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Energy efficient power allocation for underlaying mobile D2D communications with peak/average interference constraints

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Dear editor,
Recently, Device-to-Device (D2D) communication is conceived as a candidate paradigm to provide ultra-reliable and low-latency services or high data rate required applications for future intelligent transportation systems [1]. Although the feasibility of applying D2D communications to vehicular communications has been investigated, the interference caused by resource reuse is still a major obstacle to achieve envisioned advantages of mobile D2D communications and guarantee the performance of cellular communications [2].

To achieve optimal data rate, reuse channel selection and power control schemes were proposed in [3]. The authors in [4] proposed a joint resource allocation scheme to maximize the spectral efficiency (SE) of mobile D2D communications. Considering requirements of both delay and reliability of mobile D2D communications, the authors in [5] conducted resource management to maximize the capacity of cellular users. A location dependent resource allocation scheme was introduced in [6] to deal with resource reservation problems in terms of throughput and delay.

All the aforementioned studies concentrated on optimizing the SE of mobile D2D communications, while the consideration of energy efficiency (EE), an important metric for fifth-generation (5G) networks [7], for mobile D2D communications is still missing. Besides, existing papers only considered large-scale fading model [3–5] or a simplified distance model [6]. However, the high mobility of D2D users and/or the vehicular traffic density (VTD) may have a significant influence on the propagation characteristics of wireless channel [8]. An inaccurate channel model may result in inaccurate system performance evaluations. To the best of our knowledge, the resource management scheme for underlaying mobile D2D communications under reasonable channel model have not been well investigated.

To fill these gaps, we investigate the energy efficient power allocation in an underlaying mobile D2D communications scenario, where a three-dimensional (3D) vehicle-to-vehicle (V2V) channel is adopted to characterize the mobility of wireless channel propagation in a vehicular environment. Moreover, a general trade-off analysis between EE and SE is quantitatively illustrated in terms of EE loss ratio and SE gain ratio.

System model. We consider a single cell scenario where the D2D source (SU) communicates with the D2D destination (DU) sharing cellular downlink resource. In this case, the DU will suffer

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from interference from the base station (BS) while the cellular user (CU) is also interfered by the SU. We denote $h_{\rm sd}$, $h_{\rm sc}$, and $h_{\rm bd}$ as the channel coefficients of SU$\rightarrow$DU, SU$\rightarrow$CU, and BS$\rightarrow$DU links, respectively. To accurately capture the effect of the mobility of D2D users and moving vehicles on the channel characteristics, we model the involved links as the 3D V2V channel model proposed in [8].

We consider three power constraints. Due to the hardware limitations, the transmit power of the SU should never exceed the maximum transmit power $P_{\max}$, i.e., C1: $P_{\rm s} \leqslant P_{\max}$. Besides, to protect cellular communications from significant degradation, the received interference power at CUs should remain a tolerable level. Considering the diversification of services and various QoS requirements in future 5G networks, two interference constraints are taken into account. By denoting $I_{\rm ave}$ and $I_{\rm peak}$ as the average and peak interference power thresholds at the CU, we have C2: $\mathrm{E}\{P_{\rm s}|h_{\rm sc}|^2\} \leqslant I_{\rm ave}$ and C3: $P_{\rm s}|h_{\rm sc}|^2 \leqslant I_{\rm peak}$, respectively. Here, $\mathrm{E}\{\cdot\}$ is the statistical expectation.

Optimal transmit power allocation. The average SE is the ratio of average capacity to the bandwidth W, i.e., $\Psi_{\rm SE}=\frac{\mathrm{E}\{C\}}{W} = \mathrm{E}\{\log_2(1+\gamma P_{\rm s})\}$ where C is the instantaneous capacity and $\gamma=\frac{|h_{\rm sd}|^2}{N_0+P_{\rm b}|h_{\rm bd}|^2}$ with N_0 as the noise power and $P_{\rm b}$ as the transmit power of BS. The average EE is defined as the ratio of $\Psi_{\rm SE}$ to the average total power consumption, i.e., $\Psi_{\rm EE}=\frac{\Psi_{\rm SE}}{\mathrm{E}\{P\}} = \frac{E\{\log_2(1+\gamma P_{\rm s})\}}{\mathrm{E}\{\eta P_{\rm s}+P_0\}}$ with $1/\eta \in (0,1]$ denoting the drain efficiency of the power amplifier and P_0 as the circuit power [2].

We consider two typical scenarios, i.e., high VTD and low VTD scenarios. To reveal the impact of vehicular channel characteristics on EE and SE in a visible way, we plot the achievable EE versus SE under the 3D V2V channel model in Figure 1. As shown, a small degradation in EE around its peak value results in a significant gain in SE. Based on the observations from the figure, we maximize SE subject to EE threshold.

Then, combined with the power constraints, the optimization problem can be formulated as

$$\max_{P_{\rm s}} \Psi_{\rm SE} \quad \text{s.t. C1}, \mathrm{C}m, \text{C4}: \Psi_{\rm EE} \geqslant \Gamma_{\rm EE}, \qquad (1)$$

where $\Gamma_{\rm EE}$ is the EE threshold and $m = 2, 3$.

Power allocation without transmit power constraint. We first settle (1) without C1. Since the objective function is logarithmic function with respect to $P_{\rm s}$ and thus, it is concave. Note that the objective function is differentiable, so it is Pseudo-concavity in $P_{\rm s}$. Besides, since the denominator of C4 is affine, C4 is quasi-concave in $P_{\rm s}$.

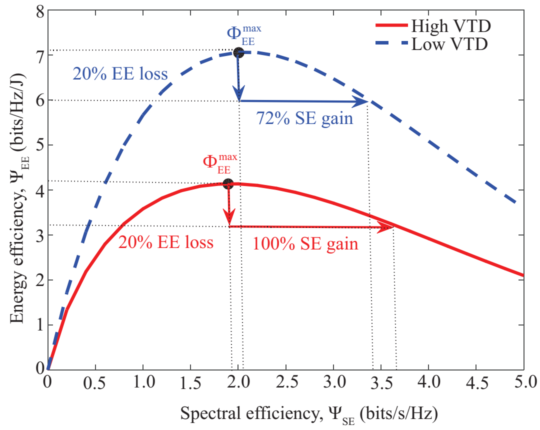

Figure 1 (Color online) EE vs. SE with peak interference constraint ($d_{\rm sd}$ = 300 m, P_0 = 100 mW, $I_{\rm th}$ = -70 dBm, v = 5 m/s).

Power allocation with peak interference constraint. Since C3 is a linear constraint, the Karush-Kuhn-Tucker (KKT) conditions are both sufficient and necessary for the optimality of (1). Using the Lagrange multiplier method, we have

$$P_{\rm s}=\frac{\alpha}{\Gamma_{\rm EE}} - \frac{\beta}{|h_{\rm sd}|^2}, \qquad (2)$$

where $\beta = N_0 + P_{\rm b}|h_{\rm bd}|^2$ and $\alpha=\frac{(1+\lambda)}{\ln 2\eta\lambda}$. Here $\lambda \geqslant 0$ is the Lagrange multiplier associated with constraint C4. If C4 is satisfied with strict inequality, the parameter λ must be zero. Otherwise, the value of λ can be obtained by substituting (2) into C4 and setting the inequality to equality, i.e.,

$$\mathrm{E}\left\{\log_2\left(\frac{\alpha|h_{\rm sd}|^4}{\beta\Gamma_{\rm EE}}\right)\right\} - \Gamma_{\rm EE}\mathrm{E}\left\{\eta\left(\frac{\alpha}{\Gamma_{\rm EE}} - \beta\right)+P_0\right\} = 0. \qquad (3)$$

Considering $P_{\rm s} \geqslant 0$ and the peak interference constraint C3, the optimal transmit power $P_{\rm s}'$ is

$$P_{\rm s}'=\min\left(\left[\frac{\alpha}{\Gamma_{\rm EE}} - \frac{\beta}{|h_{\rm sd}|^2}\right]^+, \frac{I_{\rm peak}}{|h_{\rm sc}|^2}\right), \qquad (4)$$

where $[x]^+$ means $\max(0, x)$. From (4) we can see that $P_{\rm s}'$ is dependent on the interference constraint ($I_{\rm peak}$), the channel gains ($|h_{\rm sd}|^2, |h_{\rm bd}|^2, |h_{\rm sc}|^2$), and the EE threshold ($\Gamma_{\rm EE}$), among which $\Gamma_{\rm EE}$ is the decisive parameter for the EE-SE trade-off.

Next, we discuss the impact of $\Gamma_{\rm EE}$ on $P_{\rm s}'$, where $\Gamma_{\rm EE}$ can be divided into three regions: (1) $\Gamma_{\rm EE} < \alpha(\frac{I_{\rm peak}}{|h_{\rm sc}|^2} + \frac{\beta}{|h_{\rm sd}|^2})^{-1}$: $\Gamma_{\rm EE}$ is too small to be an active constraint and we have $P_{\rm s}'=\frac{I_{\rm peak}}{|h_{\rm sc}|^2}$. (2) $\alpha(\frac{I_{\rm peak}}{|h_{\rm sc}|^2} + \frac{\beta}{|h_{\rm sd}|^2})^{-1} \leqslant \Gamma_{\rm EE} \leqslant \frac{\alpha}{\beta}|h_{\rm sd}|^2$: In this case, $P'_{\rm s}{=}\frac{\alpha}{\Gamma_{\rm EE}}-\frac{\beta}{|h_{\rm sd}|^2}$, we should adapt the transmit power according to channel fading under the given threshold $\Gamma_{\rm EE}$. (3) $\Gamma_{\rm EE}>\frac{\alpha}{\beta}|h_{\rm sd}|^2$: We have $P'_{\rm s}=0$, indicating that the D2D communication will be terminated since $\Gamma_{\rm EE}$ is too high that it cannot be satisfied by the acceptable transmit power.

Power allocation with average interference constraint. The expectation with respect to $h_{\rm sd}$, $h_{\rm bd}$, and $h_{\rm sc}$ is a linear operation for $P_{\rm s}$. Thus, the KKT conditions are still necessary and sufficient for the optimality of problem (1) with C2. Following similar procedures, we have

$$P'_{\rm s}{=}\left[\frac{(1+\mu)}{\ln 2\left(\eta\mu\Gamma_{\rm EE}+\nu|h_{\rm sc}|^2\right)}-\frac{\beta}{|h_{\rm sd}|^2}\right]^+, \quad (5)$$

where $\nu,\mu\geqslant 0$ are the Lagrange multipliers associated with constraints C2 and C4. The optimum value of μ and ν can be obtained by substituting (5) into the constraints C2 and C4, and setting the inequalities to equalities, i.e.,

$$\mathrm{E}\left\{\log_2\left(1+\frac{|h_{\rm sd}|^2P'_{\rm s}}{\beta}\right)\right\}-\Gamma_{\rm EE}\mathrm{E}\left\{\eta P'_{\rm s}+P_0\right\}=0, \quad (6)$$

and

$$\mathrm{E}\left\{P'_{\rm s}|h_{\rm sc}|^2\right\}=I_{\rm ave}. \quad (7)$$

When the transmit power constraint is considered, the optimal transmit power can be expressed as $P^*_{\rm s}=\min\left(P'_{\rm s},P_{\max}\right)$.

EE-SE trade-off. To quantitatively illustrate the EE-SE trade-off, we define $\theta_{\rm EE}$ and $\theta_{\rm SE}$ as the ratios of variation of EE and SE, respectively. Then, the SE gain ratio can be written as

$$\theta^+_{\rm SE}{=}\frac{\Psi_{\rm SE}\left(P^*_{\rm s}\left(\Gamma_{\rm EE}\right)\right)-\Psi^{\max}_{\rm SE}}{\Psi^{\max}_{\rm SE}}, \quad (8)$$

and the corresponding EE loss ratio is

$$\theta^-_{\rm EE}{=}\frac{\Psi^{\max}_{\rm EE}-\Psi_{\rm EE}\left(P^*_{\rm s}\left(\Gamma_{\rm EE}\right)\right)}{\Psi^{\max}_{\rm EE}}. \quad (9)$$

Here, $\Psi^{\max}_{\rm EE}$ is the maximum EE achieved within the feasible power region and $\Psi^{\max}_{\rm SE}$ is the corresponding SE. Moreover, $\Psi_{\rm SE}\left(P^*_{\rm s}\left(\Gamma_{\rm EE}\right)\right)$ is the SE at the optimal power $P^*_{\rm s}\left(\Gamma_{\rm EE}\right)$ related to $\Gamma_{\rm EE}$, and $\Psi_{\rm EE}\left(P^*_{\rm s}\left(\Gamma_{\rm EE}\right)\right)$ is the corresponding EE. The larger $\theta^-_{\rm EE}$ is, the larger the increment of SE can be achieved. Considering power consumption of equipment cannot be ignored, we cannot keep increasing $\theta^-_{\rm EE}$. When conducting power allocation, we should determine the operational point of $\theta^-_{\rm EE}$ according to different EE requirements.

Simulation results are shown in Appendix A.

Conclusion. We have proposed an energy efficient power allocation scheme for underlaying mobile D2D communications and derived the optimal transmit power with given constraints. Simulation results have shown little loss in EE could bring significant gain in SE.

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Supporting information Simulation results (Appendix A). The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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