Particle Swarm Optimization based Power Control Algorithms for SWIPT-Assisted D2D Communications Underlaying Cellular Networks

Xueyao Xia¹ and Guixia Kang²,*

¹,²Key Laboratory of Universal Wireless Communications, Ministry of Education, Beijing University of Posts and Telecommunications, Beijing 100876, China

*Corresponding author

Abstract. We studied power control algorithms for SWIPT-assisted D2D communications underlaying cellular networks in this paper. The particle swarm optimization (PSO) based power control algorithm is put forward to mitigate the interference and enhance the sum throughput of D2D networks. In order to avoid falling into the local optimum, we combined simulated annealing with particle swarm optimization (SA-PSO) to improve performance of the algorithm. The main idea is to allocate proper transmitting powers to D2D links while maximizing the total throughput. Unlike other related works, the transmitting power and the power splitting ratio are both optimized in this paper. Simulation results demonstrate our algorithms are conductive to boosting the total throughput of D2D networks. The PSO and SA-PSO based algorithms outperform the game-theory based algorithm in terms of the sum throughput of D2D networks.

Keywords: D2D communication; Power control; Particle swarm optimization.

1. Introduction
With the rise of mobile Internet, lower energy consumption is required recently while meeting the development demands of wireless communications [1-3]. Simultaneous wireless and power transfer (SWIPT) have caused an enormous concern to solve the energy shortage of devices which allows radio frequency (RF) signals to provide energy and information at the same time [4]. Device-to-Device communication can directly forward information between D2D users without base stations [5]. D2D users enable to reuse spectral resources of cellular users in the D2D communication underlaying a cellular network, which helps to boost the sum throughput and spectrum efficiency [6]. The communication system brings these benefits while posing a great challenge of interference problems. Power control represents an effective solution to counter the impact on mutual interference between D2D and cellular communications [7].

Recently, the research on power control for SWIPT-assisted D2D Communications has been given top priority. In [8], the authors proposed joint resource block and power allocation algorithms to maximize the sum throughput of the D2D links and satisfy constraints of the quality of service (Qos) of cellular users for D2D communication underlaying downlink cellular networks. It was addressed by the classic Lagrangian Multiplier method. In [9], the resource allocation problem was investigated for the D2D communication with energy harvesting by power control and time switching. The energy constraint was taken into consideration and the constraints of the SINR requirement of cellular user were satisfied. The non-convex problem could reach a near optimal solution by addressing convex problems. Although the convex optimization, transformed from non-convex problems, reduces the complexity,
the change range may be larger or smaller during the conversion process, so that the optimal solution may deviate. Game theory has been extensively investigated for solving distributed power control problems [4, 10, 11]. They assumed that all players in the game are rational and strategic with objectives of maximizing their individual utility to address the global maximizing optimization problems. It is not guaranteed that the sum of individual utility maximums is the same as the global optimum. Besides, the PS ratio was fixed and the solution for problems is to find the optimal transmitting power of every player. Researchers have investigated particle swarm optimization (PSO) to address resource allocation problems during these years [12, 13, 14]. However, as we know, few works on PSO algorithms in SWIPT systems are investigated. Contributed by these works, we investigate power control problems for SWIPT-assisted D2D communications underlaying cellular networks. D2D receivers enable to harvest energy from their transmitting signals and interference from other D2D links and cellular users in the downlink networks by the power splitting (PS) technique. The proposed PSO-based power control algorithm and the hybrid SA-PSO algorithm can mitigate the interference and larger throughput of all D2D links can be obtained than the existed game theory algorithm. The transmitting power and the PS ratio are jointly optimized in our algorithms.

2. System Model And Problem Formulation

2.1. System Model
A D2D network with SWIPT underlaying a cellular network is considered. The system consists of one base station (BS), N D2D links and one cellular user. D2D links and one cellular user (CU) share the spectrum resources. D2D devices with power splitting receivers can simultaneously transfer information and power in the downlink direction. Due to reusing the same spectrum, D2D users are not only interfered from cellular users but are affected by the interference from other D2D links. We assume that each D2D receiver can harvest energy from the part of received signals of its own transmitters, other D2D links and cellular users while decoding information from the received signals. We aim at finding the proper transmitting powers and PS ratios of D2D links and maximizing the sum throughput of D2D links at the same time.

In the downlink transmission, the signal received by D2D link \( i \in \{1, 2, \ldots, N\} \) is written as

\[
y_{Di} = P_i h_i + \sum_{j \neq i}^N P_j h_{ji} + P_c h_c + N_0,
\]

where \( P_t \), \( P_j \) and \( P_c \) represent the transmitting power of D2D link \( i \), other D2D links except D2D link \( i \) and the cellular user (CU), respectively. \( N_0 \) is the power of noise at the receiver, \( \sum_{j \neq i}^N P_j h_{ji} + P_c h_c \) is the interference power. \( h_i \) and \( h_{ji} \) represent the channel gain from the transmitter to the receiver of D2D link \( i \) and D2D link \( j \) to the D2D link \( i \). \( h_c \) is the channel gain between CU and D2D link \( i \).

As D2D devices are supported by the SWIPT technology, the received signals are separated into two streams and the PS ratio is written as \( \theta \). The fraction \( \theta \) of the received signal helps to harvest energy and the rest \( 1 - \theta \) is utilized for information decoding. In this regard, the harvested energy at the receiver of D2D link \( i \) is written as

\[
E_i = \eta \theta_i (P_i h_i + \sum_{j \neq i}^N P_j h_{ji} + N_0 + P_c h_c),
\]

where \( \eta \in (0, 1) \), is the harvesting conversion efficiency. And the signal-to-interference plus noise ratio (SINR) of signal at the receiver of D2D link \( i \) is defined as follows:

\[
\gamma_i = (1 - \theta_i) \frac{P_i h_i}{\sum_{j \neq i}^N P_j h_{ji} + N_0 + P_c h_c}.
\]

The rate of D2D link \( i \) is written as

\[
R_i = \log_2(1 + \gamma_i).
\]

The total throughput of all D2D links is written as
2.2. Problem Formulation

The power control problem of the system can be described as

\[ R_{tot} = \sum_{i=1}^{N} R_i. \] (5)

where \( R_{tot} \) is the total throughput of the system.

2.2. Problem Formulation

The power control problem of the system can be described as

\[ \max_{\{\theta_i, P_i\}} \sum_{i=1}^{N} \log_2 \left( 1 + \left( 1 - \theta_i \right) \frac{P_i h_i}{\sum_{j=1}^{N} P_j h_{ij} + N_0 + P_c h_c} \right) \]

s.t. \( P_{\min} \leq P_i \leq P_{\max} \) \hspace{1cm} (6-a)
\[ 0 \leq \theta_i \leq 1, \] \hspace{1cm} (6-b)

where \( P_{\min} \) and \( P_{\max} \) are minimum and maximum of the transmitting power of D2D links, respectively. With higher transmitting power, larger throughput aggregates can be obtained while it also causes larger interference. In this case, we set the transmitting power in a range from \( P_{\min} \) to \( P_{\max} \). \( \theta_i \) represents the PS ratios as has been discussed above. Our aim is to choose the proper transmitting power and the PS ratio of each D2D link while maximizing throughput aggregates of the D2D network and satisfying constraints in the system.

3. Power Control Algorithm for D2D Networks

3.1. PSO Based Power Control Algorithm

According to the PSO algorithm, the size of particles is \( n \), the position of particles is defined as \( X_i \) (\( i \in \{1, 2, \ldots, n\} \)). The fitness function is given in (6). The optimal transmitting power and PS ratio are obtained through the comparison of the difference between the personal optimum \( Q_i \) and the global optimum \( Q_g \) by multiple iterations. The velocity of particles is calculated by the following function:

\[ V_{i}^{k+1} = \omega V_{i}^{k} + c_1 r_1 (Q_i^{k} - X_i^{k}) + c_2 r_2 (Q_g^{k} - X_i^{k}) \] (7)

where \( \omega \) is inertia weight, \( c_1 \) and \( c_2 \) are both learning factors, \( r_1 \) and \( r_2 \) are random numbers ranging from zero to one. \( X_i \) is written as

\[ X_i^{k+1} = X_i^{k} + V_i^{k+1}. \] (8)

where \( k \) is the current iteration number. The search process of finding optimums repeats a fixed number of iterations.

The process of PSO based algorithm is given as follows

(a) Set the initial value of velocity \( X_i^{k} \) and postion \( V_i^{k} \) of particles and set initial \( \omega, c_2 \) and \( c_2 \), the iteration number \( k \) and its maximum is written as \( k_{\text{max}} \).

(b) Calculate the fitness of particles \( R_i^{k} \).

(c) Initialize the personal optimum \( Q_i^{k} = X_i^{k} \).

(d) Get the global optimum \( Q_g^{k} \) according to the maximum of the fitness value of every particle.

(e) If the fitness of particles \( R_i^{k} \) is larger than the personal optimum \( Q_i^{k} \), update \( Q_i^{k} \) with \( R_i^{k} \).

(f) If the fitness of particles \( R_i^{k} \) is larger than the global optimum \( Q_g^{k} \), update \( Q_g^{k} \) with \( R_i^{k} \).

(g) Update the velocity and position of particles according to (7) (8).

(h) If it satisfies that \( k < k_{\text{max}} \), return step b). Otherwise, stop the iteration and get the optimum.

3.2. SA-PSO Based Power Control Algorithm

Given the PSO algorithm is easily to converge to the local optimum, we apply simulated annealing algorithm (SA) with better ability to avoid falling into the local optimum to improve the algorithm. Metropolis rule of SA randomly generates new particles to expand the search range and the optimal solution is obtained by comparing the fitness values. Metropolis rule is used to determine whether to accept the new solution or replace the system temperature with the number of iterations. The whole process is given as follows:
where $\Delta f$ is the difference of the next fitness solution and the current fitness solution. If it satisfies that $\Delta f < 0$, a new solution is accepted. Otherwise, the probability of accepting a new solution is $\exp(-\Delta f \cdot k)$ where $k$ is the iteration number.

The SA-PSO based algorithm steps are as follows:

(a) Set the initial value of velocity $v^k_i$ and position $X^k_i$ of particles and set initial $\omega$, $c_2$ and $c_2$, the iteration number $k$ and its maximum is written as $k_{\text{max}}$.

(b) Calculate the fitness of particles $R^k_i$.

(c) Initialize the personal optimum $Q^k_i = X^k_i$.

(d) Get the global optimum $Q^k_g$ according to the maximum of the fitness value of every particle.

(e) If the fitness of particles $R^k_i$ is larger than the personal optimum $Q^k_i$, update $Q^k_i$ with $R^k_i$.

(f) If the fitness of particles $R^k_i$ is larger than the global optimum $Q^k_g$, update $Q^k_g$ with $R^k_i$.

(g) Update the velocity and position of particles according to (7) (8).

(h) Update the position of particles according to the Metropolis rule.

(i) If it satisfies that $k < k_{\text{max}}$, return step b). Otherwise, stop the iteration and get the optimum.

4. Simulation Results

Simulation parameters have been given in Table 1. There is one base station in a single cell where five D2D links and one CU share the same spectral resources. D2D devices randomly distributed among the cell. Given the general path loss model, the channel gains are defined as $\frac{1}{d^\eta}$ where $d$ is the distance between D2D transmitters and receivers and $\eta$ is a fixed value shown in Table 1.

We optimize (6) to find optimal transmitting power and PS ratio of each D2D link with proposed PSO algorithm and SA-PSO algorithm. As the PS ratio $\theta_i$ is determined as 0.2 in [11], we also apply the proposed algorithms to find the optimal transmitting power when $\theta_i = 0.2$ in comparison with the algorithm proposed in [11].

**Table 1. Simulation Results**

| Parameters                        | Values                      |
|-----------------------------------|-----------------------------|
| Cell size                         | 500×500 m                   |
| Max D2D communication range       | 50 m                        |
| $\eta$                            | 0.1                         |
| $N_0$                             | 0.01 mW                     |
| $P_c$                             | 0.2 W                       |
| $P_{min}$, $P_{max}$              | 0.005 W, 0.2 W              |
| $\alpha$                          | 2                           |
| Particle population size          | Maximum                     |
| Maximum number of iterations      | 50                          |
| $c_1$                             | 2                           |
| $c_2$                             | 2                           |
| $\omega$                          | 0.6                         |

The proposed algorithms can update the transmitting power and converge to optimal values when the PS ratio $\theta_i$ of each D2D link satisfies that $\theta_i = 0.2$. Figure 1 shows the iteration process for the transmitting power of each D2D link applied with PSO based algorithm. And Figure 2 shows the iteration process for the transmitting power of each D2D link applied with SA-PSO based algorithm. We can find that two algorithms have similar numbers of iterations to reach proper transmitting power.
As it has been discussed, the proposed algorithms can also be applied in jointly optimizing the transmitting power $P_t$ and the PS ratio $\theta_l$. Figure 3 and Figure 4 have shown the iteration process for the transmitting power $P_t$ of each D2D link applied with our PSO and SA-PSO based algorithm, respectively. The iteration process for the PS ratio $\theta_l$ of each D2D link applied with PSO algorithm and SA-PSO algorithm is displayed in Figure 5 and Figure 6, respectively. We can see that the numbers of iteration are smaller than those of only optimizing the transmitting power. In other words, the performance of iteration times is better when the transmitting power and the power splitting ratio are jointly optimized.

Figure 1. Transmitting Power $P_t$ of PSO algorithm, $\theta_l = 0.2$

Figure 2. Transmitting Power $P_t$ of SA-PSO algorithm, $\theta_l = 0.2$

Figure 3. Transmitting Power $P_t$ of PSO algorithm when $\theta_l$ and $P_t$ are jointly optimized

Figure 4. Transmitting Power $P_t$ of SA-PSO algorithm when $\theta_l$ and $P_t$ are jointly optimized

Figure 5. PS ratio $\theta_l$ of PSO algorithm when $\theta_l$ and $P_t$ jointly optimized

Figure 6. PS ratio $\theta_l$ of SA-PSO algorithm when $\theta_l$ and $P_t$ are jointly optimized

Figure 7 illustrates the comparison results of proposed algorithms and game-theory based algorithm in [12]. It demonstrates that our proposed algorithms outperform the game theory based algorithm in the throughput aggregates of all D2D links. As we can see, joint PS ratio and transmitting power optimization with proposed algorithms reach higher throughput aggregates than only transmitting
power optimization. And joint PS ratio and transmitting power optimization with the proposed SA-PSO algorithm performs best in the total throughput of D2D networks.

Figure 7. The total throughput $R_{\text{tot}}$ of all D2D links for algorithm comparisons

5. Conclusion
Power control algorithms have been discussed for SWIPT-assisted D2D communications underlaying cellular downlink networks in our research. As a result of mutual interference in the system, the non-convex problem has been addressed by the proposed PSO and SA-PSO based algorithms. The objective function is defined to maximize the total throughput of D2D links by choosing a proper transmitting power and a power splitting ratio of each D2D link. Simulation results have shown that our algorithms can effectively enhance the total throughput of D2D networks in comparison with the game theory based algorithm. And our proposed algorithms can jointly optimize the transmitting power and the power splitting ratio at the same time. However, we have not discussed energy efficient problems in our study. We will do more research on this problem combined with this paper in the future work.

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References
[1] J. G. Andrews and S. Buzzi, "What will 5G be? ", IEEE J. Sel. Areas Commun., vol. 32, no. 6, pp. 1065–1082, Jun. 2014.
[2] A. Osseiran and F. Boccardi., "Scenarios for 5G mobile and wireless communications: The vision of the METIS project", IEEE Commun. Mag., vol. 52, no. 5, pp. 26–35, May 2014.
[3] M. Agiwal, A. Roy, and N. Saxena, " Nextgeneration 5G wireless networks: A comprehensive survey", " IEEE Commun.Surveys Tuts.,vol. 18, no. 3, pp. 1617–1655, 3rd Quart., 2016.
[4] J. Huang, C.-C. Xing, C. Wang, "Simultaneous wireless information and power transfer: Technologies applications and research challenges", IEEE Commun. Mag., vol. 55, no. 11, pp. 26-32, Nov. 2017.
[5] R. I. Ansari et al., "5G D2D networks: Techniques challenges and future prospects", IEEE Systems Journal, Dec. 2017, doi: 10.1109/JSYST.2017.2773633.
[6] H.-S. Nguyen, T.-S. Nguyen, M. Voznak, "Wireless powered D2D communications underlying cellular networks: Design and performance of the extended coverage", Automatika, vol. 58, no. 4, pp. 391-399, 2018.
[7] P. Phunchongharn, E. Hossain, and D. I. Kim, "Resource allocation for device-to-device communications underlaying lte-advanced networks", IEEE Wireless Communications, vol. 20, no. 4, pp. 91–100, 2013.
[8] S. Gupta, R. Zhang, L. Hanzo, '"Energy harvesting aided device-to-device communication underlaying the cellular downlink", IEEE Access, vol. 5, pp. 7405-7413, 2016.
[9] H. Wang et al., "Resource allocation for energy harvesting-powered D2D communications underlaying cellular networks", Proc. Int. Conf. Commun. (ICC), pp. 1-6, May 2017.

[10] J. Huang, C.-C. Xing, “Efficient Power Control for D2D with SWIPT”, Association for Computing Machinery. ACM, pp.106-111, Oct. 2018.

[11] Z. Wen, Y. Liu et al., "Power allocation for SWIPT in K-user interference channels using game theory", EURASIP J. Adv. Signal Process. 2018, 27 (2018) doi: 10.1186/s13634-018-0547-7.

[12] S. C. K. Lye, H. T. Yew, B. L. Chua, R. K. Y. Chin and K. T. K. Teo, "Particle Swarm Optimization Based Resource Allocation in Orthogonal Frequency-division Multiplexing," 2013 7th Asia Modelling Symposium, Hong Kong, pp. 303-308, 2013.

[13] Y. Zhao, X. Li, Y. Li and H. Ji, "Resource allocation for high velocity railway downlink MIMO-OFDM system using quantum behaved particle swarm optimization," 2013 IEEE International Conference on Communications (ICC), Budapest, 2013, pp. 2343-2347.

[14] R. Chen and J. Xu, "Particle Swarm Optimization Based Power Allocation for D2D Underlaying Cellular Networks", 2017 IEEE 17th International Conference on Communication Technology (ICCT), pp 2576-7828, Oct. 2017.