Optimal Design for Power Beacon Assisted Wireless Communication Networks With Integrated Services

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ABSTRACT

In this paper, we consider the optimal design for a wireless-powered communication system, where an energy constrained transmitter harvests energy from a dedicated power beacon (PB). From the service integration perspective, two sorts of service messages are combined and served simultaneously, i.e., a multicast message intended for both receivers and a confidential message intended for receiver 1 but needing to be kept perfectly secret from receiver 2. Our design objective is to maximize the achievable secrecy rate region by jointly optimizing the transmit covariance matrices for the multicast message and confidential message, as well as the transfer time ratio recorded at the transmitter, subject to the multicast service and the transmit power constraints. The formulated secrecy rate region maximization (SRRM) problem is a non-convex vector maximization problem. To address it, we reformulate the SRRM problem into a scalar optimization problem. Furthermore, we propose a two-layer optimal algorithm to find all the Pareto optimal points. Numerical results are finally provided to demonstrate the effectiveness of our proposed scheme in improving the secrecy rate region.

KEYWORDS

Physical-layer service integration, wireless energy transfer, multicast message, confidential message, secrecy capacity region

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1 INTRODUCTION

Since the explosive growth of high-rate multimedia wireless services for the fifth-generation (5G) wireless communications, more energies for battery-powered mobile devices are consumed to meet the demands of various services. Therefore, how to prolong the lifetime for the energy-constrained mobile devices is a crucial issue. Recently, energy harvesting technique has emerged as a promising solution for energy sustainability of wireless devices [1]. As one of the energy harvesting methods, simultaneous wireless information and power transfer (SWIPT) has received significant attention since mobile devices can process information and harvest energy from surrounding radio frequency (RF) signals at the same time [2, 3]. However, SWIPT is only suitable for short-distance transmission and it is unrealistic to power larger wireless devices due to the practical limitations. To this end, the authors in [4] proposed a novel network architecture where a dedicated station known as power beacon (PB) is employed to power mobile devices. Related PB-assisted energy harvesting systems have been investigated in the open literature [5–8].

On the other hand, secure communication is also of great importance due to the broadcast nature of radio propagation and the inherent openness of the transmission medium [9–11]. To satisfy the high transmission rate and security simultaneously, a heuristic way is to combine the multicast service and confidential service into one integral service for one-time transmission, which results in the so-called *physical-layer service integration* [12]. The physical-layer service integration has been presented from the information theory sense in [13] and [14] over a few years. Specially, Ly *et al.* [13] studied the multiple-input multiple-output (MIMO) Gaussian broadcast channel with two receivers and two messages: a multicast message intended for both receivers, and a confidential message intended for one of the receivers but needing to be kept asymptotically perfectly secure from the other, in which the secrecy rate region was established via a channel enhancement argument. Later, Ly *et al.* [14] extended the secrecy rate of MIMO broadcast channel to the more general imperfect secrecy setting, where two receivers and three messages were considered.

More recently, physical-layer service integration has received considerable attention from the signal processing perspective. Mei *et al.* [15] was the first to optimize the transmit design for multiple-input single-output (MISO) broadcast channel with multiple receivers and two messages by employing the characteristics of wireless channel. The authors of [15] further extended the optimal design to the imperfect case where the worst-case secrecy rate region is maximized in [16]. Furthermore, Mei *et al.* [17] proposed two suboptimal resource allocation schemes to implement physical-layer service integration for practical purposes. However, these works did not took the scenario of the energy-constrained wireless network with energy harvesting into account. To the best of our knowledge,

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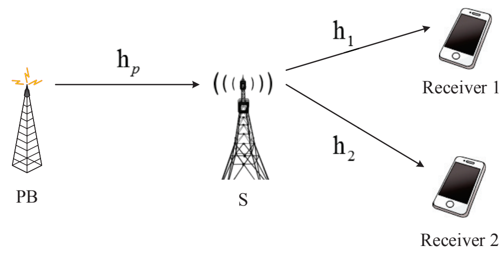

Figure 1: System model of a PB-assisted wireless communication network.

the optimal design for wireless-powered communication networks with integrated services has not been exploited.

Inspired by this, in this paper, we attempt to investigate the optimal design for a wireless-powered communication network (WPCN) with integrated services, in which the transmitter first harvests energy from a dedicated PB and then communicates with the both receivers using the energy harvested. Unlike [15], the energy harvesting (EH) is considered at the transmitter in our work. Our objective is to maximize the secrecy rate region while satisfying the requirement of multicast service and the transmit power constraint recorded at the transmitter. The SRRM problem formulated is a biobjective optimization problem, which is non-convex and challenging. To solve it, we resort to reformulate the original problem into an equivalent scalar optimization problem and a three layer algorithm is proposed to find all the Pareto optimal points.

Notations: Boldface lowercase and uppercase letters denote vectors and matrices, respectively. The transpose, conjugate transpose, rank and trace of the matrix $\mathbf{A}$ are denoted as $\mathbf{A}^T$, $\mathbf{A}^H$, rank($\mathbf{A}$) and Tr($\mathbf{A}$), respectively. $\mathbf{A} \succeq \mathbf{0}$ means $\mathbf{A}$ is a positive semidefinite matrix. $\mathbb{E}[\cdot]$ represents the expectation of a random variable, and $\|\cdot\|$ denotes the vector Euclidean norm. Random vector $\mathbf{x} \sim \mathcal{CN}(\boldsymbol{\mu}, \boldsymbol{\Phi})$ with a mean vector $\boldsymbol{\mu}$ and covariance matrix $\boldsymbol{\Phi}$ follows a complex circularly symmetric Gaussian distribution.

2 SYSTEM MODEL AND PROBLEM FORMULATION

Consider a two-user downlink WPCN scenario, in which one source node S equipped with N_t transmit antennas communicates with both receivers who each has a single receive antenna, as depicted in Fig. 1. We assume that S is energy-constrained, i.e., the information transmission can only be scheduled by utilizing energy harvested from a dedicated PB[1]. It is assumed that two receivers have ordered the multicast service and receiver 1 further ordered the confidential service. Specially, receiver 2 (also refer to as eavesdropper) is able to eavesdrop the confidential message deliberately and admits the multicast message legitimately.

Following the idea of [17], receiver 1 and receiver 2 are registered in the network as two subscribed users and exchange signalling messages with S, thus perfect channel knowledge is known at the S. In this paper, we adopt the harvest-then-transmit protocol [5, 6]. Assuming a block time of T, during the first phase of duration δT ($\delta \in (0, 1)$ is EH ratio), S harvests energy from the dedicated PB. In the second phase of duration $(1-\delta)T$, S transmits information to receivers using the harvested energy.

In the first phase, PB broadcasts an energy signal to S, and the received energy signal at S can be expressed as

$$\mathbf{y}_s = \sqrt{P_s}\mathbf{h}_p x_s + \mathbf{n}_s, \tag{1}$$

where P_s is the transmit power at PB, $\mathbf{h}_p$ is the N_t-dimensional power transfer channel from PB to S, x_s is energy signal with unit power, and $\mathbf{n}_s$ is the additive white Gaussian noise (AWGN) with $\mathbb{E}[\mathbf{n}_s\mathbf{n}_s^H] = \mathbf{I}$.

At the end of the first phase, the harvested energy can be expressed as

$$E = \eta P_s \|\mathbf{h}_p\|^2 \delta T, \tag{2}$$

where $\eta \in (0, 1]$ denotes the energy conversion efficiency. To facilitate analysis, we assume $\eta = 1$ in the following.

In the second phase, S services two receivers with the total amount of energy harvested from PB, thus the transmit power at S can be calculated as

$$P = \frac{E}{(1-\delta)T} = P_s\|\mathbf{h}_p\|^2\frac{\delta}{1-\delta} \tag{3}$$

On the other hand, the received signal at receiver k ($k \in \{1, 2\}$) can be expressed as

$$y_k = \sqrt{P}\mathbf{h}_k^H\mathbf{x} + n_k, \tag{4}$$

where $\mathbf{h}_k \in \mathbb{C}^{N_t \times 1}$ is the channel vector from S to receiver k, $n_k \sim \mathcal{CN}(0, 1)$ is AWGN at receiver k. And $\mathbf{x}$ is the transmitted signal vector by S consisting of two independent components, i.e.,

$$\mathbf{x} = \mathbf{x}_0 + \mathbf{x}_c, \tag{5}$$

where $\mathbf{x}_0$ is the multicast message intended for both receivers, $\mathbf{x}_c$ is the confidential message only intended for receiver 1. $\mathbf{x}_0$ and $\mathbf{x}_c$ are assumed to obey a complex Gaussian distribution, i.e., $\mathbf{x}_0 \sim \mathcal{CN}(\mathbf{0}, \mathbf{Q}_0)$ and $\mathbf{x}_c \sim \mathcal{CN}(\mathbf{0}, \mathbf{Q}_c)$, where $\mathbf{Q}_0$ and $\mathbf{Q}_c$ represent the transmit covariance matrices of the multicast message and confidential message, respectively.

Let R_0 and R_c denote the achievable rates associated with the multicast and confidential messages, respectively. The achievable secrecy rate region of the traditional non-EH network is defined in [17]. Similarly, the achievable secrecy rate region of the considered WPCN can be defined as

$$R = \bigcup_{\mathbf{Q}_0, \mathbf{Q}_c, \delta} (R_0, R_c), \tag{6}$$

where R_0 and R_c satisfy

$$R_0 \le \min_{k=1,2} (1-\delta)\log_2\left(1 + \frac{\frac{\delta}{1-\delta}P_s\|\mathbf{h}_p\|^2\mathbf{h}_k^H\mathbf{Q}_0\mathbf{h}_k}{1 + \frac{\delta}{1-\delta}P_s\|\mathbf{h}_p\|^2\mathbf{h}_k^H\mathbf{Q}_c\mathbf{h}_k}\right) \tag{7}$$

$$\begin{aligned} R_c \le & (1-\delta)\log_2\left(1 + \frac{\delta}{1-\delta}P_s\|\mathbf{h}_p\|^2\mathbf{h}_1^H\mathbf{Q}_c\mathbf{h}_1\right) - \\ & (1-\delta)\log_2\left(1 + \frac{\delta}{1-\delta}P_s\|\mathbf{h}_p\|^2\mathbf{h}_2^H\mathbf{Q}_c\mathbf{h}_2\right) \end{aligned} \tag{8}$$

Under such scenario, we focus on the joint design of the covariance matrix of multicast message $\mathbf{Q}_0$, the covariance matrix of confidential message $\mathbf{Q}_c$ and EH ratio δ, in order to maximize the

[1]Note that PB only supplies wireless energy to the S, and does not participate in the information transmission.

secrecy rate region while guaranteeing the requirement of multicast service and the transmit power constraint. Therefore, the SRRM problem is formulated as

$$\max_{\mathbf{Q}_0,\mathbf{Q}_c,\delta,R_0,R_c} \bigcup (R_0, R_c) \tag{9a}$$

$$\text{s.t.} \min_{k\in\{1,2\}} (1-\delta)\log_2\left(1+\frac{\delta P_s\|\mathbf{h}_p\|^2\mathbf{h}_k^H\mathbf{Q}_0\mathbf{h}_k}{(1-\delta)+\delta P_s\|\mathbf{h}_p\|^2\mathbf{h}_k^H\mathbf{Q}_c\mathbf{h}_k}\right) \geq R_0, \tag{9b}$$

$$(1-\delta)\log_2\left(1+\frac{\delta}{1-\delta}P_s\|\mathbf{h}_p\|^2\mathbf{h}_1^H\mathbf{Q}_c\mathbf{h}_1\right) - (1-\delta)\log_2\left(1+\frac{\delta}{1-\delta}P_s\|\mathbf{h}_p\|^2\mathbf{h}_2^H\mathbf{Q}_c\mathbf{h}_2\right) \geq R_c, \tag{9c}$$

$$P_s \cdot \mathrm{Tr}(\mathbf{Q}_0+\mathbf{Q}_c) \leq P_{th}, \tag{9d}$$

$$0 < \delta < 1, \tag{9e}$$

$$\mathbf{Q}_0 \succeq \mathbf{0}, \mathbf{Q}_c \succeq \mathbf{0}, \tag{9f}$$

where P_{th} is the preset transmit power target. Note that problem (9) is a challenging task due to the non-convex vector optimization objective function, which will be addressed in the following.

3 OPTIMAL SOLUTION

As mentioned above, the formulated optimization problem (9) is a biobjective optimization problem, which is non-convex. To deal with this kind of problem, the convex combination of the two objectives (i.e., R_0 and R_c) is widely used in the open literature. Using this method, however, same Pareto optimal points may not be obtained [18]. In order to obtain the boundary points, we follow the method presented in [15]. Specifically, our strategy is to transform the primal vector optimization problem into a scalar optimization problem by fixing one entry of (R_0, R_c). As a result, the maximization of the vector (R_0, R_c) will be reduced into the maximization of a scalar R_c subject to a lower bound on R_0, Motivated by this, problem (9) can be transformed as

$$\varphi^*(\gamma_{ms}) \triangleq \max_{\mathbf{Q}_0,\mathbf{Q}_c,\delta} (1-\delta)\log_2\left(\frac{1+\frac{\delta}{1-\delta}P_s\|\mathbf{h}_p\|^2\mathbf{h}_1^H\mathbf{Q}_c\mathbf{h}_1}{1+\frac{\delta}{1-\delta}P_s\|\mathbf{h}_p\|^2\mathbf{h}_2^H\mathbf{Q}_c\mathbf{h}_2}\right) \tag{10a}$$

$$\text{s.t.} \min_{k\in\{1,2\}} (1-\delta)\log_2\left(1+\frac{\delta P_s\|\mathbf{h}_p\|^2\mathbf{h}_k^H\mathbf{Q}_0\mathbf{h}_k}{(1-\delta)+\delta P_s\|\mathbf{h}_p\|^2\mathbf{h}_k^H\mathbf{Q}_c\mathbf{h}_k}\right) \geq \gamma_{ms}, \tag{10b}$$

$$P_s \cdot \mathrm{Tr}(\mathbf{Q}_0+\mathbf{Q}_c) \leq P_{th}, \tag{10c}$$

$$0 < \delta < 1, \tag{10d}$$

$$\mathbf{Q}_0 \succeq \mathbf{0}, \mathbf{Q}_0 \succeq \mathbf{0}, \tag{10e}$$

where $\gamma_{ms} \geq 0$ can be interpreted as the prescribed requirement of the achievable multicast rate. Obviously, problem (10) is a secrecy rate maximization (SRM) problem with the multicast service constraint, and all the Pareto optimal solutions of problem (9) can be found by solving problem (10). In fact, when we set $\gamma_{ms} = 0$, problem (10) reduces to be a conventional SRM problem. By contrast, the interesting here is to set γ_{ms} higher than a target γ_{max}, which is given by

$$\gamma_{max} = \max_{P_s\mathrm{Tr}(\mathbf{Q}_0)\leq P_{th}, \mathbf{Q}_0\succeq\mathbf{0}} \min_{k\in\{1,2\}} (1-\delta) \log_2\left(1+\frac{\delta}{1-\delta}P_s\|\mathbf{h}_p\|^2\mathbf{h}_k^H\mathbf{Q}_0\mathbf{h}_k\right) \tag{11}$$

Clearly, problem (11) is the multicast rate, which can be solved via an SDP reformulation given in [19]. Further, we introduce the following theorem.

Theorem 1: The rate pair $(\gamma_{ms}, \varphi^*(\gamma_{ms}))$ is a Pareto optimal point of problem (10), and all Pareto optimal points of problem (10) can be obtained by varying the level of γ_{ms} in the range of $[0, \gamma_{max}]$.

Proof: Please refer to [17].

It can be observed that problem (10) is still non-convex since the objective function is a fraction form which is quasi-convex but not convex, and the constraint in (10b) is also non-convex. To circumvent this difficulty, we first introduce a slack variable β to simplify the denominator of the objective function in problem (10), then we recast problem (10) as

$$\max_{\mathbf{Q}_0,\mathbf{Q}_c,\delta,\beta} (1-\delta)\log_2\left(\frac{1+\frac{\delta}{1-\delta}P_s\|\mathbf{h}_p\|^2\mathbf{h}_1^H\mathbf{Q}_c\mathbf{h}_1}{\beta}\right) \tag{12a}$$

$$\text{s.t.} \log_2\left(1+\frac{\delta}{1-\delta}P_s\|\mathbf{h}_p\|^2\mathbf{h}_2^H\mathbf{Q}_c\mathbf{h}_2\right) \leq \log_2\beta, \tag{12b}$$

$$\frac{\mathbf{h}_k^H\mathbf{Q}_0\mathbf{h}_k}{\frac{1-\delta}{\delta P_s\|\mathbf{h}_p\|^2}+\mathbf{h}_k^H\mathbf{Q}_c\mathbf{h}_k} \geq \gamma'_{ms}, \forall\, k, \tag{12c}$$

$$P_s \cdot \mathrm{Tr}(\mathbf{Q}_0+\mathbf{Q}_c) \leq P_{th}, \tag{12d}$$

$$0 < \delta < 1, \tag{12e}$$

$$\mathbf{Q}_0 \succeq \mathbf{0}, \mathbf{Q}_c \succeq \mathbf{0}, \tag{12f}$$

where $\gamma'_{ms} = 2^{\frac{\gamma_{ms}}{1-\delta}} - 1$. Physically, $\log_2\beta$ can be interpreted as the maximal allowable mutual information of receiver 2's link. By adjusting β, we can control the level of mutual information between S and receiver 2.

Since δ is a variable ranging from the interval $(0, 1)$, we can obtain the optimal δ by one-dimensional search, such as uniform sampling method or Golden section search method [20]. In what follows, we focus on solving problem (12) for a fixed δ.

To proceed, we show that problem (12) can be further recast as a two-stage optimization problem. The first-stage is a single-variable optimization problem over β. The lower bound about β is directly recognized from the constraint (12b), meanwhile the upper bound follows the fact of a non-negative secrecy rate, thus an upper bound of β can be calculated as

$$\beta \leq 1+\frac{\delta}{1-\delta}P_s\|\mathbf{h}_p\|^2\mathbf{h}_1^H\mathbf{Q}_c\mathbf{h}_1 \leq 1+\frac{\delta}{1-\delta}\|\mathbf{h}_p\|^2P_{th}\|\mathbf{h}_1\|^2, \tag{13}$$

where the last inequality follows from the fact that $\mathrm{Tr}(\mathbf{Q}_c) \leq P_{th}$.

Note that constraint (12b) can be expressed as

$$(\beta-1) - \frac{\delta}{1-\delta}P_s\|\mathbf{h}_p\|^2\mathbf{h}_2^H\mathbf{Q}_c\mathbf{h}_2 \geq 0, \tag{14}$$

where the function $\log_2(\cdot)$ is removed since it is monotonically increasing function which has no effect on the optimization problem.

With fixed δ, the two-stage optimization (12) can be equivalently written as

$$\max_{\beta} \ f(\beta) \tag{15a}$$

$$\text{s.t. } 1 \le \beta \le 1 + \frac{\delta}{1-\delta}\|\mathbf{h}_p\|^2 P_{th}\|\mathbf{h}_1\|^2, \tag{15b}$$

where

$$f(\beta) \triangleq \max_{\mathbf{Q}_0,\mathbf{Q}_c} \frac{1 + \frac{\delta}{1-\delta}P_s\|\mathbf{h}_p\|^2\mathbf{h}_1^H\mathbf{Q}_c\mathbf{h}_1}{\beta} \tag{16a}$$

$$\text{s.t. } (\beta-1) - \frac{\delta}{1-\delta}P_s\|\mathbf{h}_p\|^2\mathbf{h}_2^H\mathbf{Q}_c\mathbf{h}_2 \ge 0, \tag{16b}$$

$$\mathbf{h}_k^H\mathbf{Q}_0\mathbf{h}_k - \gamma'_{ms}\mathbf{h}_k^H\mathbf{Q}_c\mathbf{h}_k - \gamma'_{ms}\frac{1-\delta}{\delta P_s\|\mathbf{h}_p\|^2} \ge 0, \forall k, \tag{16c}$$

$$P_s \cdot \mathrm{Tr}(\mathbf{Q}_0+\mathbf{Q}_c) \le P_{th}, \tag{16d}$$

$$\mathbf{Q}_0 \succeq \mathbf{0}, \mathbf{Q}_c \succeq \mathbf{0}. \tag{16e}$$

Here, the function $\log_2(\cdot)$ is omitted since it is monotonically increasing function. The upshot of the reformulation (16) is that it is a single-variable optimization problem over the interval $\left[1, 1+\frac{\delta}{1-\delta}\|\mathbf{h}_p\|^2 P_{th}\|\mathbf{h}_1\|^2\right.$ In practice, we use either uniform sampling method or the golden section search method [20] to obtain optimal β. Therefore, the key to solve problem (10) lies in computing $f(\beta)$, which requires solving the non-convex problem (16).

By introducing a change of variables $\hat{\mathbf{Q}}_0 = t\mathbf{Q}_0$, $\hat{\mathbf{Q}}_c = t\mathbf{Q}_c$, and $t = \frac{1}{\beta}$, and applying the Charnes-Cooper transformation, we can equivalently express (16) as

$$\max_{\hat{\mathbf{Q}}_0,\hat{\mathbf{Q}}_c,t} \ t + \frac{\delta}{1-\delta}P_s\|\mathbf{h}_p\|^2\mathbf{h}_1^H\hat{\mathbf{Q}}_c\mathbf{h}_1 \tag{17a}$$

$$\text{s.t. } t\beta = 1, \tag{17b}$$

$$(\beta-1)t - \frac{\delta}{1-\delta}P_s\|\mathbf{h}_p\|^2\mathbf{h}_2^H\hat{\mathbf{Q}}_c\mathbf{h}_2 \ge 0, \tag{17c}$$

$$\mathbf{h}_k^H\hat{\mathbf{Q}}_0\mathbf{h}_k - \gamma'_{ms}\mathbf{h}_k^H\hat{\mathbf{Q}}_c\mathbf{h}_k - t\gamma'_{ms}\frac{1-\delta}{\delta P_s\|\mathbf{h}_p\|^2} \ge 0, \ \forall k, \tag{17d}$$

$$P_s \cdot \mathrm{Tr}(\hat{\mathbf{Q}}_0+\hat{\mathbf{Q}}_c) \le tP_{th}, \tag{17e}$$

$$\hat{\mathbf{Q}}_0 \succeq \mathbf{0}, \hat{\mathbf{Q}}_c \succeq \mathbf{0}. \tag{17f}$$

The motivation of the transformation above is that we would like to transform the fractional objective function in (16) to the linear/convex objective function in (17). It is worth noting that the second-stage problem (17) is a convex SDP, which can be efficiently solved by a standard optimization solver, e.g. CVX [18].

Based on the above analysis, a three layer optimization algorithm is proposed to solve the original Problem (10) of interest. In the first layer, we aim to update δ via uniform sampling method; In the second layer, we update β via Golden section method; In the third layer, we focus on solving the SDP problem (17). A very brief outline of the proposed algorithm is summarized in Algorithm 1.

Until now, we have successfully solved the original problem (10). To obtain further insight into problem (10), we have the following theorem.

Algorithm 1 Three Layer Algorithm for Solving Problem (17)

Input: Initialization.
Repeat: For $0 < \delta < 1$, performing one-dimension search.
Step 1: Solve the convex problem (11) and obtain γ_{max}.
Step 2: For a given δ, solve convex problem (16) by performing Golden section method on $\beta \in [1, 1+\frac{\delta}{1-\delta}\|\mathbf{h}_p\|^2 P_{th}\|\mathbf{h}_1\|^2]$, then obtain the optimal solution β^*.
Step 3: According to the obtained β^*, solve convex problem (17) and obtain $(\hat{\mathbf{Q}}_0^*, \hat{\mathbf{Q}}_c^*, t^*)$.
Output: $\mathbf{Q}_0^* = \frac{\hat{\mathbf{Q}}_0^*}{t^*}$ and $\mathbf{Q}_c^* = \frac{\hat{\mathbf{Q}}_c^*}{t^*}$.

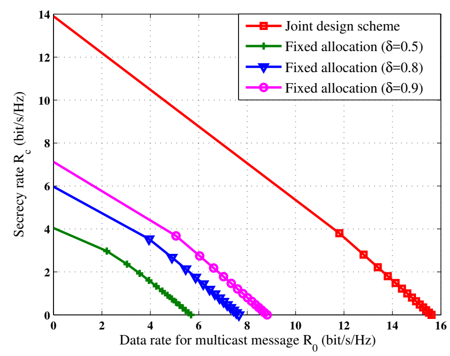

Figure 2: Secrecy rate regions comparison of various resource allocation schemes.

Theorem 2: The rank of optimal solutions to problem (10), denoted by $\mathbf{Q}_0^*$ and $\mathbf{Q}_c^*$, are always rank-one.
Proof: Please refer to Appendix A.

4 NUMERICAL RESULTS

In this section, we present simulation results to show the performance of the proposed optimal design scheme. Without loss of generality, we assume that the number of transmit antennas equipped at S is $N_t = 2$ and the transmit power threshold is set to be $P_{th} = 10$dB, unless otherwise specified. For the sake of simplicity, we assume that the noise powers are identical as 1dB, the transmit power of PB is set to be $P_s = 5$dB. All simulation results are averaged over 1000 randomly generated channel realizations.

Fig. 2 shows the secrecy rate regions comparison of our proposed joint design scheme and a fixed allocation scheme (as a benchmark). For the fixed allocation scheme, we set $\delta = \{0.5, 0.8, 0.9\}$ respectively. From Fig. 2, we can clearly see that our proposed joint design scheme outperforms the fixed allocation scheme for the same data rate R_0. Furthermore, we can observe that the secrecy rate region R_c of our proposed joint design scheme is far lager than that of the fixed allocation scheme.

Next, we examine the relationship between the secrecy rate regions achieved by different schemes and the number of transmit antennas N_t when fixing transmit power threshold $P_{th} = 10$dB. As can be seen from Fig. 3, a higher secrecy rate region can be obtained

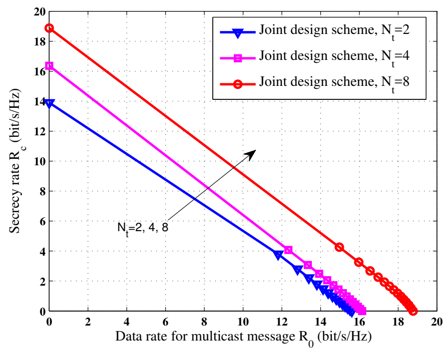

Figure 3: Secrecy rate regions comparison for different number of transmit antennas N_t.

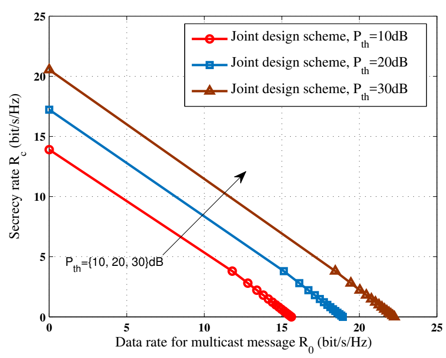

Figure 4: Secrecy rate regions versus the transmit power threshold P_{th}.

with more transmit antennas N_t, which is caused by the increased spatial degrees of freedom.

To get further insight, we study the impact of the transmit power threshold on the secrecy rate region under $N_t = 2$, as depicted in Fig. 4. It is observed that the secrecy rate region increases along with P_{th}, which reveals that a better choice of P_{th} is of significant importance to the secrecy rate region.

5 CONCLUSION

In this paper, we have studied the optimal design in a WPCN where the transmitter was powered by external PB. Both the multicast service and confidential service were jointly considered. We aimed at maximizing the secrecy rate region while satisfying multicast service constraint and transmit power constraint. Since the formulated SRRM problem was challenging to solve, we alternatively transformed the primal vector optimization problem into the maximization of scalar R_c by fixing the variable R_0. By applying the Charnes-Cooper transformation, a three layer iterative algorithm was proposed to obtain the optimal solution. Numerical results have showed that the proposed joint optimal design scheme had a good performance in improving secrecy rate region.

A PROOF OF THEOREM 2

To examine the rank conditions of $\mathbf{Q}_0^*$ and $\mathbf{Q}_c^*$, we turn our attention to the following power minimization problem:

$$\min_{\mathbf{Q}_0, \mathbf{Q}_c} \ P_s \mathrm{Tr}(\mathbf{Q}_0 + \mathbf{Q}_c) \tag{18a}$$

$$\text{s.t.} \ \frac{1 + \frac{\delta}{1-\delta} P_s \|\mathbf{h}_p\|^2 \mathbf{h}_1^H \mathbf{Q}_c \mathbf{h}_1}{\beta} \geq \mu^*, \tag{18b}$$

$$(\beta - 1) - \frac{\delta}{1-\delta} P_s \|\mathbf{h}_p\|^2 \mathbf{h}_2^H \mathbf{Q}_c \mathbf{h}_2 \geq 0, \tag{18c}$$

$$\mathbf{h}_k^H \mathbf{Q}_0 \mathbf{h}_k - \gamma'_{ms} \mathbf{h}_k^H \mathbf{Q}_c \mathbf{h}_k - \gamma'_{ms} \frac{1-\delta}{\delta P_s \|\mathbf{h}_p\|^2} \geq 0, \forall \, k, \tag{18d}$$

$$\mathbf{Q}_0 \succeq \mathbf{0}, \mathbf{Q}_c \succeq \mathbf{0}, \tag{18e}$$

where μ^* is the optimal objective value of problem (16). It is easy verified that any feasible solution to problem (18) is also an optimal solution to problem (16) [17].

We now prove the rank conditions of $\mathbf{Q}_0$ and $\mathbf{Q}_c$ through Karush-Kuhn-Tucker (KKT) conditions. The partial Lagrangian of the primal problem (18) with respect to $\mathbf{Q}_c$ is given by

$$\begin{aligned}
&\mathcal{L}(\mathbf{Q}_0, \mathbf{Q}_c, \lambda, \{\eta_k\}, \{\phi_k\}, \mathbf{A}, \mathbf{B}) = P_s \mathrm{Tr}(\mathbf{Q}_0 + \mathbf{Q}_c) \\
&- \lambda \left[1 + \frac{\delta}{1-\delta} P_s \|\mathbf{h}_p\|^2 \mathbf{h}_1^H \mathbf{Q}_c \mathbf{h}_1 - \beta \mu^* \right] \\
&- \sum_{k=1}^{2} \eta_k \left[(\beta - 1) - \frac{\delta}{1-\delta} P_s \|\mathbf{h}_p\|^2 \mathbf{h}_2^H \mathbf{Q}_c \mathbf{h}_2 \right] \\
&- \sum_{k=1}^{2} \phi_k \left[\mathbf{h}_k^H \mathbf{Q}_0 \mathbf{h}_k - \gamma'_{ms} \mathbf{h}_k^H \mathbf{Q}_c \mathbf{h}_k - \gamma'_{ms} \frac{1-\delta}{\delta P_s \|\mathbf{h}_p\|^2} \right] \\
&- \mathrm{Tr}(\mathbf{A}\mathbf{Q}_0) - \mathrm{Tr}(\mathbf{B}\mathbf{Q}_c),
\end{aligned} \tag{19}$$

where $\lambda \geq 0$, $\{\eta_k\} \geq 0$, $\{\phi_k\} \geq 0$, $\mathbf{A} \succeq \mathbf{0}$ and $\mathbf{B} \succeq \mathbf{0}$ denote the dual variables corresponding to the constraints (18b)-(18e), respectively.

By taking the partial derivative for (19) with respect to $\mathbf{Q}_c$ and applying KKT conditions, we have

$$\begin{aligned}
P_s \mathbf{I} + \sum_{k=1}^{2} \eta_k \frac{\delta}{1-\delta} P_s \|\mathbf{h}_p\|^2 \mathbf{h}_2^H \mathbf{h}_2 + \sum_{k=1}^{2} \phi_k \gamma'_{ms} \mathbf{h}_k^H \mathbf{h}_k \\
= \mathbf{B} + \lambda \frac{\delta}{1-\delta} P_s \|\mathbf{h}_p\|^2 \mathbf{h}_1^H \mathbf{h}_1,
\end{aligned} \tag{20a}$$

$$\mathbf{B}\mathbf{Q}_c^* = \mathbf{0}, \tag{20b}$$

$$\mathbf{Q}_c^* \succeq \mathbf{0}. \tag{20c}$$

Multiplying both sides of (20a) with $\mathbf{Q}_c^*$, we can obtain

$$\begin{aligned}
\left(P_s \mathbf{I} + \sum_{k=1}^{2} \eta_k \frac{\delta}{1-\delta} P_s \|\mathbf{h}_p\|^2 \mathbf{h}_2^H \mathbf{h}_2 + \sum_{k=1}^{2} \phi_k \gamma'_{ms} \mathbf{h}_k^H \mathbf{h}_k \right) \mathbf{Q}_c^* \\
= \left(\lambda \frac{\delta}{1-\delta} P_s \|\mathbf{h}_p\|^2 \mathbf{h}_1^H \mathbf{h}_1 \right) \mathbf{Q}_c^*
\end{aligned} \tag{21}$$

Since $P_s \mathbf{I} + \sum_{k=1}^{2} \eta_k \frac{\delta}{1-\delta} P_s \|\mathbf{h}_p\|^2 \mathbf{h}_2^H \mathbf{h}_2 + \sum_{k=1}^{2} \phi_k \gamma'_{ms} \mathbf{h}_k^H \mathbf{h}_k \succ \mathbf{0}$, we can get

$$\begin{aligned}
\mathrm{rank}(\mathbf{Q}_c^*) = \mathrm{rank} \left(\lambda \frac{\delta}{1-\delta} P_s \|\mathbf{h}_p\|^2 \mathbf{h}_1^H \mathbf{h}_1 \mathbf{Q}_c^* \right) \\
\leq \mathrm{rank}(\mathbf{h}_1^H \mathbf{h}_1) = 1
\end{aligned} \tag{22}$$

Discarding the trivial case $\mathbf{Q}_c^* = \mathbf{0}$, we have $\text{rank}(\mathbf{Q}_c^*) = 1$. Next, we will examine the rank condition of $\mathbf{Q}_0^*$.

By using an interesting result introduced in [21], problem (18) is a separable SDP problem, which satisfies

$$\text{rank}^2(\mathbf{Q}_0^*) + \text{rank}^2(\mathbf{Q}_c^*) \le M, \tag{23}$$

where M indicates the total number of linear equalities and inequalities in problem (18). We can observe $M = 4$ from problem (18). Based on the aforementioned $\text{rank}(\mathbf{Q}_c^*) = 1$, we can easily verify $\text{rank}(\mathbf{Q}_0^*) \le 1$. When $\text{rank}(\mathbf{Q}_0^*) = 0$, constraint (18d) is infeasible, thus $\text{rank}(\mathbf{Q}_0^*) = 1$. This completes the proof.

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REFERENCES

[1] X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, "Wireless networks with RF energy harvesting: A contemporary survey," *IEEE Commun. Surv. Tut.*, vol. 17, pp. 757–789, Second Quarter 2015.

[2] S. Bi, C. K. Ho, and R. Zhang, "Wireless powered communication: Opportunities and challenges," *IEEE Commun. Mag.*, vol. 53, pp. 117–125, Apr. 2015.

[3] B. Li and Z. Fei, "Probabilistic-constrained robust secure transmission for energy harvesting over miso channels," *SCIENCE CHINA Information Sciences*, vol. 60, Jun. 2017.

[4] K. Huang and V. K. N. Lau, "Enabling wireless power transfer in cellular networks: Architecture, modeling and deployment," *IEEE Trans. Wireless Commun.*, vol. 13, pp. 902–912, Feb. 2014.

[5] C. Zhong, X. Chen, Z. Zhang, and G. K. Karagiannidis, "Wireless-powered communications: Performance analysis and optimization," *IEEE Trans. Commun.*, vol. 63, pp. 5178–5190, Dec. 2015.

[6] Y. Ma, H. Chen, Z. Lin, Y. Li, and B. Vucetic, "Distributed and optimal resource allocation for power beacon-assisted wireless-powered communications," *IEEE Trans. Commun.*, vol. 63, pp. 3569–3583, Oct. 2015.

[7] X. Jiang, C. Zhong, X. Chen, T. Q. Duong, T. A. Tsiftsis, and Z. Zhang, "Secrecy performance of wirelessly powered wiretap channels," *IEEE Trans. Commun.*, vol. 64, pp. 3858–3871, Sep. 2016.

[8] Y. Wu, X. Chen, C. Yuen, and C. Zhong, "Robust resource allocation for secrecy wireless powered communication networks," *IEEE Commun. Lett.*, vol. 20, pp. 2430–2433, Dec. 2016.

[9] Y. Liu, H.-H. Chen, and L. Wang, "Physical layer security for next generation wireless networks: Theories, technologies, and challenges," *IEEE Commun. Surv. Tut.*, vol. 19, pp. 347–376, First Quarter 2017.

[10] B. Li, Z. Fei, and H. Chen, "Robust artificial noise-aided secure beamforming in wireless-powered non-regenerative relay," *IEEE Access*, vol. 4, pp. 7921–7929, Nov. 2016.

[11] B. Li and Z. Fei, "Robust beamforming and cooperative jamming for secure transmission in DF relay systems," *EURASIP J. Wirel. Commun.*, vol. 68, pp. 1–11, Dec. 2016.

[12] R. Schaefer and H. Boche, "Physical layer service integration in wireless networks: Signal processing challenges," *IEEE Signal Process. Mag.*, vol. 31, pp. 147–156, Apr. 2014.

[13] H. D. Ly, T. Liu, and Y. Lian, "Multiple-input multiple-output gaussian broadcast channels with common and confidential messages," *IEEE Trans. Inf. Theory*, vol. 56, pp. 5477–5487, Oct. 2010.

[14] R. Liu, T. Liu, H. V. Poor, and S. Shamai, "New results on multiple-input multiple-output broadcast channels with confidential messages," *IEEE Trans. Inf. Theory*, vol. 59, pp. 1346–1359, Mar. 2013.

[15] W. Mei, L. Li, Z. Chen, and C. Huang, "Artificial-noise aided transmit design for multi-user MISO systems with integrated services," in *Proc. IEEE GlobalSIP*, pp. 1382–1386, Orlando, USA, Dec. 2015.

[16] W. Mei, Z. Chen, and C. Huang, "Robust artificial-noise aided transmit design for multi-user MISO systems with integrated services," in *Proc. IEEE ICASSP*, pp. 3856–3860, Shanghai, China, Mar. 2016.

[17] W. Mei, Z. Chen, L. Li, J. Fang, and S. Li, "On artificial-noise aided transmit design for multi-user miso systems with integrated services," *IEEE Trans. Veh. Technol.*, 2017.

[18] S. Boyd and L. Vandenberghe, *Convex Optimization.* U.K.: Cambridge Univ. Press, 2004.

[19] H. Kim, D. J. Love, and S. Y. Park, "Optimal and successive approaches to signal design for multiple antenna physical layer multicasting," *IEEE Trans. Commun.*, vol. 59, pp. 2316–2327, Aug. 2011.

[20] D. Bertsekas, *Nonlinear Programming, 2nd ed.* Belmont, MA, USA: Athena Scientific, 1999.

[21] Y. Huang and D. Palomar, "Rank-constrained separable semidefinite programming with applications to optimal beamforming," *IEEE Trans. Signal Process.*, vol. 58, pp. 664–678, Sep. 2010.