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Secure communication in wireless powered communication networks with energy accumulation

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Dear editor,

Wireless powered communication network (WPCN) is a wireless network where user devices are powered wirelessly by harvesting radio frequency (RF) signals transmitted by dedicated power stations or nearby power sources [1]. WPCN is attractive for wireless networks with low-power user devices, such as wireless sensor networks [2] and backscatter networks [3]. Meanwhile, physical layer security (PLS) is a technique that can guarantee secure communication from the aspect of the physical layer by exploring the randomness of physical channels [4, 5]. PLS in WPCN is different from that in non-WPCN mainly owing to the requirement of balancing between the RF energy harvesting and secure information transmission in WPCN [6, 7]. Existing studies on PLS in WPCN considered that the eavesdroppers are not legitimate users in the WPCN. For the situation when the legitimate user in the WPCN is interested in other user's information, the legitimate user can be treated as an eavesdropper for other users. Such a situation is more difficult to handle because each user has to balance between transmitting their own information and eavesdropping on other users.

The main contributions of this study are as follows. (1) A brand new scenario for PLS in WPCN with multiple transmitter and receiver pairs is considered, where each receiver in WPCN is a potential eavesdropper for other receivers. The energy harvested by each wireless powered transmitter is assumed to be accumulated for usage in the current or future slots. For improving the secrecy performance, a portion of available energy at each transmitter is used for sending jamming signals to interfere with the potential eavesdroppers. (2) Both offline and online settings of channel power gains are considered, where the channel power gains of all slots are known as a priori in the offline setting and only the channel power gains of current slot are known in the online setting. (3) Based on the alternating optimization, suboptimal algorithms to jointly allocate time, power and subcarrier for maximizing the weighted sum secrecy rate under the transmit power constraint at the power station and the energy causality constraint at each transmitter are proposed for both the offline and online settings. It is verified by simulations that the proposed algorithms outperform the benchmark algorithms.

System model and problem formulation. This study considers a WPCN with K pairs of users and a power station. Each pair of users consists of a wireless powered transmitter (TX) and a receiver (RX). It is assumed that each RX is a potential eavesdropper for the other users. The total spectrum bandwidth is equally divided into N subcarriers, each with bandwidth B. The interested scheduled transmission time consists of M slots. Let $h_{k,k',n,m}$ and $g_{k,n,m}$ denote the channel power gains in slot m on subcarrier n from TX k to RX k', and from the power station to TX k, respectively. Two settings of the channel power gains are considered, i.e., an offline setting and an online setting. Specifically, in the offline setting, the channel power gains of all slots are known as a priori before the transmission starts, while in the online setting, only the channel power gains of the current slot are known. In each slot, the time is normalized to 1 and divided into two phases. During the first phase of slot m with time duration $\tau_{1,m}$, the power station broadcasts energy signals to all the TXs with power $P_{n,m}$ on subcarrier n, and the TXs harvest energy from these energy signals. Let ξ denote the energy harvesting efficiency. Then, the energy harvested by TX k during the first phase of slot m is written as $\xi\tau_{1,m}\sum_{n=1}^{N}P_{n,m}g_{k,n,m}$. It is assumed that the harvested energy by each TX can be accumulated in a rechargeable battery for future usage. During the second phase of slot m with time duration $\tau_{2,m}$, each TX k transmits information to its destination RX k with power $p_{k,n,m}$ on subcarrier n. It is assumed that each subcarrier can be allocated to one user for information transmission, i.e., $p_{k,n,m}p_{k',n,m} = 0, \forall m, n, k \neq k'$. For improving the secrecy performance, it is assumed that each TX k in slot m can transmit jamming signals to interfere with the potential eavesdroppers with power $q_{k,n,m}$ on its allocated subcarrier n. The achievable rate of user k in slot m on subcarrier n is written as

$$r_{k,n,m} = \tau_{2,m}\log_2\left(1+\frac{p_{k,n,m}h_{k,k,n,m}}{N_0B}\right), \quad (1)$$

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where N_0 is the noise spectral density. The maximum achievable rate of all the potential eavesdroppers for user k in slot m on subcarrier n is written as

$$\tilde{r}_{k,n,m} = \max_{k' \neq k} \tau_{2,m} \log_2 \left(1 + \frac{p_{k,n,m} h_{k,k',n,m}}{N_0 B + q_{k,n,m} h_{k,k',n,m}}\right). \tag{2}$$

Then the secrecy rate of user k in slot m on subcarrier n is given by

$$c_{k,n,m} = (r_{k,n,m} - \tilde{r}_{k,n,m})^+, \tag{3}$$

where $(\cdot)^+ = \max(\cdot, 0)$.

The aim is to maximize the weighted sum secrecy rate of all the users by optimizing the time allocation, subcarrier allocation and power allocation. The problem is formulated as (P1)

$$\max_{\boldsymbol{P},\boldsymbol{p},\boldsymbol{q},\boldsymbol{\tau}_1,\boldsymbol{\tau}_2} \sum_{m=1}^{M} \sum_{k=1}^{K} \omega_k \sum_{n=1}^{N} c_{k,n,m} \tag{4}$$

$$\text{s.t.} \sum_{n=1}^{N} P_{n,m} \leqslant P_{\max}, \forall m, \tag{5}$$

$$\sum_{j=1}^{m} \tau_{2,j} \sum_{n=1}^{N} (p_{k,n,j} + q_{k,n,j}) \leqslant \sum_{j=1}^{m} \xi \tau_{1,j} \sum_{n=1}^{N} P_{n,j} g_{k,n,j},\ \forall m, k, \tag{6}$$

$$\tau_{1,m} + \tau_{2,m} \leqslant 1,\ \tau_{1,m} \geqslant 0,\ \tau_{2,m} \geqslant 0,\ \forall m, \tag{7}$$

$$p_{k,n,m} p_{k',n,m} = 0,\ \forall m, n, k \neq k', \tag{8}$$

$$P_{n,m} \geqslant 0,\ p_{k,n,m} \geqslant 0,\ q_{k,n,m} \geqslant 0,\ \forall m, n, k, \tag{9}$$

where $\boldsymbol{P} = \{P_{n,m}, \forall m, n\}$, $\boldsymbol{p} = \{p_{k,n,m}, \forall m, n, k\}$, $\boldsymbol{q} = \{q_{k,n,m}, \forall m, n, k\}$, $\boldsymbol{\tau}_1 = \{\tau_{1,m}, \forall m\}$, $\boldsymbol{\tau}_2 = \{\tau_{2,m}, \forall m\}$ and $P_{\max}$ is the transmit power limit in each slot at the power station. The constraint in (6) is the energy causality constraint [8].

Proposed offline algorithm. Here, the problem (P1) under the offline setting of the channel power gains is investigated. Since the problem (P1) is highly non-convex, the optimal solution is difficult to obtain. Thus, this study proposes a suboptimal algorithm based on the alternating optimization [7], which optimizes $\boldsymbol{P}, \boldsymbol{p}, \boldsymbol{q}, \boldsymbol{\tau}_1, \boldsymbol{\tau}_2$ iteratively. With given $\boldsymbol{P}, \boldsymbol{p}, \boldsymbol{q}$, the problem (P1) is simplified to the following problem given by

$$\max_{\boldsymbol{\tau}_1,\boldsymbol{\tau}_2} \sum_{m=1}^{M} \sum_{k=1}^{K} \omega_k \sum_{n=1}^{N} c_{k,n,m} \tag{10}$$

$$\text{s.t. } (6), (7).$$

It is easily seen that the above problem belongs to linear programming and thus can be efficiently solved. With given $\boldsymbol{\tau}_1, \boldsymbol{\tau}_2$, the problem (P1) of optimizing $\boldsymbol{P}, \boldsymbol{p}, \boldsymbol{q}$ can be solved by the Lagrange duality method, since the duality gap converges to zero when N is large [7]. Thus, this study solves this problem based on the Lagrange duality method, which can be seen in Appendix A. The proposed offline algorithm to solve the problem (P1) is summarized in Appendix B.

Proposed online algorithm. Here, the problem (P1) under the online setting of the channel power gains is investigated. Since the channel power gains of future slots are unavailable in the current slot, this study proposes to exhaustively use the harvested energy in each slot and formulate the following problem for each slot as given by (P2)

$$\max_{\boldsymbol{P}_m,\boldsymbol{p}_m,\boldsymbol{q}_m,\tau_{1,m},\tau_{2,m}} \sum_{k=1}^{K} \omega_k \sum_{n=1}^{N} c_{k,n,m} \tag{11}$$

$$\text{s.t.} \sum_{n=1}^{N} P_{n,m} \leqslant P_{\max}, \tag{12}$$

$$\tau_{2,m} \sum_{n=1}^{N} (p_{k,n,m} + q_{k,n,m}) \leqslant \xi \tau_{1,m} \sum_{n=1}^{N} p_{n,m} g_{k,n,m},\ \forall k, \tag{13}$$

$$\tau_{1,m} + \tau_{2,m} \leqslant 1,\ \tau_{1,m} \geqslant 0,\ \tau_{2,m} \geqslant 0, \tag{14}$$

$$p_{k,n,m} p_{k',n,m} = 0,\ \forall n, k \neq k', \tag{15}$$

$$P_{n,m} \geqslant 0,\ p_{k,n,m} \geqslant 0,\ q_{k,n,m} \geqslant 0,\ \forall n, k, \tag{16}$$

for $\forall m$. The problem (P2) is highly non-convex, and thus the optimal solution is hard to obtain. Similar to the problem (P1), a suboptimal algorithm based on the alternating optimization is proposed. Given $\boldsymbol{P}_m, \boldsymbol{p}_m, \boldsymbol{q}_m$, since the objective function of the problem (P2) is maximized at the maximum allowable value of $\tau_{2,m}$, the optimal solution can be easily obtained as $\tau_{1,m} = 1 - \tau_{2,m}$ and

$$\tau_{2,m} = \frac{\xi \sum_{n=1}^{N} p_{n,m} g_{k,n,m}}{\sum_{n=1}^{N} (p_{k,n,m} + q_{k,n,m} + \xi p_{n,m} g_{k,n,m})}. \tag{17}$$

Given $\tau_{1,m}, \tau_{2,m}$, the problem (P2) of optimizing $\boldsymbol{P}_m, \boldsymbol{p}_m, \boldsymbol{q}_m$ can be solved using the Lagrange duality method, which can be seen in Appendix C. The proposed online algorithm to solve the problem (P2) is summarized in Appendix D.

Simulation results. It is assumed that two pairs of users exist and the distance between the transmitter and the power station is 5 m. The distance of the legitimate communication link is 10 m and the distance of the eavesdropping link is 5 m. The channel power gains are modeled as $10^{-4} d^{-2} x$, where d is the distance and x is a random variable with unit mean exponential distribution. Furthermore, set $N = 8$, $N_0 = -130$ dBm/Hz, $B = 1$ MHz, $\xi = 0.5$ and $\omega_1 = \omega_2 = 0.5$. Since the existing researches have not considered the investigated scenario in this study, three heuristic algorithms for both the offline and online settings are designed as benchmark algorithms. The benchmark algorithms 1–3 aim at maximizing the weighted sum secrecy rate without jamming, maximizing the weighted sum rate without jamming, and maximizing the weighted sum secrecy rate with equal information and jamming powers on each subcarrier, respectively. Figure 1 illustrates the impact of $P_{\max}$ on the secrecy performance of different algorithms. It is shown that the weighted sum secrecy rate increases as $P_{\max}$ increases for all the algorithms. As $P_{\max}$ increases, the proposed offline/online algorithm is shown to achieve increasingly higher weighted sum secrecy rate than the benchmark offline/online algorithms. This is because jamming is more effective in improving the secrecy performance with higher available harvested energy. It is shown that the benchmark offline/online algorithm 3 underperforms the proposed offline/online algorithm and the benchmark offline/online algorithm 1. This indicates that jamming may degrade the secrecy performance if jamming power allocation is not well

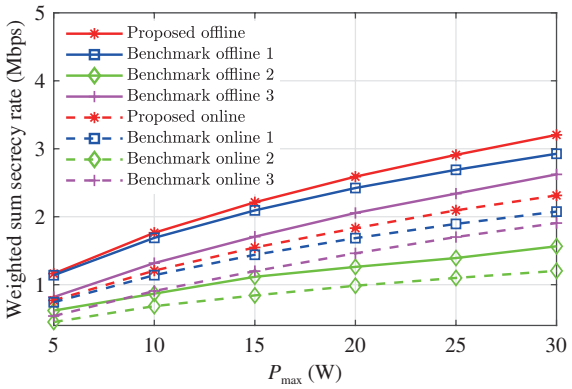

Figure 1 (Color online) Impact of $P_{\max}$ on the secrecy performance.

designed. Furthermore, the offline algorithm is shown to greatly outperform its corresponding online algorithm.

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Supporting information Appendixes A–D. 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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