Energy-Efficient Power Allocation for Fading Device-to-Device Channels in Downlink Resource Sharing Communication

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Abstract. Green wireless communications have received increasing attentions from researchers, who committed to improving energy efficiency for the ubiquity of wireless applications. This paper deals with the power allocation strategies for nearby users' high speed download services to effectively address the energy consumption of D2D communications underlying cellular systems. Energy efficiency maximization problems are analyzed with respect to ergodic sum capacity under different power constraint cases, relating to average power thresholds over all the fading stations and instantaneous power thresholds over each fading station of D2D transmission links and frequency-shared interference links. By applying the Dinkelbach method and the Lagrange duality method, the original intractable problems are decomposed into sub-dual functions that are lower complexity and solvable. Accordingly, we infer closed-form solutions of the proposed optimal problems, which resemble "water-filling" solutions for the parallel fading channels. Simulation results verify that the proposed strategies provide effective uses of limited energy.

Keywords: Device-to-Device · Green communication · Energy efficient · Power allocation

1 Introduction

Wireless communication usage has reached new heights over the past decade and will continue to grow in the upcoming years in the field of medium of choice. A major issue for wireless communication system design is the continuing consumption of the energy. The green low-power wireless communication is an inevitable trend for the oncoming 5G or 6G network. As a promising technology, D2D communication technology has been regarded as an effective technique to provide better wireless services in local areas [1] and D2D standard is ready for products [2].

In a D2D underlaid mobile communication system, to satisfy the quality of service (QoS) of the cellular user, we should consider the interference causes

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to the cellular user while managing wireless resource for the D2D link. The introduction of D2D should not only effectively improve spectrum efficiency, but also well control the interference to the normal cellular users. Relying on this premise, many optimal power allocation strategies have been well designed for both uplink [3] and downlink [4] D2D communication.

While the cellular users (CUs) are interference-limited, the D2D users (DUs) are power-limited, whose energy are generally produced by battery. Evaluating power control in cellular networks involves the use of a number of metrics, of which energy efficiency (EE) is the most common one. The previous works also have launched some investigations into the energy efficiency problems of D2D communication, such as [5] in uplink and [6] in downlink resources sharing. To prolong the lifetime of networks, energy harvesting has also been applied to D2D underlaying networks [7]. All of these works for the energy efficiency considered static optimization on the basis of instantaneous channel state information (CSI). Since the system performance should be based on all the fading states to protect the cellular users' quality of services, the investigations of average energy efficiency and the protection of the QoS are necessary.

Different from these previous works on energy efficiency, our goal is to design energy efficient power allocation strategies over fading channels. The ergodic sum capacity can be a relevant measure for the maximum achievable throughput of the D2D link, when the D2D transportation has a sufficiently large delay tolerance [8,9]. The maximum ergodic sum capacity problems of secondary links are considered in [8] for cognitive radio network, but in which the interference from primary links to secondary links didn't be considered. In [9], the energy efficiency maximization problems are analyzed in both delay-insensitive cognitive radio and delay-sensitive cognitive radio.

In this paper, we investigate the energy efficiency of the D2D links sharing downlink spectrum resource with cellular system. We take an information theoretic approach to characterize the maximum achievable rate of D2D links averaged over the channel fading states. The energy efficiency maximization problems are formulated under the statistical average or instantaneous transmit power constraints. As for the cellular users, the performance metrics of the QoS are considered under both the instantaneous and the average interference power too. The formulated problems are nonlinear fractional programming problems, which are intricate and difficult to find their globally optimal solution. Despite the difficulty, we decouple the original problems into sets of independent concave problems which can be solved separately. Hence the problems can be solved bia standard optimization methods, such as Dinkelbach iterative methods and sub-gradient methods. Finally, the effect of the proposed energy efficient optimal power allocation strategies is verified by proper numerical examples.

2 System Model

We consider D2D communication as an underlay downlink resource sharing of cellular systems. Let $\mathfrak{K}$ and $\mathfrak{J}$ represent the sets of downlink cellular users and

D2D pairs, respectively, $|\mathfrak{K}| = K$ and $|\mathfrak{J}| = J$. Each user k occupies a dedicated orthogonal resource block (RB). We assume each CU's RB can be used by at most one D2D link, which is constraint has been widely used [3,4,10,11]. Denote the instantaneous transmission channel gain at fading state v from the BS to CU k by $h_k(v)$, and the D2D link j which reuse the resource of the CU k by $h_j(v)$. The interference channels from BS to D2D link and from the D2D link to CU are represented by $g_{kj}(v)$ and $g_{jk}(v)$, respectively. These channel gains are assumed to be independently drawn from a vector random process, which to be ergodic over the transmission blocks.

It is assumed that the BS and D2D transmit signals in the same narrow-band frequency channel. Let x_k and x_j represent the transmitted signals of the CU k and D2D link j respectively. Then, the received signals of the user k and the inband D2D link j are

$$y_k^C(v) = h_k(v)x_k + g_{jk}(v)x_j + n_k$$

$$y_j^D(v) = h_j(v)x_j + g_{kj}(v)x_k + n_j$$

where n_k and n_j are the additive zero mean Gaussian noise with variances δ_k^2 and δ_j^2, respectively.

Assume that both the CUs and DUs use Gaussian codes on each frequency band with transmit power $p_k = E\,|x_k|^2$ and $p_j = E\,|x_j|^2$. Due to the coexistence of cellular and D2D users on the same frequency band, the throughput of the D2D link j are given by

$$R_j^D(v) \triangleq log\left[1 + \frac{p_j(v)\tilde{h}_j(v)}{1 + p_k(v)\tilde{g}_{kj}(v)}\right] \tag{1}$$

where $\tilde{h}_j(v) = l_j\,|h_j(v)|^2/\delta_j^2$, and $\tilde{g}_{kj}(v) = l_{kj}\,|g_{kj}(v)|^2/\delta_k^2$ are normalized channel gains which integrate with the path-loss.

Since the energy consumption of D2D transmitters are generally produced by battery, our work is mainly focused on allocating the transmit power of D2D to raise the energy efficiency of mobilizable devices. If we use $\eta(p_j(v))$ to denote the energy efficiency of the D2D link, the energy efficiency maximization problem over all the fading states can be formulated as

$$\begin{aligned} \max_{\{p_j(v)\in\mathfrak{F}\}} \eta &= \frac{R^D(p_j(v))}{P^D(p_j(v))} \\ &= \frac{E\left\{log_2\left(1 + \frac{p_j(v)\tilde{h}_j(v)}{p_k(v)\tilde{g}_{kj}(v)+1}\right)\right\}}{E\left\{p_j(v)/\zeta + P_c^D\right\}} \end{aligned} \tag{2}$$

where ζ and P_c^D denote the amplifier and the constant consumption of circuit power of D2D link, which is a power offset derived from signal processing, as well as batter backup, etc. According to the definition, the energy efficiency is affected by not only the transmit power allocation of D2D link but also the interference power from the cellular system.

Assuming the cellular system will communicate without concerning the interference to D2D link, which means it transmits with the quota power

$$p_k(v) = P_{th}^C, \forall v. \tag{3}$$

The condition set $\mathfrak{F}$ is the different cases of power constraints, in addition to the default nonnegative condition,

$$p_j(v) \geq 0, \forall v \tag{4}$$

more details of power constraints will describe in the following Sects. 3 and 4.

The energy efficient problems considered in problem (2) are correlated to the ergodic capacity of D2D link, which is averaged over all the channel fading states. The ergodic capacity can be a relevant measure for the maximum achievable throughput of the communication system when the data traffic has a sufficiently large delay tolerance. As an optional service introduced to the cellular systems, the D2D links generally have lower priorities than the cellular users. The D2D communication is typically implemented as a complement to the cellular systems. Therefore, the QoS target should be imposed to ensure the normal cellular communications. The BS transmit power allocation $p_k(v)$ and the power allocation of D2D link $p_l(v)$ lead to a theoretical limit of the cellular users' performance.

3 Average Transmit Power Constraints

As we optimize the performance of the D2D link, some protections to the cellular user are necessary. The D2D link should reuse the resource of cellular user without exceeding the maximum transmit power,

$$E\left\{p_j(v)\right\} \leq \bar{P_{th}^D}, \forall v \tag{5}$$

where the expectation is taken over v with respect to its cumulative distribution function(CDF). The power threshold $\bar{P_{th}^D}$ is the average transmit power budget for the D2D link.

The average interference power constraints should be imposed on the D2D link in order to protect the cellular from tolerable average interference to noise power ratio

$$E\left\{p_j(v)\tilde{g}_{jk}(v)\right\} \leq \gamma_I^D, \forall v \tag{6}$$

or more restrictive instantaneous power constraints

$$p_j(v)\tilde{g}_{jk}(v) \leq \gamma_I^D, \forall v. \tag{7}$$

The optimal problem defined in (2) seems intractable. Fortunately $P^D(p_j(v))$ and $R^D(p_j(v))$ are both differentiable and concave in $p_j(v)$ under the power constraints (3), (4), (5), (6) and (7). Therefore the nonlinear concave fractional programming can be related to nonlinear parametric programming by using Dinkelbach algorithm [12].

Let η^* denote the maximum $\eta(p_j(v))$, the optimization objection function can be written as

$$\eta^* = max \frac{R^D(p_j(v))}{P^D(p_j(v))} \tag{8}$$

Since the denominator of η^* is positive with $P^D(p_j(v)) \geq 2P_c^D$, the fractional programming problem (2) can be transformed into a corresponding subtractive form

$$\max_{\{p_j(v)\in\mathfrak{F}\}} E\left\{log_2\left(1+\frac{p_j(v)\tilde{h}_j(v)}{p_k(v)\tilde{g}_{kj}(v)+1}\right)\right\} - \eta^* E\left\{p_j(v)/\zeta + P_c^D\right\}. \tag{9}$$

The equivalence of (8) and (9) can be easily verified at $p_j^*(v)$ with corresponding maximal η^*. With an strictly concave numerator and convex denominator, the η can be updated by Dinkelbach's method [12]. In a concave fractional programming problem, local maximum is a global maximum [13]. Then, motivated by the works in [8,9], we transform the problem into an equivalent subtractive mixed integer programming problem under condition set $\mathfrak{F}$

$$\max_{\{p_j(v)\in\mathfrak{F}\}} f\left(p_j(v), \eta\right), \tag{10}$$

where

$$f\left(p_j(v), \eta\right) = E\left\{log_2\left(1+\frac{p_j(v)\tilde{h}_j(v)}{p_k(v)\tilde{g}_{kj}(v)+1}\right)\right\} - \eta E\left\{p_j(v)/\zeta + P_c^D\right\}.$$

Finally, the optimal solution can be found by using classical Lagrange multipliers.

3.1 Average Interference Power Constrains

Under the average transmit power and the average interference power constrains, the condition set $\mathfrak{F}$ is the combination of (3), (4), (5) and (6).

All the power constraints in current section and following sections are affine and so do their combinations. It is easy to prove that the problem (9) is a strictly quasi-convex problem [9], which can be solved by using the Lagrange duality method [13]. Here we introduce the non-negative Lagrange multipliers λ and μ for the inequality constraints. The Lagrangian with respective to the transmit power $p_j(v)$ is

$$\begin{aligned} L(p_j(v), \lambda, \mu) = E&\left\{log_2\left(1+\frac{p_j(v)\tilde{h}_j(v)}{p_k(v)\tilde{g}_{kj}(v)+1}\right)\right\} \\ &- \eta E\left\{p_j(v)/\zeta + P_c^D\right\} - \lambda\left\{E\left\{p_j(v)\right\} - P_{th}^D\right\} \\ &- \mu\left\{E\left\{p_j(v)\tilde{g}_{jk}(v)\right\} - \gamma_I^D\right\} \end{aligned} \tag{11}$$

We can get the Lagrange dual function as

$$G\left(\lambda, \mu\right) = \max_{0\leq p_j(v)} L\left(p_j(v), \lambda, \mu\right) \tag{12}$$

The dual function serves as an upper bound on the optimal value of the original problem, denoted by γ^*, that is $\gamma^* \leq G(\lambda, \mu)$ for any nonnegative λ and μ. The dual problem is then defined as $\underset{\lambda \geq 0, \mu \geq 0}{min} G(\lambda, \mu)$.

Let the optimal value of the dual problem be denoted by d^*, which is achievable by the optimal dual solutions λ^* and μ^*, that is $d^* \leq G(\lambda^*, \mu^*)$. For a convex optimization problem with a strictly feasible point as in our problem, the Slater's condition is satisfied and thus the duality gap $r^* - d^* \leq 0$ is indeed zero. So the problem (9) can be equivalently solved from its dual problem, i.e. by first maximizing its Lagrangian to obtain the dual function for some given dual variables, and then minimizing the dual function over the dual variables.

Firstly, obtain $G(\lambda, \mu)$ with given λ and μ,

$$G(\lambda, \mu) = E\left\{\tilde{G}(v)\right\} - \eta P_c^D + \lambda P_{th}^D + \mu \gamma_I^D \tag{13}$$

where

$$\begin{aligned}\tilde{G}(p_j(v)) = max log_2 &\left(1 + \frac{p_j(v)\tilde{h}_j(v)}{p_k(v)\tilde{g}_{kj}(v) + 1}\right) \\ &- \eta p_j(v)/\zeta - \lambda p_j(v) - \mu p_j(v)\tilde{g}_{jk}(v).\end{aligned} \tag{14}$$

The dual function can be obtained via solving for sub-dual-functions $\tilde{G}(p_j(v))$, each for one fading state with channel realization.

Note that the maximization problem with different (v) all have the same structure and can be solved using the same computational routine. For conciseness, we drop the index (v) for the maximization problem at each fading state in the expression below. For a particular fading state, the associated subproblem can be defined as

$$\underset{0 \leq p_j}{max} log_2\left(1 + \frac{p_j\tilde{h}_j}{p_k\tilde{g}_{kj} + 1}\right) - \eta p_j/\zeta - \lambda p_j - \mu p_j\tilde{g}_{jk} \tag{15}$$

The problems (9) has been transformed into sets of independent concave problems which can be solved separately.

Proposition 1. *The energy efficient optimal power allocation strategy to problem (15) can be given as a quasi-water-filling form*

$$p_j^* = \left[\frac{1}{(\eta/\zeta + \lambda + \mu\tilde{g}_{jk})\, ln2} - \frac{p_k\tilde{g}_{kj} + 1}{\tilde{h}_j}\right]^+, \forall v \tag{16}$$

where $[a]^+ = max(a, 0)$ *and max(a,0) denotes the maximum between a and 0.*

Proof. Since the objective function is concave function related to p_j and the constraints are linear, the problem (15) is convex. Hence the problems can be solved bia standard optimization methods. To satisfy the KKT conditions, the following dual solution need to be satisfied

$$\frac{1}{ln2}\frac{\tilde{h}_j}{p_k\tilde{g}_{kj}+1+p_j^*\tilde{h}_j}-(\eta/\zeta+\lambda+\mu\tilde{g}_{jk})+\vartheta^*=0,\forall v \qquad (17)$$
$$\vartheta^* p_j^*=0,\forall v$$

With $\vartheta^*\geq 0$ and $p_j^*\geq 0,\forall v$, from the KKT optimality conditions, it is easy to obtain that the energy efficient optimal power allocation strategy can be given as in (16).

3.2 Instantaneous Interference Power Constraints

When the interference constraints are more strict on each fading state, the problem can also be proven to be a concave fractional programming problem. Similar to the above subsection, the condition set $\mathfrak{F}$ is now the combination of (3), (4), (5) and (7).

The Lagrangian with respective to the transmit power $p_j(v)$ is

$$\begin{aligned}L(p_j(v),\lambda,\mu)=E\left\{log_2\left(1+\frac{p_j(v)\tilde{h}_j(v)}{p_k(v)\tilde{g}_{kj}(v)+1}\right)\right\}\\ -\eta E\left\{p_j(v)/\zeta+P_c^D\right\}-\lambda\left\{E\left\{p_j(v)\right\}-P_{th}^D\right\}\end{aligned} \qquad (18)$$

Let $\mathfrak{B}$ denote the set of $p_j(v)$ specified by the constrains in (5) and (7), $\mathfrak{B}=\left\{p_j(v)\mid p_j(v)\geqslant 0, p_j(v)\tilde{g}_{jk}(v)\leq\gamma_I^D,\forall v\right\}$. We can get the Lagrange dual function as

$$G(\lambda)=\max_{p_j(v)\in\mathfrak{B}}L(p_j(v),\lambda) \qquad (19)$$

The dual problem is then defined as $\min_{\lambda\geq 0}G(\lambda,\mu)$. Similar to problem 9, this dual problem can be decomposed into individual sub-dual-functions. Firstly, obtain $G(\lambda)$ with given λ,

$$G(\lambda)=E\left\{\tilde{G}(v)\right\}-\eta P_c^D+\lambda P_{th}^D \qquad (20)$$

where

$$\tilde{G}(p_j(v))=\max_{p_j(v)\in\mathfrak{B}}log_2\left(1+\frac{p_j(v)\tilde{h}_j(v)}{p_k(v)\tilde{g}_{kj}(v)+1}\right)-\eta p_j(v)/\zeta-\lambda p_j(v). \qquad (21)$$

The dual function can be obtained via solving for sub-dual-functions $\tilde{G}(p_j(v))$, each for one fading state with channel realization. Drop the index (v) for the maximization problem at each fading state in the expression below. For a particular fading state, the associated subproblem can be defined as

$$\begin{aligned}&max\ log_2\left(1+\tfrac{p_j\tilde{h}_j}{p_k\tilde{g}_{kj}+1}\right)-\eta p_j/\zeta-\lambda p_j\\ &s.t.\qquad p_j\geqslant 0\\ &\qquad\quad p_j\tilde{g}_{jk}\leq\gamma_I^D\end{aligned} \qquad (22)$$

Proposition 2. *The energy efficient optimal power allocation strategy to problem (22) can be given as*

$$p_j^* = min\left(\left[\frac{1}{(\eta/\zeta+\lambda)\, ln2} - \frac{p_k\tilde{g}_{kj}+1}{\tilde{h}_j}\right]^+, \frac{\gamma_I^D}{\tilde{g}_{jk}}\right) \tag{23}$$

where min(a,b) denotes the minimum between a and b, $[a]^+ = max(a,0)$ *and max(a,0) denotes the maximum between a and 0.*

Proof. Since the objective function is concave function related to p_j and the constraints are linear, the problem (22) is convex. Hence the problems can be solved bia standard optimization methods. To satisfy the KKT conditions, the following primal and dual solution need to be satisfied

$$\begin{aligned} \tfrac{1}{ln2}\tfrac{\tilde{h}_j}{p_k\tilde{g}_{kj}+p_j^*\tilde{h}_j+1} - (\eta/\zeta+\lambda) - \mu^*\tilde{g}_{jk} + \vartheta^* = 0 \ &, \forall v \\ \vartheta^* p_j^* = 0 \qquad\qquad &, \forall v \\ \mu^*\left(p_j^*\tilde{g}_{jk} - \gamma_I^D\right) = 0 \qquad\qquad &, \forall v \end{aligned} \tag{24}$$

With $\mu^* \geq 0$, $\vartheta^* \geq 0$ and $p_j^* \geq 0, \forall v$. Suppose that $p_j^* \geq 0, \forall v$, it follows that $\vartheta^* = 0$. Unlike in the (17), where μ^* is fixed, the μ^* in (24) is different for each fading state. As we consider an egoistic cellular, the base station transmits at maximum power $p_k(v) = P_{th}^C, \forall v$. To satisfy the KKT optimality conditions, we analyze the following two cases, sinceμ^*, ϑ^* and p_j^* are strictly positive.

Firstly, consider the case where $\mu^* = 0$. Since $\vartheta^* \geq 0$, the following must be true:

$$\frac{1}{ln2}\frac{\tilde{h}_j}{p_k\tilde{g}_{kj}+p_j^*\tilde{h}_j+1} - (\eta/\zeta+\lambda) \leq 0$$

Thus the power allocation follows

$$p_j^* = \left[\frac{1}{ln2\,(\eta/\zeta+\lambda)} - \frac{p_k\tilde{g}_{kj}+1}{\tilde{h}_j}\right]^+$$

Secondly, consider the case where $\mu^* > 0$. It follows that $p_j^* = \frac{\gamma_I^D}{\tilde{g}_{jk}}$ and $p_j^* < \frac{1}{ln2(\eta/\zeta+\lambda)} - \frac{p_k\tilde{g}_{kj}+1}{\tilde{h}_j}$. Then the following condition must be satisfied:

$$\frac{\gamma_I^D}{\tilde{g}_{jk}} < \frac{1}{ln2\,(\eta/\zeta+\lambda)} - \frac{p_k\tilde{g}_{kj}+1}{\tilde{h}_j}$$

The energy efficient optimal power allocation strategy in (23) can achieved by summing up the above analysis.

4 Instantaneous Transmit Power Constraints

Similar to the interference power, more strict instantaneous transmit power constraint for the D2D link can be given as

$$p_j(v) \leq P_{th}^D, \forall v \tag{25}$$

As we maximum the $f\left(p_j(v), \eta\right)$ under the instantaneous transmit power and the average interference power constraints, the condition set $\mathfrak{F}$ in (10) is the combination of (3), (4), (6) and (25).

Proposition 3. *The energy efficient optimal power allocation strategy for instantaneous transmit power and average interference power constraints can be given as*

$$p_j^* = min\left(\left[\frac{1}{\left(\eta/\zeta + \mu\tilde{g}_{jk}\right)ln2} - \frac{p_k\tilde{g}_{kj}+1}{\tilde{h}_j}\right]^+, P_{th}^D\right) \tag{26}$$

where min(a, b) denotes the minimum between a and b, $[a]^+ = max(a, 0)$ *and max(a, 0) denotes the maximum between a and 0.*

Finally, while both the transmit and interference power constraints are instantaneous, the condition set $\mathfrak{F}$ is the combination of (3), (4), (7) and (25).

Proposition 4. *The energy efficient optimal power allocation strategy for instantaneous transmit and interference power constraints can be given as*

$$p_j^* = min\left(\left[\frac{1}{ln2\eta/\zeta} - \frac{p_k\tilde{g}_{kj}+1}{\tilde{h}_j}\right]^+, \frac{\gamma_I^D}{\tilde{g}_{jk}}, P_{th}^D\right) \tag{27}$$

The two propositions in this section can be solved by using proving process similar to Propositions 1 and 2. For brevity, the details are not given here.

In the Proposition 3, only μ is required to be updated. In an extreme case of $\mu = 0$, the ergodic capacity of the D2D user is achieved with the maximum available power, which is consistent with no interference constraints (6).

5 Simulation Results and Discussion

In this section, simulation results are presented to evaluate the energy efficiency of the D2D link with the proposed optimal power allocation strategies. An power allocation algorithms based on classical Dinkelbach's iterative method and subgradient method can be applied to solve the energy efficient optimal problems. Main system parameters are listed in Table 1.

Table 1. Simulation parameters

Parameter	Value
Carrier frequency	2 GHz
Cell radius	500 m
BS transmit power	43 dBm
D2D transmit power	20 dBm
Circuit power of D2D	600 mW
Path loss factor α_l in urban environments	1.75
Path loss factor α_l of D2D links	1.5
Log-Normal Shadowing standard deviation	4 dB
Noise variance	-120 dBm

The large scale path-loss is calculated by $L = 32.45 + 20log_{10}f_c + \alpha_l 20log_{10}d$, where f_c and d are united by GHz and meters. The channels of the D2D links follow the Rician fading while other channels follow the Rayleigh fading. In the following simulations, we set the cell radius 500 m, and the CUs and D2D links are uniformly distributed within the cell. While not involving with distance change, the distances are identically set to $d_j = 50$ m, $d_k = 200$ m, $d_{kj} = 350$ m, $d_{jk} = 400$ m.

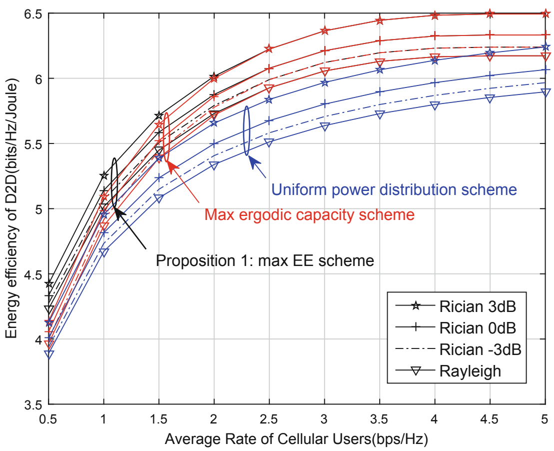

Fig. 1. Energy efficient performance comparison.

Figure 1 shows the average energy efficiency of D2D versus the average interference to noise power ratios γ_I^D, which restrict the degree of resource sharing between the CUs and D2D links. The different degrees of Rician factor of the D2D links ($K = 3, 0, -3$ dB) are investigated. Three power allocation strategies are compared, that is the proposed energy efficient optimal power allocation, the ergodic capacity maximization allocation and the baselines, in which uniform power distribution scheme are employed. In the schemes of propositions, the power amplifier coefficients of D2D are set to $\zeta = 1$. We compare the simulation result with the ergodic capacity maximization problems, which is approximately in consistent with schemes [8]. As for frequency sharing interferences, not only the sharer to the provider, but the provider to the sharer, are considered in our propositions, which are an improvement over the ergodic capacity maximization schemes in [9]. The higher transmit power of D2D link means the high interference to the CUE. As is indicated in the graph, the energy efficiency of D2D increases with the transmit power. But, as Shannon principle reveals that the spectrum efficiency and power efficiency cannot infinitely increase with the power, the energy efficiency approaches to the limit as well.

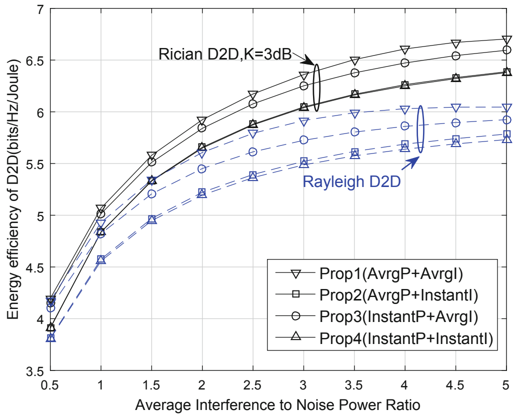

Fig. 2. Energy efficiency of four propositions with different transmit power and interference power constraints.

In Fig. 2, we compare the energy efficiency of D2D link of the four proposed propositions corresponding to different power constraints. The simulation parameters are consistent with those of Fig. 1. The black full lines depict the D2D links with Rician factor of $K = 3\,\mathrm{dB}$ and the dotted blue lines depict Rayleigh D2D links. The instantaneous power constrains are more stringent explicitly over the average power constrains. Through analyzing the result, the interference power constraints are more dominant than the transmit power constraints. Therefore the energy efficiency of D2D under the average interference power constraints is much larger than that under the instantaneous interference power constraints.

As we considering the average spectral efficiency, the reduction of CUE rate with the invasive spectral sharers and the increment of D2D rate are compared in Fig. 3. The admission of D2D link causes only modest loss of CUE rate, therefore there are significant increases in spectral efficiency. The proposed energy-efficient

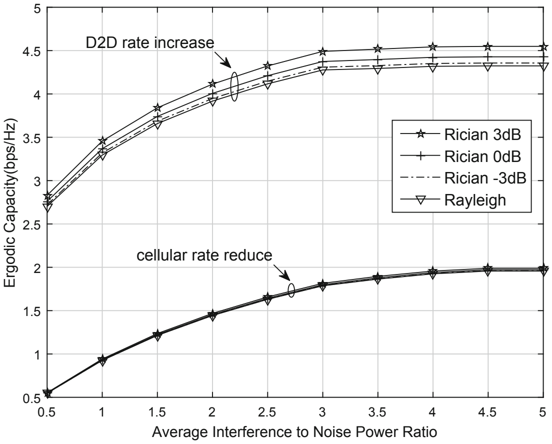

Fig. 3. Rate performance with the introduce of D2D in cellular system

optimal power allocation strategies not only improve the energy efficiency of the D2D links but also on the premise that cellular communication performance is guaranteed.

6 Conclusions

In this paper, the energy-efficient power allocation strategy has been studied for D2D communications underlaying downlink cellular networks. The energy efficiency maximization problem was formulated under both average and instantaneous power constraints. The numerical results proved the proposed strategies of better performance at both energy and spectrum efficiency with the D2D underlaying normal cellular communication.

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References

1. Gandotra, P., Jha, R., Jain, S.: Green communication in next generation cellular networks: a survey. IEEE Access **5**(6), 11727–11758 (2017)
2. David, K., Berndt, H.: 6G vision and requirements: is there any need for beyond 5G. IEEE Veh. Technol. Mag. **13**(3), 72–80 (2018)
3. Wang, J., Zhu, D., Zhao, C., et al.: Resource sharing of underlaying device-to-device and uplink cellular communications. IEEE Commun. Lett. **17**(6), 1148–1151 (2013)

4. Zhu, D., Wang, J., Swindlehurst, A.L., et al.: Downlink resource reuse for device-to-device communications underlaying cellular networks. IEEE Signal Process. Lett. **21**(5), 531–534 (2014)
5. Wu, D., Wang, J., Hu, R.Q., et al.: Energy-efficient resource sharing for mobile device-to-device multimedia communications. IEEE Trans. Veh. Technol. **63**(5), 2093–2103 (2014)
6. Hu, J., Heng, W., Li, X., et al.: Energy-efficient resource reuse scheme for D2D communications underlaying cellular networks. IEEE Commun. Lett. **21**(9), 2097–210 (2017)
7. Dai, H., Huang, Y., Xu, Y., et al.: Energy-efficient resource allocation for energy harvesting-based device-to-device communication. IEEE Trans. Veh. Technol. **68**(1), 509–524 (2018)
8. Zhang, R., Cui, S., Liang, Y.C.: On ergodic sum capacity of fading cognitive multiple-access and broadcast channels. IEEE Trans. Inform. Theory **55**(11), 5161–5178 (2009)
9. Zhou, F., Beaulieu, N.C., Li, Z., et al.: Energy-efficient optimal power allocation for fading cognitive radio channels: ergodic capacity, outage capacity, and minimum-rate capacity. IEEE Trans. Wirel. Commun. **15**(4), 2741–2755 (2016)
10. Dominic, S., Jacob, L.: Distributed resource allocation for D2D communications underlaying cellular networks in time-varying environment. IEEE Commun. Lett. **22**(2), 388–391 (2018)
11. Nguyen, H.H., Hasegawa, M., Hwang, W.J.: Distributed resource allocation for D2D communications underlay cellular networks. IEEE Commun. Lett. **20**(5), 942–945 (2016)
12. Dinkelbach, W.: On nonlinear fractional programming. Manage. Sci. **13**(7), 492–498 (1967)
13. Boyd, S., Vandenberghe, L.: Convex Optimization, 5th edn. Cambridge University Press, Cambridge (2004)