algorithm for EE optimization is analyzed. In Section 5, the proposed PR scheme and PC algorithm are evaluated through computational simulations. Finally, the conclusions are drawn in Section 6.

Notations: Bold uppercase letters represent matrices and bold lowercase letters represent vectors. $(\cdot)^*$ and $(\cdot)^{-1}$ denote the Hermitian transpose and the inverse operation, respectively. $\mathcal{CN}(0, \mathbf{A})$ denotes the circular symmetric complex Gaussian distribution with zero mean and covariance $\mathbf{A}$, and $\mathbf{I}_N$ denotes the N-dimensional identity matrix. $\|\cdot\|$ denotes the two-norm and $\mathbb{E}[\cdot]$ denotes the expectation operation.

2 System model

The uplink transmission of a single-cell D2D communications underlaying massive MIMO system is considered, as illustrated in Figure 1. A BS equipped with N antennas is located at the center of the cell serving K single-antenna CUEs and M single-antenna D2D pairs, where $N \gg K + M$. The user sets of CUEs and D2D pairs are represented by $\mathcal{K} = \{1, 2, \ldots, K\}$ and $\mathcal{M} = \{1, 2, \ldots, M\}$, respectively. The channel gain from the ith CUE to BS is modeled as $\sqrt{\beta_i^c}\boldsymbol{h}_i$, where $\{\beta_i^c\}$ are the CUEs' large-scale fading coefficients assumed to be known at the BS, and $\{\boldsymbol{h}_i \in \mathbb{C}^{N\times 1} \sim \mathcal{CN}(0, \mathbf{I}_N)\}$ denote the i.i.d. small-scale fading vectors. Similarly, the channel gain from the jth D2D transmitter (D2DT) to BS is given by $\sqrt{\beta_j^d}\mathbf{g}_j$. In addition, $\sqrt{\beta_{kj}^{cd}}g_{kj}^{cd}$ is introduced to denote the channel gain from the kth CUE to the jth D2D receiver (D2DR), where $\sqrt{\beta_{kj}^{cd}}$ is the large scale fading coefficient and $g_{kj}^{cd} \sim \mathcal{CN}(0, 1)$ is the Rayleigh fast fading coefficients. $\sqrt{\beta_{ij}^{dd}}g_{ij}^{dd}$ is similarly defined for the channel gain from the ith D2DT to the jth D2DR. Furthermore, the uplink coherent time interval, T, is divided into the channel estimation phase and the data transmission phase. It is assumed that the channel gain is constant within one channel coherent interval.

2.1 Uplink channel estimation

Let $\boldsymbol{\Phi} = \{\boldsymbol{\phi}_1, \boldsymbol{\phi}_2, \ldots, \boldsymbol{\phi}_K\} \in \mathbb{C}^{\tau\times K}(\boldsymbol{\phi}_k^*\boldsymbol{\phi}_k = 1,\ \boldsymbol{\phi}_k^*\boldsymbol{\phi}_j = 0)$ denote the pilots set, where $\boldsymbol{\phi}_k$ represents the

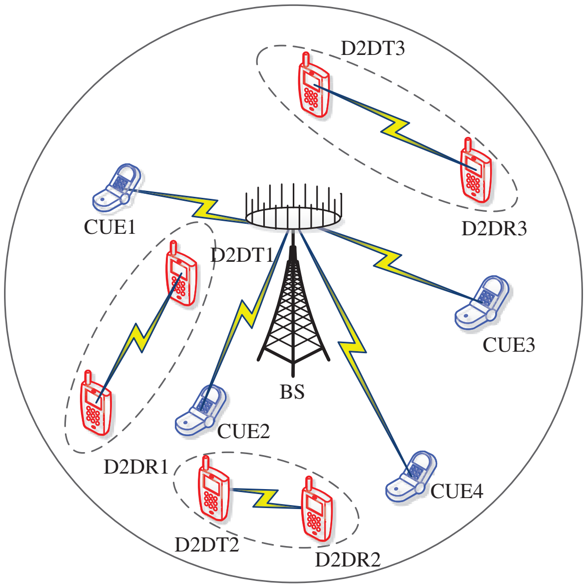

Figure 1 (Color online) System model of D2D underlaying massive MIMO system under consideration.

pilot assigned to the kth CUE and τ is the pilot length. During the channel estimation phase, since all the K orthogonal pilots are assigned to all K CUEs, D2D pairs will reuse the pilots of CUEs. Therefore, the estimated channels of users employing the same pilot will be interfered with each other. Denoting the set of D2D pairs reusing pilot $\boldsymbol{\phi}_k$ as $\mathcal{D}_k$, we have

$$\sum_{k=1}^{K} \mathcal{D}_k = \mathcal{M}, \quad \mathcal{D}_i \cap \mathcal{D}_j = \emptyset \ (i \neq j)\,. \tag{1}$$

The received signal matrix at the BS can be expressed as

$$\boldsymbol{Y} = \sum_{x=1}^{K} \sqrt{P_p^c \beta_x^c}\boldsymbol{h}_x \boldsymbol{\phi}_x^* + \sum_{x=1}^{K} \sum_{j\in\mathcal{D}_x} \sqrt{P_p^d \beta_j^d}\mathbf{g}_j \boldsymbol{\phi}_x^* + \boldsymbol{W}, \tag{2}$$

where P_p^c and P_p^d denote the pilot transmit power of CUEs and D2DTs, respectively, and $\boldsymbol{W}$ is the additive noise matrix whose elements are all i.i.d. complex Gaussian random variables with identical power spectral densities N_0, i.e., $\mathcal{CN}(0, N_0)$.

Similarly, the received signal at the ith D2DR is given by

$$\mathbf{Y}_i^d = \sum_{x=1}^{K} \sum_{j\in\mathcal{D}_x} \sqrt{P_p^d \beta_{ji}^d} g_{ji}^{dd} \boldsymbol{\phi}_x^* + \sum_{x=1}^{K} \sqrt{P_p^c \beta_{xi}^{cd}} g_{xi}^{cd} \boldsymbol{\phi}_x^* + \boldsymbol{n}_i^d, \tag{3}$$

where $\boldsymbol{n}_i^d \sim \mathcal{CN}(0, N_0 \mathbf{I}_\tau)$ represents the noise vector.

At the BS, a MMSE channel estimator is employed and the estimated channel vector of the kth CUE can be found as

$$\widehat{\boldsymbol{h}}_k = \frac{\sqrt{P_p^c \beta_k^c}\mathbf{Y} \boldsymbol{\phi}_k}{N_0 + P_p^c \beta_k^c + P_p^d \sum_{j\in\mathcal{D}_k} \beta_j^d}. \tag{4}$$

Defining $\widetilde{\boldsymbol{h}}_k$ as the estimation error of $\boldsymbol{h}_k$, we have $\widetilde{\boldsymbol{h}}_k = \boldsymbol{h}_k - \widehat{\boldsymbol{h}}_k$. According to the properties of MMSE estimation, $\widehat{\boldsymbol{h}}_k$ is independent of $\widetilde{\boldsymbol{h}}_k$, and their distributions can be mathematically expressed as

$$\widehat{\boldsymbol{h}}_k \sim \mathcal{CN}\left(0, \frac{P_p^c \beta_k^c}{N_0 + P_p^c \beta_k^c + P_p^d \sum_{j\in\mathcal{D}_k} \beta_j^d}\mathbf{I}_N\right) \tag{5a}$$

and

$$\widetilde{\boldsymbol{h}}_k \sim \mathcal{CN}\left(0, \frac{N_0 + P_p^d \sum_{j\in\mathcal{D}_k} \beta_j^d}{N_0 + P_p^c \beta_k^c + P_p^d \sum_{j\in\mathcal{D}_k} \beta_j^d}\mathbf{I}_N\right). \tag{5b}$$

Similarly, by assuming that the pilot ϕ_k is assigned to the ith D2D pair, for a given $\boldsymbol{Y}_i^d$ in (3), the MMSE estimated channel coefficient $\widehat{g}_{ii}^{dd}$ is

$$\widehat{g}_{ii}^{dd} = \frac{\sqrt{P_p^d \beta_{ii}^{dd}} \boldsymbol{Y}_i^d \boldsymbol{\phi}_k}{N_0 + P_p^c \beta_{ki}^{cd} + P_p^d \sum_{n \in \mathcal{D}_k} \beta_{ni}^{dd}}. \tag{6}$$

Similarly, $\widehat{g}_{ii}^{dd}$ is independent of $\widetilde{g}_{ii}^{dd}$, and thus

$$\widehat{g}_{ii}^{dd} \sim \mathcal{CN}\left(0, \frac{P_p^d \beta_{ii}^{dd}}{N_0 + P_p^c \beta_{ki}^{cd} + P_p^d \sum_{n \in \mathcal{D}_k} \beta_{ni}^{dd}}\right) \tag{7a}$$

and

$$\widetilde{g}_{ii}^{dd} \sim \mathcal{CN}\left(0, \frac{N_0 + P_p^c \beta_{ki}^{cd} + P_p^d \sum_{n \in \mathcal{D}_k, n \neq i} \beta_{ni}^{dd}}{N_0 + P_p^c \beta_{ki}^{cd} + P_p^d \sum_{n \in \mathcal{D}_k} \beta_{ni}^{dd}}\right). \tag{7b}$$

All above mentioned estimated channel coefficients or vectors will be used to assist the second time phase data transmission.

2.2 Uplink data transmission

In the data transmission phase, the CUEs and the D2DTs transmit their data to the BS and corresponding D2DRs, respectively.

To detect the signal transmitted from the kth CUE, a matched filter is employed at the BS, i.e.,

$$\boldsymbol{v}_k^c = \widehat{\boldsymbol{h}}_k^*. \tag{8}$$

Let x_i^c and x_j^d represent the normalized transmitted signal of the ith CUE and the jth D2DT, respectively, i.e., $\mathbb{E}\left[x_i^c\right] = \mathbb{E}\left[x_j^d\right] = 1$. Then, the detected signal of the kth CUE can be expressed as

$$\begin{aligned} r_k^{BS} =& \boldsymbol{v}_k^c \left(\sum_{i=1}^K \sqrt{P_i^c \beta_i^c} \boldsymbol{h}_i x_i^c + \sum_{j=1}^M \sqrt{P_j^d \beta_j^d} \mathbf{g}_j x_j^d + \boldsymbol{n}\right) \\ =& \sqrt{P_k^c \beta_k^c} \widehat{\boldsymbol{h}}_k^* \widehat{\boldsymbol{h}}_k x_k^c + \sum_{i \neq k}^K \sqrt{P_i^c \beta_i^c} \widehat{\boldsymbol{h}}_k^* \widehat{\boldsymbol{h}}_i x_i^c + \sum_{i=1}^K \sqrt{P_i^c \beta_i^c} \widehat{\boldsymbol{h}}_k^* \widetilde{\boldsymbol{h}}_i x_i^c + \sum_{j=1}^M \sqrt{P_j^d \beta_j^d} \widehat{\boldsymbol{h}}_k^* \mathbf{g}_j x_j^d + \widehat{\boldsymbol{h}}_k^* \boldsymbol{n}, \end{aligned} \tag{9}$$

where P_i^c and P_j^d are the transmit power of the ith CUE and the jth D2DT, respectively, and $\boldsymbol{n} \sim \mathcal{CN}\left(0, \mathbf{I}_N\right)$ denotes the additive noise vector at the BS. Therefore, the signal-to-interference-plus-noise (SINR) at the kth CUE can be calculated as follows:

$$\begin{aligned} \mathrm{SINR}_k^c &= \frac{P_k^c \beta_k^c |\widehat{\boldsymbol{h}}_k^* \widehat{\boldsymbol{h}}_k|^2}{\sum_{i \neq k}^K P_i^c \beta_i^c |\widehat{\boldsymbol{h}}_k^* \widehat{\boldsymbol{h}}_i|^2 + \sum_{j=1}^M P_j^d \beta_j^d |\widehat{\boldsymbol{h}}_k^* \mathbf{g}_j|^2 + \sum_{i=1}^K P_i^c \beta_i^c \widehat{\boldsymbol{h}}_k^* \mathbb{E}[\|\widetilde{\boldsymbol{h}}_i \widetilde{\boldsymbol{h}}_i^*\|] \widehat{\boldsymbol{h}}_k + \|\widehat{\boldsymbol{h}}_k^*\|^2 N_0} \\ &= \frac{P_k^c \beta_k^c |\widehat{\boldsymbol{h}}_k^* \widehat{\boldsymbol{h}}_k|^2}{\eta_1^c + \eta_2^c + \eta_3^c + \|\widehat{\boldsymbol{h}}_k^*\|^2 N_0}, \end{aligned} \tag{10}$$

where $\eta_1^c = \sum_{i \neq k}^K P_i^c \beta_i^c |\widehat{\boldsymbol{h}}_k^* \widehat{\boldsymbol{h}}_i|^2$ is the interference from the rest of the CUEs, $\eta_2^c = \sum_{j=1}^M P_j^d \beta_j^d |\widehat{\boldsymbol{h}}_k^* \mathbf{g}_j|^2$ denotes the interference from all D2DTs, and $\eta_3^c = \sum_{i=1}^K P_i^c \beta_i^c \widehat{\boldsymbol{h}}_k^* \mathbb{E}[\|\widetilde{\boldsymbol{h}}_i \widetilde{\boldsymbol{h}}_i^*\|] \widehat{\boldsymbol{h}}_k$ represents the interference caused by channel estimation error.

Based on the distribution of $\widehat{\boldsymbol{h}}_k$ and $\widetilde{\boldsymbol{h}}_k$ which was presented in Subsection 2.1, we define

$$\delta_k^c \triangleq \frac{P_p^c \beta_k^c}{N_0 + P_p^c \beta_k^c + P_p^d \sum_{j \in \mathcal{D}_k} \beta_j^d} \tag{11a}$$

and

$$\varepsilon_k^c \triangleq \frac{N_0 + P_p^d \sum_{j \in \mathcal{D}_k} \beta_j^d}{N_0 + P_p^c \beta_k^c + P_p^d \sum_{j \in \mathcal{D}_k} \beta_j^d}. \tag{11b}$$

Theorem 1. When $N \gg K + M$, the approximated SINR of the kth CUE given in (10) can be formulated as

$$\widetilde{\mathrm{SINR}}_k^c = \frac{P_k^c \beta_k^c \delta_k^c}{\frac{1}{N}(\sum_{i\neq k}^K P_i^c \beta_i^c + \sum_{j=1}^M P_j^d \beta_j^d + P_k^c \beta_k^c \varepsilon_k^c) + \frac{\delta_k^c P_p^d}{P_p^c \beta_k^c}\sum_{j\in\mathcal{D}_k} P_j^d (\beta_j^d)^2} = \frac{P_k^c \beta_k^c \delta_k^c}{\mu_1^c + \mu_2^c + \mu_3^c}, \tag{12}$$

where

$$\mu_1^c = \frac{1}{N}\left(\sum_{i\neq k}^K P_i^c \beta_i^c + \sum_{j=1}^M P_j^d \beta_j^d\right), \quad \mu_2^c = \frac{1}{N} P_k^c \beta_k^c \varepsilon_k^c, \quad \mu_3^c = \frac{\delta_k^c P_p^d}{P_p^c \beta_k^c}\sum_{j\in\mathcal{D}_k} P_j^d \left(\beta_j^d\right)^2.$$

Proof. The proof of Theorem 1 is given in Appendix A.

Using (12), the spectral efficiency (SE) of the kth CUE can be obtained as

$$R_k^c = \log_2\left(1 + \widetilde{\mathrm{SINR}}_k^c\right). \tag{13}$$

Similarly, the received signal of the mth D2DR can be mathematically expressed as

$$\begin{aligned} r_m^d &= \sum_{j=1}^M \sqrt{P_j^d \beta_{jm}^{dd}} g_{jm}^{dd} x_j^d + \sum_{i=1}^K \sqrt{P_i^c \beta_{im}^{cd}} g_{im}^{cd} x_i^c + N_m^d \\ &= \sqrt{P_m^d \beta_{mm}^{dd}} \widehat{g}_{mm}^{dd} x_m^d + \sum_{i=1}^K \sqrt{P_i^c \beta_{im}^{cd}} g_{im}^{cd} x_i^c + \sum_{j\neq m}^M \sqrt{P_j^d \beta_{jm}^{dd}} g_{jm}^{dd} x_j^d + \sqrt{P_m^d \beta_{mm}^{d}} \widetilde{g}_{mm}^{dd} x_m^d + N_m^d, \end{aligned} \tag{14}$$

where $N_m^d \sim \mathcal{CN}(0, N_0)$ represents the additive noise. Then, the SINR at the mth D2DR can be written as

$$\begin{aligned} \mathrm{SINR}_m^d &= \frac{P_m^d \beta_{mm}^{dd} \left|\widehat{g}_{mm}^{dd}\right|^2}{\sum_{j\neq m}^M P_j^d \beta_{jm}^{dd} \left|g_{jm}^{dd}\right|^2 + \sum_{k=1}^K P_k^c \beta_{km}^{cd} \left|g_{km}^{cd}\right|^2 + P_m^d \beta_{mm}^{dd} \mathbb{E}\left\{\left|\widetilde{g}_{mm}^{dd}\right|^2\right\} + N_0} \\ &= \frac{P_m^d \beta_{mm}^{dd} \left|\widehat{g}_{mm}^{dd}\right|^2}{\eta_1^d + \eta_2^d + N_0}, \end{aligned} \tag{15}$$

where $\eta_1^d = \sum_{j\neq m}^M P_j^d \beta_{jm}^{dd} |g_{jm}^{dd}|^2 + \sum_{k=1}^K P_k^c \beta_{km}^{cd} |g_{km}^{cd}|^2$ is the interference from other D2D pairs and all CUEs, and $\eta_2^d = P_m^d \beta_{mm}^{dd} \mathbb{E}\{|\widetilde{g}_{mm}^{dd}|^2\}$ represents the interference caused by the channel estimation error. By defining

$$\varepsilon_m^d \triangleq \frac{N_0 + P_p^c \beta_{km}^{cd} + P_p^d \sum_{n\in\mathcal{D}_k, n\neq m} \beta_{nm}^{dd}}{N_0 + P_p^c \beta_{km}^{cd} + P_p^d \sum_{n\in\mathcal{D}_k} \beta_{nm}^{dd}}, \tag{16}$$

the SINR at the mth D2DR can be expressed as

$$\mathrm{SINR}_m^d = \frac{P_m^d \beta_{mm}^{dd} |\widehat{g}_{mm}^{dd}|^2}{\eta_1^d + P_m^d \beta_{mm}^{dd} \varepsilon_m^d + N_0}. \tag{17}$$

Then, the SE of the mth D2D pair can be formulated by

$$R_m^d = \log_2\left(1 + \mathrm{SINR}_m^d\right). \tag{18}$$

The total SE calculated by (13) and (18) will be taken as the main performance metric for the proposed pilot reuse scheme, which will be presented next.

3 Pilot reuse scheme

As previously discussed, pilot reuse causes channel estimation error, and further degrades the overall system performance. To overcome this, a novel heuristic pilot reuse scheme will be introduced here and its detailed operation will be presented. Under the assumption that the pilot $\boldsymbol{\phi}_k$ is reused by the mth D2D pair, σ_{km} is used to indicate the amount of the interference caused by the pilot reuse, as follows

$$\sigma_{km} = \frac{\beta_m^d}{\beta_k^c}. \tag{19}$$

Clearly, the larger σ_{km} is, the higher the interference will be. Furthermore, $\mathcal{C}_m$ is introduced to denote the set of candidates of CUEs that can share their pilots with the mth D2D pair. If $\sigma_{km} \leqslant 1$, $k \in \mathcal{C}_m$; otherwise, $k \notin \mathcal{C}_m$. Considering that the distance between D2D transceivers is smaller than that between the CUEs and the BS, the pilot transmit power of D2DTs can be assumed to be much smaller than that of CUEs.

Based on (12), it is clear that when the number of antennas at the BS is very large, the SINR at a CUE mainly depends on the D2D pairs who reuse its pilot. Meanwhile, the SINR at a D2DR depends mainly on the channel estimation error. Therefore, a proper pilot reuse strategy is very important to reduce the co-pilot interference and the channel estimation error and thus improve the SINR at each user. From the definition of EE, if the transmit power is constant, increasing the SINR (SE) is equivalent of improving the EE. Motivated by this idea, we have designed a pilot reuse algorithm which maximizes the system SE (calculated through (13) and (18)) by considering constant maximum power transmission. Note that the optimization of the transmit power will be presented in the next section. The index of the CUE that the mth D2D pair chooses to reuse its pilot is denoted by Ω_m and the detailed pilot reuse scheme can be found in Algorithm 1.

Algorithm 1 Pilot reuse scheme

Initialize the set of D2D pairs which have not been allocated with pilot as $\lambda = \mathcal{M}$
Calculate σ_{kj} for all $k \in \mathcal{K}, j \in \mathcal{M}$, and get $\mathcal{C}_m$
Allocate pilots for D2D pairs randomly, get $\mathcal{D}_k$ for all $k \in \mathcal{K}$, and Ω_m for all $m \in \mathcal{M}$
while $\lambda \neq \emptyset$ **do**
  $m = \arg\max_{m_0 \in \lambda} \sum_{k \in \mathcal{K}} \sigma_{km_0}$
  $\mathcal{D}_{\Omega_m} = \mathcal{D}_{\Omega_m} \backslash m$
  for $k \in \mathcal{C}_m$ **do**
    $\mathcal{D}_k = \mathcal{D}_k \bigcup m$
    get R_k^c and R_i^d for all $i \in \mathcal{D}_k$
    $\Delta_{km} = R_k^c + \sum_{i \in \mathcal{D}_k} R_i^d$
    $\mathcal{D}_k = \mathcal{D}_k \backslash m$
  end for
  $k^* = \arg\max_{k \in \mathcal{K}} \Delta_{km}$
  $\mathcal{D}_{k^*} = \mathcal{D}_{k^*} \bigcup m$, $\lambda = \lambda \backslash m$
end while

4 Power control algorithm

The power, which is assumed to be constant when designing pilot reuse scheme presented in the previous section, is optimized by a power control algorithm through maximizing the system energy efficiency (EE). According to [28], the overall system EE can be defined as the sum ratio of each user's SE to its total power consumed. Thus, the total EE of the communication system under consideration can be formulated as

$$U_{EE} \triangleq \sum_{k=1}^{K} U_k^c + \sum_{m=1}^{M} U_m^d = \sum_{k=1}^{K} \frac{R_k^c}{P_k^c + P_{cir}} + \sum_{m=1}^{M} \frac{R_m^d}{P_m^d + 2P_{cir}}, \tag{20}$$

where U_k^c and U_m^d denote the EE of the kth CUE and the mth D2D pair respectively, and P_{cir} is the static circuit power of each user device.

Since our objective is to maximize the overall system EE while guaranteeing the QoS requirements of both CUEs and D2D pairs, the optimization problem can be formulated as

$$\begin{aligned} \max. \quad & U_{EE}(\mathcal{P}_c, \mathcal{P}_d) \\ \text{s.t.} \quad & A1: \widetilde{\text{SINR}}_k^c \geqslant \xi_{k,\min}^c, \quad k \in \mathcal{K}, \\ & A2: \text{SINR}_m^d \geqslant \xi_{m,\min}^d, \quad m \in \mathcal{M}, \\ & A3: 0 \leqslant P_k^c \leqslant P_{\max}^c, \quad k \in \mathcal{K}, \\ & A4: 0 \leqslant P_m^d \leqslant P_{\max}^d, \quad m \in \mathcal{M}, \end{aligned} \tag{21}$$

where $\mathcal{P}_c$ and $\mathcal{P}_d$ represent the transmit power sets of CUEs and D2DTs, $\xi_{k,\min}^c$ and $\xi_{m,\min}^d$ denote the minimum SINR requirements of the kth CUE and the mth D2D pair, and $P_{\max}^c$ and $P_{\max}^d$ denote the maximum transmit power constraints of CUEs and D2DTs, respectively.

Since the computational complexity increases along with the increase of the number of users, searching the global optimal solution to (21) is NP-hard. To solve this, a distributed iterative power control algorithm is proposed by modeling the problem as a non-cooperative game, as shown in Algorithm 2. It can be observed that, with the proposed algorithm, each user is self-interested and tries to maximize its own EE without considering other users. Since typically the users will update their power sequentially, the power strategies will eventually converge to a Nash equilibrium, which is proved to exist in Theorem 2. For the kth CUE, the power strategy set of other users (CUEs and D2DTs) is denoted as $\boldsymbol{P}_{-k}^c = \{P_i^c, P_j^d \mid 0 \leqslant P_i^c \leqslant P_{\max}^c, 0 \leqslant P_j^d \leqslant P_{\max}^d, i \in \mathcal{K}\backslash k, j \in \mathcal{M}\}$. Then, its EE U_k^c depends not only on its own power strategy P_k^c, but also on the power strategies of the other users $\boldsymbol{P}_{-k}^c$. Similarly, for the mth D2D pair, the power strategy set of other CUEs and D2DTs is denoted as $\boldsymbol{P}_{-m}^d = \{P_i^c, P_j^d \mid 0 \leqslant P_i^c \leqslant P_{\max}^c, 0 \leqslant P_j^d \leqslant P_{\max}^d, i \in \mathcal{K}, j \in \mathcal{M}\backslash m\}$. Clearly, the EE U_m^d depends on P_m^d and $\boldsymbol{P}_{-m}^d$.

Theorem 2. A Nash equilibrium exists in the non-cooperative game, and is the power strategy set of users $\left\{P_k^{c*}, P_m^{d*} \mid k \in \mathcal{K}, m \in \mathcal{M}\right\}$ obtained by Algorithm 2.

Proof. The proof of Theorem 2 is given in Appendix B.

The detailed operation of the proposed power control algorithms for both CUEs and D2D pairs will be presented next.

4.1 Power control for CUE

For the kth CUE, its energy efficiency can be expressed as

$$U_k^c(P_k^c, \boldsymbol{P}_{-k}^c) = \frac{\log_2(1 + \widetilde{\text{SINR}}_k^c)}{P_k^c + P_{cir}} = \frac{\log_2(1 + \frac{P_k^c \beta_k^c \delta_k^c}{\frac{1}{N} P_k^c \beta_k^c \varepsilon_k^c + \chi_k^c})}{P_k^c + P_{cir}}, \tag{22}$$

where $\chi_k^c = \frac{P_p^d \delta_k^c}{P_p^c \beta_k^c} \sum_{j \in \mathcal{D}_k} P_j^d (\beta_j^d)^2 + \frac{1}{N}(\sum_{i \neq k}^K P_i^c \beta_i^c + \sum_{j=1}^M P_j^d \beta_j^d)$. Then, the individual optimization problem maximizing the EE of the kth CUE can be reformulated as

$$\begin{aligned} \max. \quad & U_k^c\left(P_k^c, \boldsymbol{P}_{-k}^c\right) \\ \text{s.t.} \quad & B1: \widetilde{\text{SINR}}_k^c \geqslant \xi_{k,\min}^c, \\ & B2: 0 \leqslant P_k^c \leqslant P_{\max}^c. \end{aligned} \tag{23}$$

It should be noted that $U_k^c\left(P_k^c, \boldsymbol{P}_{-k}^c\right)$ in (22) is not a concave function on P_k^c, so the formulated optimization problem in (23) cannot be solved directly by using convex optimization methods. Suppose that $\boldsymbol{P}_{-k}^c$ is given, the first-order derivative of U_k^c can be written as

$$\frac{\partial U_k^c}{\partial P_k^c} = \frac{\zeta_k^c\left(P_k^c\right)}{\left(P_k^c + P_{cir}\right)^2}, \tag{24}$$

where $\zeta_k^c\left(P_k^c\right)$ is formulated as

$$\zeta_k^c\left(P_k^c\right) = \frac{\beta_k^c \delta_k^c \chi_k^c \log_2 e\left(P_k^c + P_{cir}\right)}{\left(P_k^c \beta_k^c \delta_k^c + \frac{1}{N} P_k^c \beta_k^c \varepsilon_k^c + \chi_k^c\right)\left(\frac{1}{N} P_k^c \beta_k^c \varepsilon_k^c + \chi_k^c\right)} - \log_2\left(1 + \frac{P_k^c \beta_k^c \delta_k^c}{\frac{1}{N} P_k^c \beta_k^c \varepsilon_k^c + \chi_k^c}\right). \tag{25}$$

Algorithm 2 Distributed iterative power control algorithm

$\kappa = 10^{-3}, I_{\max} = 20, q(0) = 0$
Allocate power for CUEs and D2DTs randomly, get $\mathcal{P}_c$ and $\mathcal{P}_d$
for $n = 1$ to $I_{\max}$ **do**
  for $k \in \mathcal{K}$ **do**
    get $P^c_{k,\min}$ and $P^c_{k,\max}$ from (27) and (28)
    if $\zeta^c_k(P^c_{k,\min}) \leqslant 0$ **then**
      $P^{c*}_k(n) = P^c_{k,\min}$
    else if $\zeta^c_k(P^c_{k,\max}) \geqslant 0$ **then**
      $P^{c*}_k(n) = P^c_{k,\max}$
    else
      $P^{c*}_k(n) = \arg \min\limits_{P^c_{k,\min} \leqslant P^c_k \leqslant P^c_{k,\max}} |\zeta^c_k(P^c_k)|$
    end if
  end for
  for $j \in \mathcal{M}$ **do**
    get $P^d_{m,\min}$ and $P^d_{m,\max}$ from (35) and (36)
    if $\zeta^d_m(P^d_{m,\min}) \leqslant 0$ **then**
      $P^{d*}_m(n) = P^d_{m,\min}$
    else if $\zeta^d_m(P^d_{m,\max}) \geqslant 0$ **then**
      $P^{d*}_m(n) = P^d_{m,\max}$
    else
      $P^{d*}_m(n) = \arg \min\limits_{P^d_{m,\min} \leqslant P^d_m \leqslant P^d_{m,\max}} |\zeta^d_m(P^d_m)|$
    end if
  end for
  $q = \max\{|\mathcal{P}_c(n) - \mathcal{P}_c(n-1)|, |\mathcal{P}_d(n) - \mathcal{P}_d(n-1)|\}$
  if $q \leqslant \kappa$ **then**
    break
  else
    update $\mathcal{P}_c$ and $\mathcal{P}_d$
  end if
end for

Further, the first-order derivative of ζ^c_k can be obtained as

$$\frac{\partial \zeta^c_k\left(P^c_k\right)}{\partial P^c_k} = -\frac{\beta^c_k \delta^c_k \chi^c_k \log_2 e\left(P^c_k + P_{cir}\right)\left[\left(\beta^c_k\delta^c_k + \frac{1}{N}\beta^c_k\varepsilon^c_k\right)\left(\frac{2}{N}P^c_k\beta^c_k\varepsilon^c_k + \chi^c_k\right) + \frac{1}{N}\beta^c_k\varepsilon^c_k\chi^c_k\right]}{\left(P^c_k\beta^c_k\delta^c_k + \frac{1}{N}P^c_k\beta^c_k\varepsilon^c_k + \chi^c_k\right)^2\left(\frac{1}{N}P^c_k\beta^c_k\varepsilon^c_k + \chi^c_k\right)^2} < 0, \tag{26}$$

which indicates that ζ^c_k is a monotone decreasing function. Since the function U^c_k is continuous and $\zeta^c_k(0) > 0$ and $\zeta^c_k(\infty) < 0$, when P^c_k increases from 0, U^c_k firstly increases and then decreases. In other words, given a power range to the kth CUE, a power point maximizing U^c_k, i.e., making ζ^c_k equal to or very close to zero, can be found. According to $B1$ and $B2$, the minimum and maximum transmit power of the kth CUE can be expressed as

$$P^c_{k,\min} = \frac{\chi^c_k \xi^c_{k,\min}}{\beta^c_k\delta^c_k - \frac{1}{N}\xi^c_{k,\min}\beta^c_k\varepsilon^c_k} \tag{27}$$

and

$$P^c_{k,\max} = P^c_{\max}, \tag{28}$$

respectively. Therefore, at each iteration, $P^c_k\left(P^c_{k,\min} \leqslant P^c_k \leqslant P^c_{k,\max}\right)$ that makes ζ^c_k equal to or very close to zero can be chosen as a sub-optimal power for the kth CUE when given $\boldsymbol{P}^c_{-k}$. Mathematically, this can be formulated as

$$P^{c*}_k = \arg \min_{P^c_{k,\min} \leqslant P^c_k \leqslant P^c_{k,\max}} |\zeta^c_k\left(P^c_k\right)|. \tag{29}$$

Next, the iterative power control operation for each D2D pair will be presented.

4.2 Power control for D2D Pair

The energy efficiency of the mth D2D pair can be expressed as

$$U_m^d(P_m^d, \boldsymbol{P}_{-m}^d) = \frac{\log_2(1+\mathrm{SINR}_m^d)}{P_m^d + 2P_{cir}} = \frac{\log_2(1+\frac{P_m^d \beta_{mm}^{dd} |\widehat{g}_{mm}^{dd}|^2}{P_m^d \beta_{mm}^{dd} \varepsilon_m^d + \chi_m^d})}{P_m^d + 2P_{cir}}, \tag{30}$$

where $\chi_m^d = \sum_{j\neq m}^{M} P_j^d \beta_{jm}^{dd} |g_{jm}^{dd}|^2 + \sum_{k=1}^{K} P_k^c \beta_{km}^{cd} |g_{km}^{cd}|^2 + N_0$. The EE maximization problem for the mth D2D pair is formulated as

$$\begin{aligned} \max. \quad & U_m^d\left(P_m^d, \boldsymbol{P}_{-m}^d\right) \\ \text{s.t.} \quad & C1: \mathrm{SINR}_m^d \geqslant \xi_{m,\min}^d, \\ & C2: 0 \leqslant P_m^d \leqslant P_{\max}^d. \end{aligned} \tag{31}$$

When $\boldsymbol{P}_{-m}^d$ is given, the first-order derivative of U_m^d is

$$\frac{\partial U_m^d}{\partial P_m^d} = \frac{\zeta_m^d\left(P_m^d\right)}{\left(P_m^d + 2P_{cir}\right)^2}. \tag{32}$$

Similar to Subsection 4.1, $\zeta_m^d\left(P_m^d\right)$ can be expressed as

$$\zeta_m^d(P_m^d) = \frac{\beta_{mm}^{dd} |\widehat{g}_{mm}^{dd}|^2 \chi_m^d \log_2 e(P_m^d + 2P_{cir})}{(P_m^d \beta_{mm}^{dd}(|\widehat{g}_{mm}^{dd}|^2 + \varepsilon_m^d) + \chi_m^d)(P_m^d \beta_{mm}^{dd} \varepsilon_m^d + \chi_m^d)} - \log_2\left(1 + \frac{P_m^d \beta_{mm}^{dd} |\widehat{g}_{mm}^{dd}|^2}{P_m^d \beta_{mm}^{dd} \varepsilon_m^d + \chi_m^d}\right). \tag{33}$$

Furthermore, the first-order derivative of ζ_m^d is

$$\begin{aligned} \frac{\partial \zeta_m^d(P_m^d)}{\partial P_m^d} &= -\frac{(|\widehat{g}_{mm}^{dd}|^2 + \varepsilon_m^d)[2P_m^d \beta_{mm}^{dd} \varepsilon_m^d + \chi_m^d] + \varepsilon_m^d \chi_m^d}{(P_m^d \beta_{mm}^{dd}(|\widehat{g}_{mm}^{dd}|^2 + \varepsilon_m^d) + \chi_m^d)^2} \cdot \frac{(\beta_{mm}^{dd})^2 |\widehat{g}_{mm}^{dd}|^2 \chi_m^d \log_2 e(P_m^d + 2P_{cir})}{(P_m^d \beta_{mm}^{dd} \varepsilon_m^d + \chi_m^d)^2} \\ &< 0. \end{aligned} \tag{34}$$

According to $C1$ and $C2$, the minimum and maximum transmit power of the mth D2DT can be denoted by

$$P_{m,\min}^d = \frac{\chi_m^d \xi_{m,\min}^d}{\beta_{mm}^{dd} \left|\widehat{g}_{mm}^{dd}\right|^2 - \beta_{mm}^{dd} \varepsilon_m^d} \tag{35}$$

and

$$P_{m,\max}^d = P_{\max}^d, \tag{36}$$

respectively. Finally, the sub-optimal power for the mth D2DT can be obtained by

$$P_m^{d*} = \arg \min_{P_{m,\min}^d \leqslant P_m^d \leqslant P_{m,\max}^d} \left|\zeta_m^d\left(P_m^d\right)\right|. \tag{37}$$

So far, the power strategy of each user in one iteration maximizing the EE has been obtained. According to Theorem 2, after sufficient iterations, a Nash equilibrium will be reached, and the sum of the maximum EE of all the users can be regarded as the sub-optimal total EE of the overall network.

5 Simulation results

The performance of the proposed pilot reuse scheme and power control algorithm has been obtained by means of extensive Monte Caro computer simulations. The specific simulation parameters, which have been used to obtain the various performance evaluation results, can be found in Table 1. During the experiments, a single-cell network is considered, where the BS is located in the center of the cell, and CUEs and D2D pairs have been assumed to be uniformly distributed within the cell. The important parameter $\Gamma = P_p^c/P_p^d$ denotes the ratio of the pilot powers allocated between CUE and D2DT. The

Table 1 Simulation parameters

Parameter	Value
Cell radius	500 m
Maximum transmit power of CUEs	200 mW
Maximum transmit power of D2DTs	20 mW
Pilot power of CUEs	100 mW
Circuit power	10 mW
Path-loss exponent α_c	3.76
Path-loss exponent α_d	4.37
Noise power N_0	−174 dBm
SINR requirement of users	10 dB
Distance from D2DT to the corresponding D2DR	10 m
The uplink coherent time interval	98

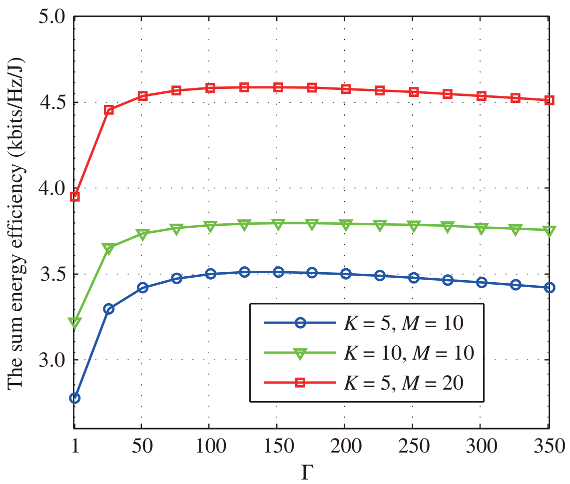

Figure 2 (Color online) The system sum energy efficiency vs. Γ for different numbers of users and for $N = 1000$.

large-scale fading coefficient of the user-BS link is $\beta^x = d_B^{-\alpha_c}$, where $x = \{c, d\}$ (referred to the CUE and D2DT, respectively), d_B denotes the distance from the users (CUEs and D2DTs) to the BS, and α_c represents the path-loss exponent. Similarly, the large-scale fading coefficient of the user-user link is $\beta^{xd} = d_U^{-\alpha_d}$, where d_U is the distance between user equipments and α_d is the path-loss exponent of user-user links. The overall system EE is used as the performance metric in the comparison of different schemes.

The effect of pilot power ratio Γ on the overall system EE has been obtained and the performance results are shown in Figure 2. Compared to the EE when $\Gamma = 1$, the EE is significantly improved as Γ increases, and the optimal value of Γ is in the range of 100–150. It is important to underline that the optimal Γ is insensitive to the changes of the number of users. The reason for this is because D2D is the short-distance communication, and thus a smaller pilot transmit power will degrade the channel estimation of the D2D links only slightly, but at the same time it will reduce the consumed power and the interference to CUEs. Most of the previous works suppose that the same pilot transmit power is allocated for both CUEs and D2DTs, which our research has shown that is far from optimal in terms of the overall system EE.

The convergence rate of the proposed power control algorithm is also investigated, and its convergence performance are shown in Figures 3 and 4. By first initializing the power of each user randomly, at each iteration users update their own power strategy based on the proposed power control algorithm according to the strategies of other users during the last iteration. The convergence of the transmit power of each user is illustrated in Figure 3, where it can be seen that both the power of CUE and that of D2DT

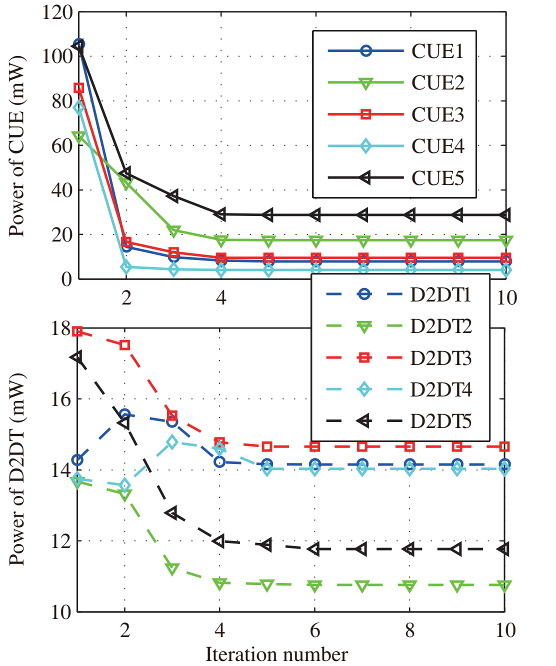

Figure 3 (Color online) Convergence of the individual users' power in proposed power control algorithm with $K = 5$, $M = 10$, $N = 1000$.

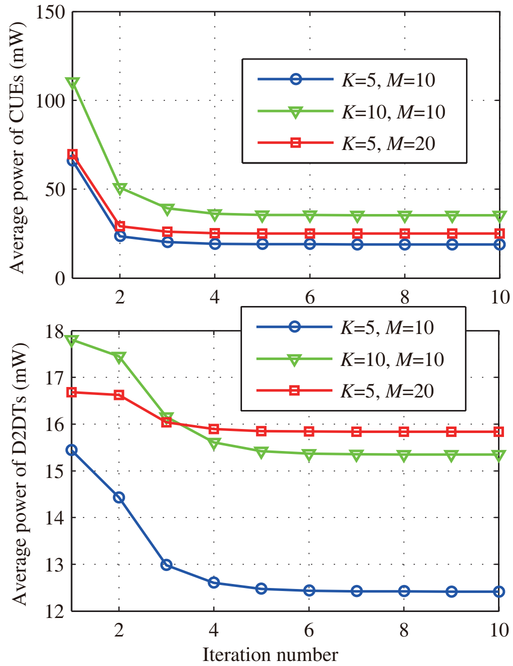

Figure 4 (Color online) Convergence of the average power of CUEs and D2DTs in proposed power control algorithm with $N = 1000$.

converge very fast within 5 to 7 iterations. After power control, the power of each CUE decreases by 40–70 mW, and the power consumed by most of the D2DTs is reduced too. The average convergence rate of the power control scheme has been also obtained by taking the average of 5000 Monte-Carlo simulations, and these results are shown in Figure 4. Again here, the average power of both CUEs and D2DTs converge within 6 to 7 iterations. After sufficient iterations, the average consumed power of CUEs decreases by 50–80 mW and that of D2DTs also decreases compared to the initial iterative value. Clearly, it can be concluded that using our proposed approach, the power consumption is reduced and the overall system EE is improved.

The total EE performance of the whole network as a function of the number of the transmit antennas at the BS has also been investigated. To compare the performance of the proposed pilot reuse scheme, under the same power control algorithm, two other schemes have been also considered. These are i) the MMSE-CE PR with PC proposed in [27] by selecting D2D transmitters to reuse the pilots of CUEs to minimize the sum of mean square errors of channel estimation, and ii) the Random PR with PC where the D2D pair reuses the pilots randomly. Performance evaluation results for all three schemes are illustrated in Figure 5 where it is clear that the MMSE-CE scheme achieves a higher EE gain than the random scheme. This is because the pilot assignment algorithm reduces the channel estimation error and thus it can improve the SINR. Compared with the MMSE-CE PR with PC, the Proposed PR with PC increases even more the overall system EE, since the distance constraints are considered and the objective of the proposed scheme is to optimize the overall system EE.

The overall system EE obtained based on the proposed PC algorithm has also investigated, and results are shown in Figure 6. Two other schemes are included as reference, the PR with Random PC where the power of CUEs and D2DTs is randomly assigned and the PR with Maximum PC where each user transmits signal with its maximum power. For fair comparison, the same pilot reuse scheme is assumed for all three simulated schemes. From Figure 6, it can be seen that the proposed power control algorithm, i.e., the PR with Proposed PC, achieves the best performance compared with the other two schemes. This is because the proposed algorithm optimizes each user's power to maximize the EE, and the QoS requirements of users are satisfied at the smallest transmit power. The simulations results also show that the EE gain brought by the proposed algorithm increases as the number of antennas at the BS increases.

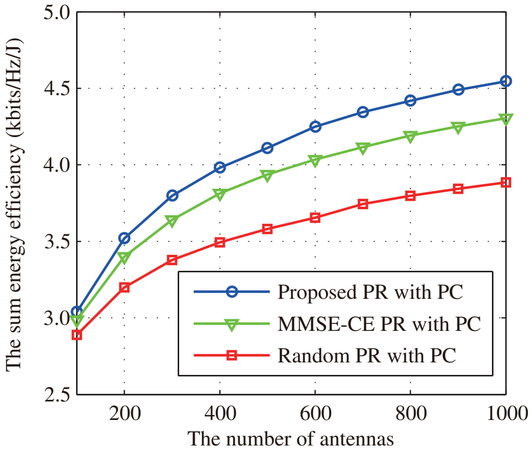

Figure 5 (Color online) The system sum energy efficiency for different pilot reuse schemes with proposed power control algorithm when $K = 5$, $M = 20$.

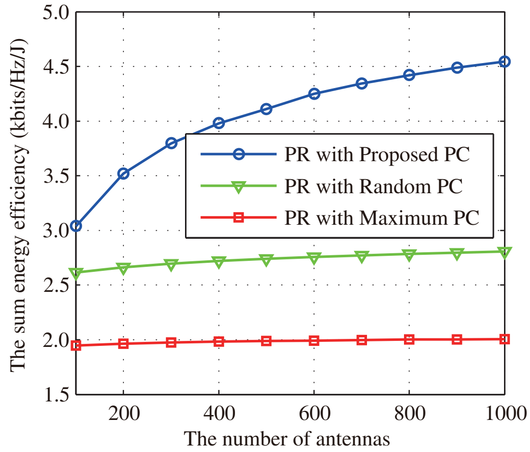

Figure 6 (Color online) The system sum energy efficiency for different power control algorithms with proposed pilot reuse scheme when $K = 5$, $M = 20$.

6 Conclusion

In this paper, the D2D communications underlaying massive MIMO systems are investigated in terms of the pilot reuse scheme and the overall system energy efficiency (EE) optimization. To reduce the pilot overhead, the pilot reuse scenario which allows the D2D pairs to reuse the orthogonal pilots of CUEs is assumed. With the purpose of reducing channel estimation error and maximizing the overall system EE, a heuristic pilot reuse scheme has been proposed. Considering the communication distance difference, the pilot power of CUEs and that of D2DTs were set to be different, and the optimal power ratio has been found via computer simulations. By assuming MMSE channel estimator at the BS, the SINR expressions are derived. To maximize the overall system EE, a total EE optimization problem is formulated, which is proved to be NP-hard and thus difficult to find its global optimal solution. As an alternative, a sub-optimal solution and a distributed iterative power control algorithm based on the non-cooperative game have been proposed. Simulation results have shown that the proposed pilot reuse scheme and power control algorithm can significantly improve the EE of the overall network.

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Conflict of interest The authors declare that they have no conflict of interest.

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Appendix A Proof of Theorem 1

From (10), the SINR at the kth CUE can be rewritten as

$$\mathrm{SINR}_k^c = \frac{P_k^c \beta_k^c |\frac{\widehat{\boldsymbol{h}}_k^* \widehat{\boldsymbol{h}}_k}{N}|^2}{\frac{\eta_1^c + \eta_2^c + \eta_3^c}{N^2} + \|\frac{\widehat{\boldsymbol{h}}_k^*}{N}\|^2 N_0}. \tag{A1}$$

Based on the favorable propagation condition [12] in massive MIMO systems and the distribution of $\widehat{\boldsymbol{h}}_k$ in (5a), when the number of antennas at BS is much larger than the number of users, i.e., $N \gg K + M$, we have

$$\left|\frac{\widehat{\boldsymbol{h}}_k^* \widehat{\boldsymbol{h}}_k}{N}\right|^2 \approx (\delta_k^c)^2. \tag{A2}$$

Then, from (4), it can be observed that the estimation of channel of the kth CUE, i.e., $\widehat{\boldsymbol{h}}_k$, is only affected by the D2D pairs who reuse its pilot, so $\widehat{\boldsymbol{h}}_k$ is independent of $\widehat{\boldsymbol{h}}_i$, $\forall i \in \mathcal{K}\backslash k$, and $\mathbf{g}_j$, $\forall j \in \mathcal{K}\backslash \mathcal{D}_k$. Next, according to (5a) and (11a), we have

$$\left|\frac{\widehat{\boldsymbol{h}}_k^* \widehat{\boldsymbol{h}}_i}{N}\right|^2 \approx \frac{\delta_k^c \delta_i^c}{N}, \quad \forall i \in \mathcal{K}\backslash k \tag{A3}$$

and

$$\left|\frac{\widehat{\boldsymbol{h}}_k^*\mathbf{g}_j}{N}\right|^2 \approx \frac{\delta_k^c}{N}, \quad \forall j \in \mathcal{K}\backslash\mathcal{D}_k. \tag{A4}$$

Similarly, because $\widehat{\boldsymbol{h}}_k$ is independent of $\widetilde{\boldsymbol{h}}_i$, $\forall i \in \mathcal{K}$, according to (5b) and (11b), we get

$$\frac{\widehat{\boldsymbol{h}}_k^*\mathbb{E}\{\|\widetilde{\boldsymbol{h}}_i\widetilde{\boldsymbol{h}}_i^*\|\}\widehat{\boldsymbol{h}}_k}{N^2} \approx \frac{\delta_k^c\varepsilon_i^c}{N}, \quad \forall i \in \mathcal{K}. \tag{A5}$$

Moreover, we can obtain that $\mathbf{g}_j$ $(\forall j \in \mathcal{D}_k)$ is not independent of $\widehat{\boldsymbol{h}}_k$ from (4). As a result, we have

$$\begin{aligned}\left|\frac{\widehat{\boldsymbol{h}}_k^*\mathbf{g}_j}{N}\right|^2 &= \frac{\delta_k^c|\sqrt{P_p^c\beta_k^c}\boldsymbol{h}_k^*\mathbf{g}_j + \sum_{i\in\mathcal{D}_k}\sqrt{P_p^d\beta_i^d}\mathbf{g}_i^*\mathbf{g}_j + (\boldsymbol{W}\boldsymbol{\phi}_k)^*\mathbf{g}_j|^2}{N^2(N_0 + P_p^c\beta_k^c + P_p^d\sum_{i\in\mathcal{D}_k}\beta_i^d)} \\ &\approx \frac{\delta_k^c(\frac{1}{N}P_p^c\beta_k^c + \frac{1}{N}\sum_{i\in\mathcal{D}_k\backslash j}P_p^d\beta_i^d + P_p^d\beta_j^d + \frac{1}{N}N_0)}{N_0 + P_p^c\beta_k^c + P_p^d\sum_{i\in\mathcal{D}_k}\beta_i^d} \\ &= \frac{\delta_k^c(\frac{1}{N}N_0 + \frac{1}{N}P_p^c\beta_k^c + \frac{1}{N}\sum_{i\in\mathcal{D}_k}P_p^d\beta_i^d + \frac{N-1}{N}P_p^d\beta_j^d)}{N_0 + P_p^c\beta_k^c + P_p^d\sum_{i\in\mathcal{D}_k}\beta_i^d} \\ &\approx \frac{\delta_k^c}{N} + \frac{(\delta_k^c)^2P_p^d\beta_j^d}{P_p^c\beta_k^c}.\end{aligned} \tag{A6}$$

By substituting (A2)–(A6) into (A1), we can obtain

$$\mathrm{SINR}_k^c = \frac{P_k^c\beta_k^c|\frac{\widehat{\boldsymbol{h}}_k^*\widehat{\boldsymbol{h}}_k}{N}|^2}{\frac{\eta_1^c+\eta_2^c+\eta_3^c}{N^2} + \|\frac{\widehat{\boldsymbol{h}}_k^*}{N}\|^2N_0} \approx \frac{(\delta_k^c)^2P_k^c\beta_k^c}{\delta_k^c(\mu_1^c+\mu_2^c+\mu_3^c)} = \frac{P_k^c\beta_k^c\delta_k^c}{\mu_1^c+\mu_2^c+\mu_3^c} \triangleq \widetilde{\mathrm{SINR}}_k^c. \tag{A7}$$

Therefore, the SINR at the kth CUE given in (10) can be deterministically approximated by (12).

Appendix B Proof of Theorem 2

A Nash equilibrium exists if the utility function is continuous and quasi-concave, and the set of strategies is a nonempty compact convex subset of a Euclidean space1). For the kth CUE $(\forall k \in \mathcal{K})$, denote the sublevel set of the objective function given by (22) which, for convenience, is repeated below

$$U_k^c(P_k^c, \boldsymbol{P}_{-k}^c) = \frac{R_k^c}{P_k^c + P_{cir}} = \frac{\log_2(1 + \frac{\delta_k^cP_k^c\beta_k^c}{\frac{1}{N}P_k^c\beta_k^c\varepsilon_k^c + \chi_k^c})}{P_k^c + P_{cir}} \tag{B1}$$

as $S_\alpha = \{P_k^c \geqslant 0 \mid U_k^c(P_k^c, \boldsymbol{P}_{-k}^c) \geqslant \alpha\}$. $U_k^c(P_k^c, \boldsymbol{P}_{-k}^c)$ is quasi-concave if S_α is convex for $\alpha \in \mathbf{R}$2). If $\alpha \leqslant 0$, it is obvious that S_α is convex. For $\alpha > 0$, since $U_k^c(P_k^c, \boldsymbol{P}_{-k}^c) = \frac{R_k^c}{P_k^c+P_{cir}} \geqslant \alpha$, S_α can be rewritten as $S_\alpha = \{P_k^c \geqslant 0 \mid R_k^c - \alpha(P_k^c + P_{cir}) \geqslant 0\}$. Then, let's consider $R_k^c = \log_2(1 + \frac{\delta_k^cP_k^c\beta_k^c}{\frac{1}{N}P_k^c\beta_k^c\varepsilon_k^c+\chi_k^c})$, for all $P_k^c \geqslant 0$, the second-order derivation of which can be expressed as

$$\frac{\partial^2R_k^c}{\partial\left(P_k^c\right)^2} = -\frac{\left(\beta_k^c\delta_k^c + \frac{1}{N}\beta_k^c\varepsilon_k^c\right)\left(\frac{2}{N}P_k^c\beta_k^c\varepsilon_k^c + \chi_k^c\right) + \frac{1}{N}\beta_k^c\varepsilon_k^c\chi_k^c}{\left(\delta_k^cP_k^c\beta_k^c + \frac{1}{N}P_k^c\beta_k^c\varepsilon_k^c + \chi_k^c\right)^2} \cdot \frac{\beta_k^c\delta_k^c\chi_k^c\log_2 e}{\left(\frac{1}{N}P_k^c\beta_k^c\varepsilon_k^c + \chi_k^c\right)^2} < 0. \tag{B2}$$

So, R_k^c is concave in $P_k^c \geqslant 0$ given the power strategies of other users. Since $P_k^c + P_{cir}$ is an affine function of P_k^c, $R_k^c - \alpha(P_k^c + P_{cir})$ is a concave function of $P_k^c(P_k^c \geqslant 0)$. Therefore, S_α is also convex when $\alpha > 0$, i.e., S_α is convex for $\alpha \in \mathbf{R}$, so that $U_k^c(P_k^c, \boldsymbol{P}_{-k}^c)$ is continuous and quasi-concave. The power strategy P_k^c is a nonempty, compact, and convex subset of the Euclidean space $\mathbb{R}$. Similarly, for the mth D2D pair $(\forall m \in \mathcal{M})$, $U_m^d(P_m^d, \boldsymbol{P}_{-m}^d)$ can be proved to be continuous and quasi-concave and the power strategy P_m^d is also a nonempty, compact, and convex subset of the Euclidean space $\mathbb{R}$. Hence, a Nash equilibrium exists in the noncooperaive game.

If the power strategy P_k^{c*} obtained by using Algorithm 2 is not the Nash equilibrium, the kth CUE can choose the Nash equilibrium $\widehat{P}_k^c$ $(\widehat{P}_k^c \neq P_k^{c*})$ to obtain the maximum EE. However, since in Algorithm 2, P_k^{c*} has converged, then we must have $P_k^{c*} = \widehat{P}_k^c$, which contradicts with the assumption. Therefore, P_k^{c*} is part of the Nash equilibrium. A similar proof holds for P_m^{d*}. It thus can be concluded that the power strategy set of users $\{P_k^{c*}, P_m^{d*} \mid k \in \mathcal{K}, m \in \mathcal{M}\}$ obtained by using Algorithm 2 is the Nash equilibrium.

1) Osborne M J, Rubinstein A. A Course in Game Theory. Cambridge: MIT Press, 1994. 11–29.
2) Boyd S, Vandenberghe L. Convex Optimization. New York: Cambridge University Press, 2004. 95–103.