Joint Mode Selection and Power Allocation Scheme for Power-Efficient Device-to-Device (D2D) Communication

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***Abstract*—This paper proposes a power-efficient mode selection and power allocation scheme in device-to-device (D2D) communication system as an underlay coexistence with cellular networks. The proposed scheme is performed based on the exhaustive search of all possible mode combinations of the devices which consist of the mode indices for all devices in the system. Specifically, the proposed scheme consists of two steps. First, we calculate the optimal power with respect to the maximum power-efficiency for all possible modes of each device. Since the power-efficiency is not a concave function for the transmission power, we obtain the suboptimal solution by using the concavity of the lower and upper bound for the power-efficiency. The power-efficiencies for all possible modes of each device are obtained by the suboptimal power allocation in the first step. In the second step, we select a mode sequence which has the maximal power-efficiency among all possible mode combinations of the devices based on the obtained power-efficiencies in the first step. Then we can jointly obtain the suboptimal transmission power and the mode maximizing the power-efficiency. The proposed suboptimal scheme for the power allocation and mode selection performs close to the upper bound with respect to the power-efficiency. The simulation results also show that the proposed scheme outperforms the conventional schemes with respect to the power-efficiency and system capacity.**

I. Introduction

Device-to-device (D2D) communication as an underlay coexistence with cellular networks have been proposed in order to enhance a cell throughput and save the transmission power of device [1]-[6]. Therefore, D2D communication underlaying cellular networks has recently received great attention [1]-[6].

In D2D communication underlaying cellular networks, the devices transmit a signal in uplink spectrum of cellular networks for the direct communication [1][7]. Since the transmit signals of the D2D devices and the uplink signals of the cellular devices interfere each other, D2D communication underlaying cellular networks is an interference-limited system. Therefore, power allocation strategies are generally used as the interference management techniques [1]-[4].

An efficient mode selection scheme is also necessary to operate D2D communication. The devices in the same cell within the possible range for direct communication have an opportunity to select the D2D mode. In this paper, the D2D mode indicates the direct communication between a pair of the D2D devices, and the cellular mode indicates the communication via the base station as in [1][5][6]. The mode selection scheme makes a decision on whether the device operates in the D2D mode or cellular mode. In order to save the transmission power of the device, the mode selection scheme to minimize the transmission power has been proposed in [1]. Also, the mode selection scheme to maximize the system capacity has been investigated to enhance the cell throughput in [2][3][5].

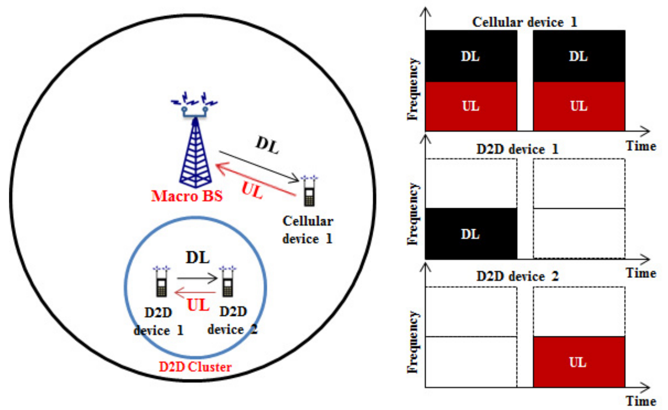

Fig. 1. System model for underlay D2D communication and cellular network.

Therefore, it is necessary to jointly consider those two aspects the transmission power and the system capacity in D2D communication underlaying cellular networks. In this paper, we define the utility function as power-efficiency in order to jointly consider the system capacity and the transmission power. The power-efficiency is defined as the system capacity per total power in this paper. The joint mode selection and power allocation scheme is proposed to maximize the utility function. In the proposed scheme, we calculate the optimal power with respect to the maximal power-efficiency for each all possible modes of each device. Since the power-efficiency is not a concave function for the transmission power, we obtain the suboptimal solution by using the concavity of the lower and upper bounds for the power-efficiency. Based on the suboptimal power allocation, we select a mode which has the maximal power-efficiency among all possible mode combinations of the devices. Then we obtain the proposed suboptimal joint mode selection and power allocation scheme maximizing the utility function.

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II. System Model

We consider D2D communication as an underlay coexistence with frequency division duplexing (FDD) wideband code division multiple access (WCDMA) cellular networks. It is assumed that D2D communications utilize the uplink spectrum of cellular networks with time division duplexing (TDD) mode as in [1][7]. In Fig. 1, the D2D device 1 transmits downlink signal to the D2D device 2 in which the D2D device 1 and D2D device 2 are a pair for direct communication and the transmit signal interferes with the uplink signal of cellular network at the first time slot (odd time slot).

Simultaneously, the uplink signal of the cellular device 1 interferes with the downlink signal of the D2D device 1 and reduces the SINR for the D2D device 1. At the next time slot (even time slot), the D2D device 2 transmits uplink signal to the D2D device 1. Also, the uplink signals of the D2D device 2 and cellular device 1 interfere each other. The D2D devices which transmit downlink signal at the odd time slot take the odd index and the D2D devices which transmit uplink signal at the even time slot take the even index as [1]. According to Fig. 1, the SINR for each device at the odd time slot is given as

$$\mathrm{SINR}_{d1} = \frac{\left(1-m_1^t\right) P_{d1}^t \alpha_{d1}^{d2} g_d}{P_{c1}^t \alpha_{c1}^{d2} + n_u} \geqslant \gamma_d, \tag{1}$$

$$\mathrm{SINR}_{c1} = \frac{P_{c1}^t \alpha_{c1}^{BS} g_c}{\left(1-m_1^t\right) P_{d1}^t \alpha_{d1}^{BS} + n_b} \geqslant \gamma_c, \tag{2}$$

where P_{di}^t and P_{ci}^t are the transmission power of the ith D2D device and cellular device at the time slot t, respectively. α_A^B is a link gain from A to B, g_d and g_c are the processing gains for the D2D and cellular communication, n_u and n_b are noise power over the bandwidth at the user and base station, and γ_d and γ_c are the target SINRs for the D2D and cellular communication, respectively. m_i^t is the TDD activity indicator for the D2D communication ($m_i^t = 0$ if both t and i are simultaneously the even or odd value, otherwise $m_i^t = 1$).

The SINR for each device at the even time slot is given as

$$\mathrm{SINR}_{d2} = \frac{\left(1-m_2^t\right) P_{d2}^t \alpha_{d2}^{d1} g_d}{P_{c1}^t \alpha_{c1}^{d1} + n_u} \geqslant \gamma_d, \tag{3}$$

$$\mathrm{SINR}_{c1} = \frac{P_{c1}^t \alpha_{c1}^{BS} g_c}{\left(1-m_2^t\right) P_{d2}^t \alpha_{d2}^{BS} + n_b} \geqslant \gamma_c. \tag{4}$$

In general case, we assumed that there are N cellular mode devices and M D2D mode devices. Then the SINR for the ith device at the time slot t is given as

$$\mathrm{SINR}_{di}^t = \frac{\left(1-m_i^t\right) P_{di}^t \alpha_{di}^{di'} g_d}{\sum\limits_{k=1}^{N} P_{ck}^t \alpha_{ck}^{di} + \sum\limits_{\substack{l=1 \\ l\neq i}}^{M} \left(1-m_l^t\right) P_{dl}^t \alpha_{dl}^{di} + n_u} \geqslant \gamma_d, \tag{5}$$

$$\mathrm{SINR}_{ci}^t = \frac{P_{ci}^t \alpha_{ci}^{BS} g_c}{\sum\limits_{\substack{k=1 \\ k\neq i}}^{N} P_{ck}^t \alpha_{ck}^{BS} + \sum\limits_{l=1}^{M} \left(1-m_l^t\right) P_{dl}^t \alpha_{dl}^{BS} + n_b} \geqslant \gamma_c, \tag{6}$$

where the ith and i'th devices are D2D device pair. Then the system capacity is given by

$$C_{sr}^t = \mathrm{W}\left(\sum_{i=1}^{M} \log_2\left(1+\mathrm{SINR}_{di}^t\right) + \sum_{j=1}^{N} \log_2\left(1+\mathrm{SINR}_{cj}^t\right)\right), \tag{7}$$

where W is uplink bandwidth of cellular network.

III. Joint Mode Selection and Power Allocation Scheme

In this paper, we consider the system environment for the coexisting D2D communications and cellular networks in which D2D communications utilize the uplink spectrum of the cellular networks as in [1][7]. A pair of the D2D mode devices is close to each other and the transmission power of the D2D mode devices is lower than the cellular mode. However, since the D2D mode devices utilize only a half of the resources compared to the cellular mode [1][7], it is necessary to jointly consider the transmission power and system capacity in D2D communication underlaying cellular networks. Therefore, we establish the utility function as power-efficiency as given by

$$U^t = \frac{C_{sr}^t}{\sum\limits_{m=1}^{M} \left(1-m_m^t\right) P_{dm}^t + \sum\limits_{n=1}^{N} P_{cn}^t} \tag{8}$$

$$= \frac{W\left(\sum\limits_{i=1}^{M} \log_2\left(1+\mathrm{SINR}_{di}^t\right) + \sum\limits_{j=1}^{N} \log_2\left(1+\mathrm{SINR}_{cj}^t\right)\right)}{\sum\limits_{m=1}^{M} \left(1-m_m^t\right) P_{dm}^t + \sum\limits_{n=1}^{N} P_{cn}^t}. \tag{9}$$

A. Power Allocation Scheme

In order to obtain the optimal power for the maximal utility value, the objective function is given as

$$\max_{\mathbf{P}_d^t, \mathbf{P}_c^t} \frac{W\left(\sum\limits_{i=1}^{M} \log_2\left(1+\mathrm{SINR}_{di}^t\right) + \sum\limits_{j=1}^{N} \log_2\left(1+\mathrm{SINR}_{cj}^t\right)\right)}{\sum\limits_{m=1}^{M} \left(1-m_m^t\right) P_{dm}^t + \sum\limits_{n=1}^{N} P_{cn}^t}, \tag{10}$$

$$\text{s.t.} \quad 0 \leqslant P_{di}^t \leqslant P_{\max}, \mathrm{SINR}_{di}^t \geqslant \gamma_d, \forall i \in \Im, \tag{11}$$

$$0 \leqslant P_{cj}^t \leqslant P_{\max}, \mathrm{SINR}_{cj}^t \geqslant \gamma_c, \forall j \in \aleph, \tag{12}$$

where $\mathbf{P}_d^t = [P_{d1}^t, P_{d2}^t, ..., P_{dM}^t]$, $\mathbf{P}_c^t = [P_{c1}^t, P_{c2}^t, ..., P_{cN}^t]$, $\Im = [1, 2, ..., M]$ and $\aleph = [1, 2, ..., N]$. The utility function (9) is not a concave function of either of the two elements $\mathbf{P}_d^t$ and $\mathbf{P}_c^t$. Also, the utility function is not a monotonically increasing or decreasing function for the constraints (11) and (12). However, alternate optimization algorithm based on concavities of the lower and upper bound can be devised to maximize the utility function. The lower and upper bound for the utility function can be derived, respectively, as

$$U_l^t = \frac{W\left(\sum_{i=1}^{M}\log_2\left(\mathrm{SINR}_{di}^t\right)+\sum_{j=1}^{N}\log_2\left(\mathrm{SINR}_{cj}^t\right)\right)}{\sum_{m=1}^{M}\left(1-m_m^t\right)P_{dm}^t+\sum_{n=1}^{N}P_{cn}^t}, \tag{13}$$

$$U_u^t = \frac{W\left(\sum_{i=1}^{M}\log_2\left(\frac{\gamma_d+1}{\gamma_d}\mathrm{SINR}_{di}^t\right)+\sum_{j=1}^{N}\log_2\left(\frac{\gamma_c+1}{\gamma_c}\mathrm{SINR}_{cj}^t\right)\right)}{\sum_{m=1}^{M}\left(1-m_m^t\right)P_{dm}^t+\sum_{n=1}^{N}P_{cn}^t}. \tag{14}$$

The lower bound (13) can be easily obtained by replacing $1+\mathrm{SINR}^t$ in (10) with SINR^t under the simple inequality $1+\mathrm{SINR}^t \geqslant \mathrm{SINR}^t$. From the constraint inequations (11) and (12), we obtain the inequality $\mathrm{SINR}^t/\gamma \geqslant 1$, and then the upper bound (13) also can be easily obtained by replacing 1 in (10) with SINR^t/γ.

We show that (13) and (14) are $(\log, \log)$-concave function of $\mathbf{P}_d^t$ and $\mathbf{P}_c^t$ in the section C of this chapter. The concavity of the function guarantees that there is a unique convergent point and the convergent point is global maximum. Let us assumed that the optimal power vectors of the lower and upper bound are $\mathbf{P}_*^t$ and $\mathbf{P}^{t*}$, respectively, where $\mathbf{P}^t = [\mathbf{P}_d^t, \mathbf{P}_c^t]$. The global maximum value of utility function exists between $U^t\left(\mathbf{P}_*^t\right)$ and $U^t\left(\mathbf{P}^{t*}\right)$, where $U^t(\mathbf{x})$ is defined as $U^t(\mathbf{P}^t = \mathbf{x})$. The smaller the difference between the two values $U^t\left(\mathbf{P}_*^t\right)$ and $U^t\left(\mathbf{P}^{t*}\right)$, the closer the $U^t\left(\mathbf{P}_*^t\right)$ and $U^t\left(\mathbf{P}^{t*}\right)$ approach the global maximum value of utility function. The proposed suboptimal power allocation is given by

$$\mathbf{P}\text{=}\underset{[\mathbf{P}^{t-1},\mathbf{P}^t]}{\arg\max}\left(U^{t\text{-}1}\left(\mathbf{P}_*^{t\text{-}1}\right)+U^t\left(\mathbf{P}_*^t\right),\ U^{t\text{-}1}\left(\mathbf{P}^{t\text{-}1*}\right)+U^t\left(\mathbf{P}^{t*}\right)\right). \tag{15}$$

As the target SINR goes to infinity, (13) and (14) converge on equal value and the (15) converge on optimal power having global maximum value of utility function. Although the actual target SINR is finite value, the target SINR is large enough to guarantee the quality of service (QoS) for the desired signal [8].

B. Mode Selection Scheme

The direct communication mode (D2D mode) requires the pair of devices in the same macro cell within possible range for direct communication. Even though the devices are close to each other to communicate directly, the cellular mode can be better than the D2D mode when the direct channel is in deep fading. The mode selection scheme makes a decision either the device operates in the D2D mode or cellular mode.

We calculate the utility values which are the power-efficiencies for all possible mode sequences by using the previous power allocation scheme. Then we select a mode sequence which has the maximal utility value among all mode sequences. The procedure for the proposed joint mode selection and power allocation scheme is summarized as given in Table I.

TABLE I
PROPOSED JOINT MODE SELECTION AND POWER ALLOCATION SCHEME

L: The number of the device pairs to select mode
$H = H_1H_2...H_L$: A mode sequence of length L
($H_i = 1$ if the ith device is in the cellular mode,
and $H_i = 0$ if the ith device is in the D2D mode)
Input: $\alpha, g_d, g_c, n_u, n_b, \gamma_d, \gamma_c, W, L$
0: **Initialization** $k=0, \mathbf{P}=\{\}, \mathbf{P}_k=\{\}, \mathbf{P}_{\text{select}}=\{\}, U_k=\{\}$
1: **for** $H = 00...0 : 11...1$
2: $\mathrm{SINR}_{di}^t = \frac{\left(1-m_i^t\right)P_{di}^t\alpha_{di}^{di'}g_d}{\sum_{k=1}^{N}P_{ck}^t\alpha_{ck}^{di}+\sum_{l=1, l\neq i}^{M}\left(1-m_l^t\right)P_{dl}^t\alpha_{dl}^{di}+n_u}$;
$\mathrm{SINR}_{ci}^t = \frac{P_{ci}^t\alpha_{ci}^{BS}g_c}{\sum_{k=1, k\neq i}^{N}P_{ck}^t\alpha_{ck}^{BS}+\sum_{l=1}^{M}\left(1-m_l^t\right)P_{dl}^t\alpha_{dl}^{BS}+n_b}$;
3: $U^t = \frac{C_{sr}^t}{\sum_{m=1}^{M}\left(1-m_m^t\right)P_{dm}^t+\sum_{n=1}^{N}P_{cn}^t}$;
$U_l^t = \frac{W\left(\sum_{i=1}^{M}\log_2\left(\mathrm{SINR}_{di}^t\right)+\sum_{j=1}^{N}\log_2\left(\mathrm{SINR}_{cj}^t\right)\right)}{\sum_{m=1}^{M}\left(1-m_m^t\right)P_{dm}^t+\sum_{n=1}^{N}P_{cn}^t}$;
$U_u^t = \frac{W\left(\sum_{i=1}^{M}\log_2\left(\frac{\gamma_d+1}{\gamma_d}\mathrm{SINR}_{di}^t\right)+\sum_{j=1}^{N}\log_2\left(\frac{\gamma_c+1}{\gamma_c}\mathrm{SINR}_{cj}^t\right)\right)}{\sum_{m=1}^{M}\left(1-m_m^t\right)P_{dm}^t+\sum_{n=1}^{N}P_{cn}^t}$;
4: $\mathbf{P}_*^t = \underset{\mathbf{P}^t}{\arg\max}\left(U_l^t\right)$; $\mathbf{P}^{t*} = \underset{\mathbf{P}^t}{\arg\max}\left(U_u^t\right)$;
5: $\mathbf{P}\text{=}\underset{[\mathbf{P}^{t-1},\mathbf{P}^t]}{\arg\max}\left(U^{t\text{-}1}(\mathbf{P}_*^{t\text{-}1})+U^t(\mathbf{P}_*^t),\ U^{t\text{-}1}(\mathbf{P}^{t\text{-}1*})+U^t(\mathbf{P}^{t*})\right)$;
6: $\mathbf{P}_k = \mathbf{P}$; $U_k = U^{t-1}\left(\mathbf{P}^{t-1}\right)+U^t\left(\mathbf{P}^t\right)$;
7: $k = k+1$;
8: **end**
9: $k_{\text{mode}} = \underset{k}{\arg\max}\left(U_k\right)$; $\mathbf{P}_{\text{select}} = \mathbf{P}_{k_{\text{mode}}}$;
Output: $k_{\text{mode}}, \mathbf{P}_{\text{select}}$

As shown Step 1 of Table I, we consider all possible mode sequences to select. At the second step, we can obtain SINRs as a function of $\mathbf{P}^t$ and also obtain lower and upper bound in Step 3 as a function of $\mathbf{P}^t$. At the next Step 4, we obtain the optimal power vectors for the lower and upper bound, $\mathbf{P}_*^t$ and $\mathbf{P}^{t*}$, from the optimization algorithm based on gradient method. Then we derive the power vector $\mathbf{P}$ via maximizing an utility value combined from two consecutive time slots $t-1$ and t as in Step 5.

For all the possible mode sequences, the same procedure is performed iteratively. Finally, the proposed scheme selects a mode sequence which has the best utility value among all mode sequences and the associated power is also obtained as a proposed suboptimal power, simultaneously.

C. Proof of Concavity

In this section, we prove that the bounds (13) and (14) are $(\log, \log)$-concave function of the transmission power $\mathbf{P}_d^t$ and $\mathbf{P}_c^t$. The equations (13) and (14) are represented as a simple

TABLE II
SYSTEM LEVEL SIMULATION PARAMETERS

Parameter	Value
Macro cell radius (Single cell)	500 m
Maximum distance between D2D	20 m
System bandwidth	Cellular : 5 MHz / D2D : 2.5 MHz
Path loss model [9]	Cellular : 128.1 +37.6$log10(d[km])$ D2D : 148.1+40$log10(d[km])$
Shadowing standard deviation [9]	Cellular : 10 dB / D2D : 12 dB
Processing gain	Cellular : 18 dB / D2D : 15 dB
Antenna gain (Omnidirectional)	BS : 14 dBi / Device : 0 dBi
Noise figure	BS : 5 dB / Device : 9 dB
Noise spectral density	-174dBm/Hz

equation, as given by

$$U = \frac{\sum_{i=1}^{M} W \log_2 \left(\text{SINR}\left(P_i^t\right)\right)}{\sum_{j=1}^{M} P_j^t}. \tag{16}$$

In order to prove $(\log, \log)$-concavity, the equation (16) is transformed by

$$\log U = -\log\left(\sum_{j=1}^{M} e^{\tilde{P}_j^t}\right) + \underbrace{\log\left(\sum_{i=1}^{M} W \log_2\left(\text{SINR}\left(P_i^t\right)\right)\right)}_{\alpha}, \tag{17}$$

where $\tilde{P}_l^t = \log P_l^t$.

From [10], $-\log(e^{\tilde{P}_1^t} + \cdots + e^{\tilde{P}_M^t})$ is concave on M dimensional real numbers. The high-SINR approximation of the Shannon link capacity $W \log_2 \left(\text{SINR}\left(P_i^t\right)\right)$ is also $(\log, x)$-concave function as proved in [11]. Since the summation of concave function is also concave, $\sum_i W \log_2 \left(\text{SINR}\left(P_i^t\right)\right)$ is $(\log, x)$-concave function. Then, α in (17) is $(\log, x)$-concave function as defined in [10], since the logarithm function is concave and nondecreasing, and $\sum_i W \log_2 \left(\text{SINR}\left(P_i^t\right)\right)$ is $(\log, x)$-concave function. Therefore, the equation (16) is $(\log, \log)$-concave function and the equation (13) and (14) are also $(\log, \log)$-concave function of the transmission power $\mathbf{P}_d^t$ and $\mathbf{P}_c^t$.

IV. SIMULATION RESULTS

The proposed scheme is compared with the lowest power selection [1], forced D2D and forced cellular schemes. The forced D2D and forced cellular schemes indicate that all devices are in the D2D mode and cellular mode, respectively. It is assumed that the target SINRs for the D2D and cellular communication are equal, $\gamma_d = \gamma_c$. The simulation is carried out by using system level simulation and the simulation parameters are provided in Table II. The simulation results show the power-efficiency, system capacity and average transmission power with respect to the target SINR.

Fig. 2 shows the power-efficiency versus the target SINR. The power-efficiency decreases as the target SINR increases and the proposed scheme outperforms the conventional schemes over the target SINR. Moreover, the proposed scheme

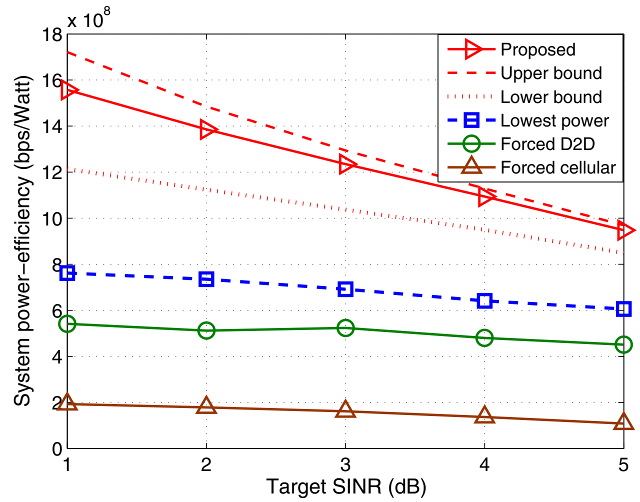

Fig. 2. Power-efficiency versus target SINR

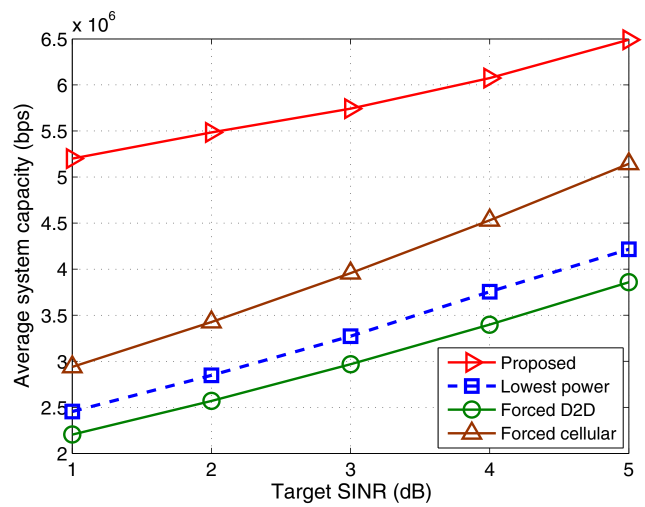

Fig. 3. Average system capacity versus target SINR.

performs close to upper bound which means the proposed suboptimal algorithm approaches the optimal value for the power-efficiency.

The system capacity versus the target SINR is shown in Fig. 3. The system capacity increases with the target SINR and the proposed scheme always has the best performance over the target SINR. Since the cellular network utilizes the whole system bandwidth, the forced cellular scheme outperforms the lowest power selection and forced D2D scheme. On the other hand, the forced D2D scheme has the worst system capacity since the D2D network only utilizes the uplink spectrum of the cellular network.

Fig. 4 shows the average transmission power of the devices versus the target SINR. The average transmission power increases with the target SINR. The forced cellular scheme consumes a lot of power to communicate with base station. However, the lowest power selection and forced D2D schemes require the power relatively lower than cellular mode, and the

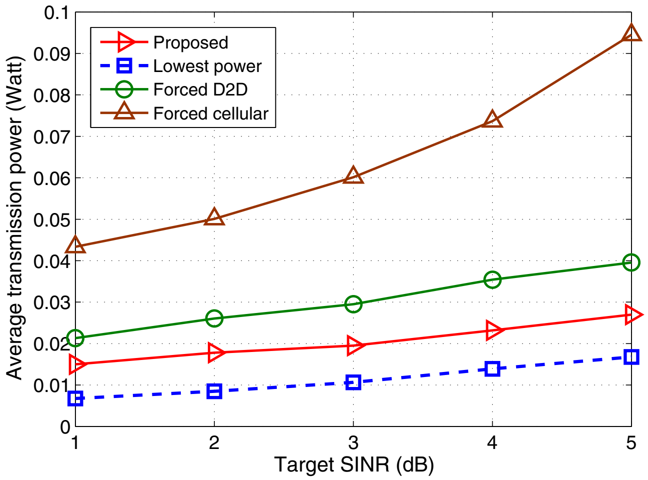

Fig. 4. Average transmission power versus target SINR.

average transmission power of the proposed scheme is lower than the forced D2D scheme.

From the simulation results, the proposed scheme has the best performance with respect to the power-efficiency and system capacity over the target SINR.

V. Conclusion

A D2D communication underlaying cellular networks has the advantages of enhancing a cell throughput and saving the battery at the device [1]-[6]. In this paper, we defined an utility function as the power-efficiency to jointly consider these two advantages.

A joint mode selection and power allocation scheme is proposed for the power-efficient D2D communication. In the proposed scheme, the mode is selected based on the suboptimal power allocation with respect to the power-efficiency. From the simulation results, the proposed scheme shows the best power-efficiency and performs close to the delivered upper bound. Also, the proposed scheme outperforms the conventional schemes with respect to the system capacity. The proposed joint mode selection and power allocation scheme could be an effective method for power-efficient D2D communication systems.

Acknowledgment

This work was supported in part by the National Research Foundation of Korea Grant funded by the Korean Government(MEST) (No. 2011-0005729) and the Seoul R&BD Program (WR080951).

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