SCIENCE CHINA
Information Sciences

• **Supplementary File** •

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

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Appendix A Simulation Results

We evaluate the schemes described in previous section through Monte Carlo simulations. In the simulations, the pathloss model between BS and users is $PL = 128.1 + 37.6\log_{10}(d\ \text{[in Km]})$ and the pathloss model between users is $PL = 148.1 + 40\log_{10}(d\ \text{[in Km]})$. We set $N_0 = -174$ dBm/Hz and $W = 1$ MHz. We denote $d_{\rm sd}$, $d_{\rm sc}$, and $d_{\rm bd}$ as the distances of SU→DU, SU→CU, and BS→DU links, respectively. Unless specifically stated, we set $d_{\rm sd} = 300$ m, $d_{\rm cd} = 400$ m, and $d_{\rm sb} = 400$ m. For simplicity, we assume that the SU and the DU move toward each other and in the same speed $\nu = 5$ m/s. The velocity of the CU is set to zero. Specific values of channel parameters of the 3D V2V channel model are consistent with [1].

We firstly conduct simulations to demonstrate the impact of P_0 on the energy efficiency of underlaying mobile D2D communications in both low VTD and high VTD scenarios, as shown in Fig. A1. As expected, the energy efficiency increases in the beginning and deteriorates afterwards for each P_0. The larger the P_0 is, the smaller the EE becomes. Nevertheless, the optimal point of SE that maximizes EE moves right as the circuit power consumption increases, which implies that when P_0 increases, we need to increase transmit power rather than decreasing it to achieve higher EE, although the total power consumption will increase. Moreover, the EE in low VTD outperforms that in high VTD, where the signals suffer from poor propagation environment.

Next, we take the high VTD scenario as an example to illustrate the impact of EE threshold on the transmission power and average achievable EE of mobile D2D communications, where the peak interference constraint is adopted. As shown in Fig. A2, as $I_{\rm th}$ increases, i.e., larger interference power is acceptable for cellular communications, $P_{\rm s}$ increases. Due to the transmit power constraint, $P_{\rm s}$ with different EE thresholds remain unchanged eventually. As expected, the larger $\Gamma_{\rm EE}$ is, the smaller $P_{\rm s}$ is. This is because that tight EE constraint restricts the maximum feasible transmission power. Besides, similar to the observation in Fig. A1, EE increases at first and then decreases. Eventually, due to the EE constraint, EE remains constant. Moreover, the higher the EE requirement is, i.e., $\Gamma_{\rm EE}$ gets larger, the lower the achievable EE is. This is because that $\Psi_{\rm EE}$ is the mean value of EE on multiple simulation times. For a given $I_{\rm th}$, as $\Gamma_{\rm SE}$ increases, the probability that $\Psi_{\rm EE} > \Gamma_{\rm EE}$ decreases. When the EE constraint is destroyed, the mobile D2D communication will be terminated and $\Psi_{\rm EE}$ is zero. Therefore, from the perspective of statistics, achievable average EE decreases with the EE requirement increases.

To illustrate the different impacts of peak and average interference constraints on SE performance of mobile D2D communications, Fig. A3 and Fig. A4 perform the spectral efficiency versus interference threshold for different $d_{\rm sd}$ and $\Gamma_{\rm EE}$, respectively. As observed in both figures, the SE with average interference constraint outperforms that with peak interference constraint, since that the peak interference constraint is stricter by restricting resultant interference power at each fading state to be below a predefined value. Meanwhile, the performance gap in high VTD scenario is larger than that in low VTD scenario, which implies it makes much more sense to adapt the transmit power of D2D users according to different QoS requirements of cellular users in high VTD scenario. Moreover, due to the transmit power constraint, the SE with different interference constraints reach the same level eventually in Fig. A3.

For Fig. A4, it is interesting to note that a few points are unavailable at the beginning of the SE curves with average interference constraint, which is due to that when the interference constraint is strict, i.e., $I_{\rm th}$ is small, the permitted transmit power is too small that the EE requirement cannot be satisfied. Moreover, since higher $\Gamma_{\rm EE}$ requires more transmit power,

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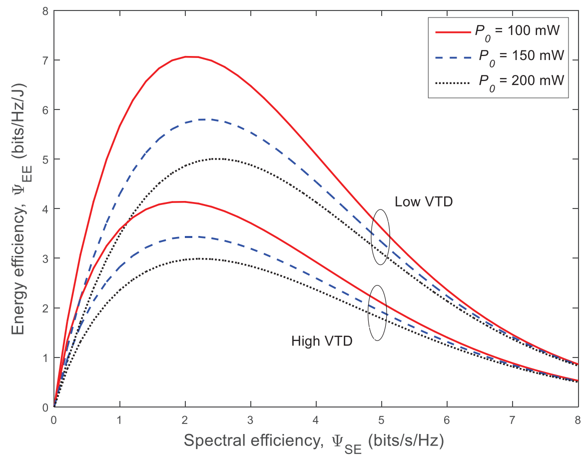

Figure A1 Energy efficiency versus spectral efficiency with different P_0 ($P_B = 23$ dBm, $I_{th} = \infty$, and $d_{sd} = 300$ m).

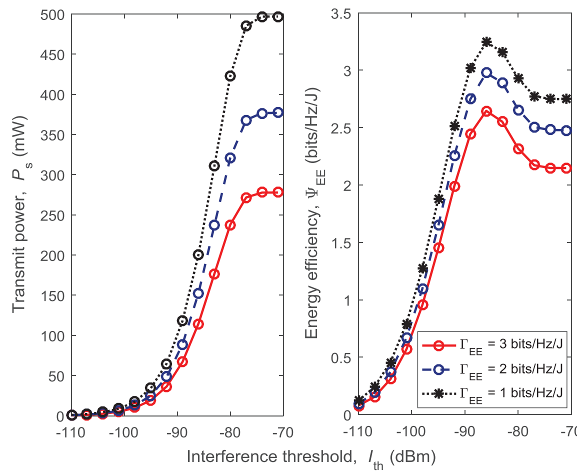

Figure A2 Transmit power and energy efficiency versus interference threshold with different energy efficiency thresholds ($d_{sd} = 300$ m, $P_B = 23$ dBm, $P_{max} = 28$ dBm, and $P_0 = 150$ mW).

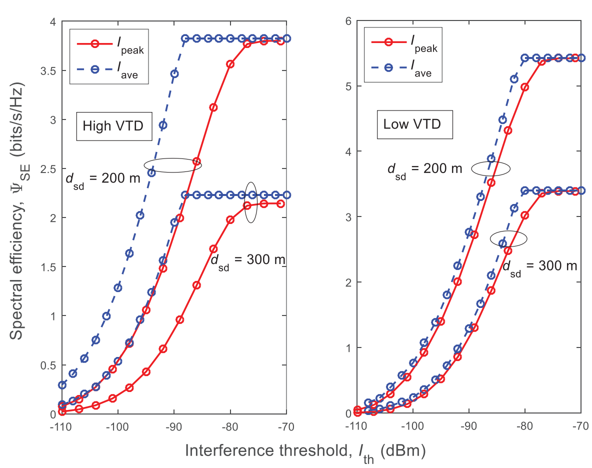

Figure A3 Spectral efficiency versus interference threshold with different communication distances ($\Gamma_{EE} = 1$ bits/Hz/J, $P_B = 23$ dBm, $P_{max} = 28$ dBm, and $P_0 = 150$ mW).

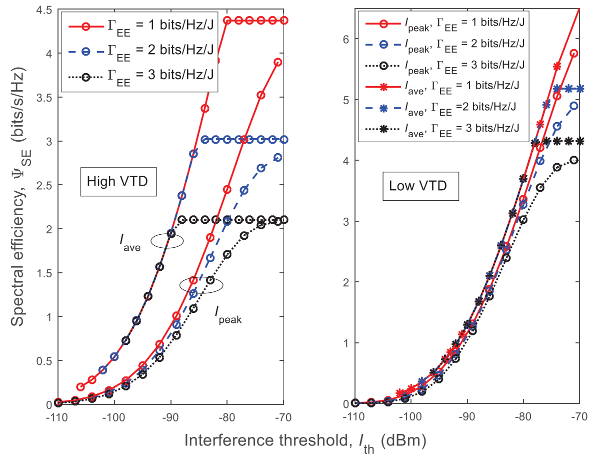

Figure A4 Spectral efficiency versus interference threshold with different energy efficiency thresholds ($d_{\mathrm{sd}} = 300$ m, $P_{\max} = \infty$, $P_{\mathrm{B}} = 23$ dBm, and $P_0 = 150$ mW).

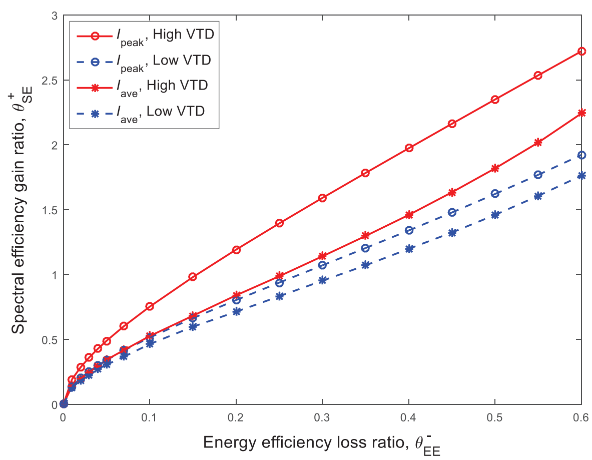

Figure A5 Spectral efficiency gain ratio versus energy efficiency loss ratio ($d_{\mathrm{sd}} = 300$ m, $P_{\mathrm{B}} = 23$ dBm, $P_{\max} = \infty$, $I_{\mathrm{th}} = -70$ dBm, and $P_0 = 100$ mW).

more points are unavailable as Γ_{EE} increases. Meanwhile, although there is no transmit power constraint, the achievable SE remains constant at last. This is because that the EE constraint starts to determine the maximum value of transmit power, rather than interference constraint anymore.

In the following, we conduct simulations to quantitatively illustrate the trade-off between EE and SE in mobile D2D communications. Fig. A5 performs the SE gain ratio θ_{SE}^{+} versus EE loss ratio θ_{EE}^{-} with peak/average interference constraints. In all cases, θ_{SE}^{+} increases as θ_{EE}^{-} increases. Meanwhile, we can see that a fairly little loss in EE around its maximum value, i.e., θ_{EE}^{-} is close to 0, generates a significant gain in SE. Moreover, θ_{SE}^{+} with peak interference constraint is superior to that with average interference constraint in the same VTD scenario. While θ_{SE}^{+} in high VTD scenario is larger than that in low VTD scenario for both interference constraints.

Finally, we take the high VTD scenario as an example to evaluate the impact of d_{sd} and d_{bd} on θ_{SE}^{+} in Fig. A6, where θ_{SE}^{+} increases as d_{sd} increases or d_{bd} decreases. These phenomena reveal that when D2D users suffer from poor communications conditions, e.g., strict interference constraint, long communication distance, server interference, or high VTD, we tend to sacrifice energy efficiency since we can achieve great gain in SE. It can be seen that the SE gain increases as the interference constraint increase, i.e., the looser the I_{th} is. This phenomenon can be explained by integrating two facts into account. One is that the optimal EE is usually obtained with small transmission power as shown in Fig. A1, and another is the tight interference constraint restricts the maximum feasible transmission power, which leads to smaller achievable SE.

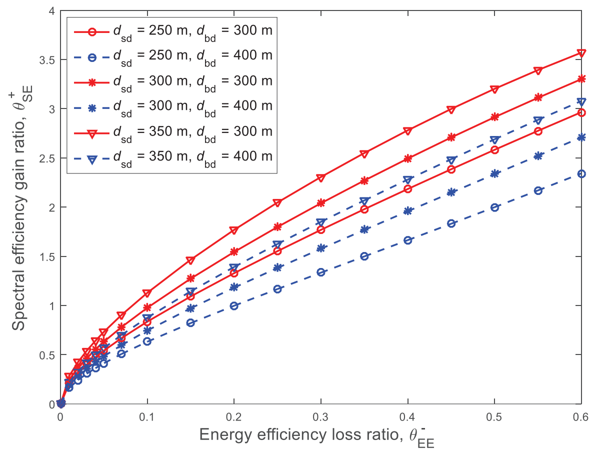

Figure A6 Spectral efficiency gain ratio with different interference and communication distances in high VTD scenario ($P_0 = 100$ mW, $I_{\rm th} = -70$ dBm, $P_{\max} = \infty$, and $P_{\rm B} = 23$ dBm).

References

1 Yuan Y, Wang C-X, Cheng X, *et al.* Novel 3D geometry-based stochastic models for non-isotropic MIMO Vehicle-to-Vehicle channels. IEEE Trans. Wireless Commun., 2014, 13(1): 298-309.