Robust Beamforming Design for SWIPT-Based Multi-Radio Wireless Mesh Network with Cooperative Jamming

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Abstract: Wireless mesh networks (WMNs) can provide flexible wireless connections in a smart city, internet of things (IoT), and device-to-device (D2D) communications. The performance of WMNs can be greatly enhanced by adopting a multi-radio technique, which enables a node to communicate with more nodes simultaneously. However, multi-radio WMNs face two main challenges, namely, energy consumption and physical layer secrecy. In this paper, both simultaneous wireless information and power transfer (SWIPT) and cooperative jamming technologies were adopted to overcome these two problems. We designed the SWIPT and cooperative jamming scheme, minimizing the total transmission power by properly selecting beamforming vectors of the WMN nodes and jammer to satisfy the individual signal-to-interference-plus-noise ratio (SINR) and energy harvesting (EH) constrains. Especially, we considered the channel estimate error caused by the imperfect channel state information. The SINR of eavesdropper (Eve) was suppressed to protect the secrecy of WMN nodes. Due to the fractional form, the problem was proved to be non-convex. We developed a tractable algorithm by transforming it into a convex one, utilizing semi-definite programming (SDP) relaxation and S-procedure methods. The simulation results validated the effectiveness of the proposed algorithm compared with the non-robust design.

Keywords: simultaneous wireless information and power transfer (SWIPT); wireless mesh network (WMN); cooperative jamming; robust beamforming design

1. Introduction

Wireless mesh networks (WMNs) are able to wirelessly cover a large area with low deployment and maintenance costs. Particularly, when combining with multi-radio (MR) technology, the capacity of WMNs is significantly improved [1–3]. Due to such a feature, WMNs are suitable for both providing ubiquitous connection to the internet and carrying data generated by multiple services, such as internet of things (IoT), smart grids, vehicle-to-vehicle (V2V), etc. [4–6], where mesh nodes need to be deployed without fixed power connections. In this case, most of the mesh nodes are supplied by the batteries, which have limited operation time and need to be replaced or recharged frequently.

Energy harvesting (EH) WMNs yield low battery maintenance costs and less energy storage requirements at each node by harvesting the energy from the environment (e.g., solar or wind power) [7–10]. However, the intermittent and unpredictable nature of these energy sources makes it difficult to supply a certain amount of power for applications continuously and stably with EH technology, and most conventional EH technologies are only applicable in specific environments.
Recently, radiofrequency (RF) EH has opened up the possibility to overcome the above limitations, where the nodes can charge their batteries from electromagnetic radiation. Since RF signals can transmit information and power at the same time, simultaneous wireless information and power transfer (SWIPT) schemes for various networks have been widely researched [11–13].

Information security is a prime concern for critical infrastructures or some sensitive services. However, due to the vulnerability of the wireless links, limited physical protection, and the dynamically changing topology, WMNs tend to be generally susceptible to attacks [14]. Traditional security mechanisms, typically involving cryptographic algorithms, implicitly assume that any potential eavesdroppers have limited computational abilities [15,16]. However, the rapid development of computing hardware brings more kinds of attacking methods, making these traditional mechanisms more vulnerable. To address this problem, physical layer security mechanisms have recently attracted significant attention to WMNs [17–19]. Among them, the cooperative jamming method is a popular physical layer security solution, which was adopted in our work.

In this paper, we applied the cooperative jamming method and SWIPT technology to multi-radio WMN to enhance network security and alleviate energy consumption problems. Under the premise of imperfect channel state information, we designed a robust beamforming scheme to minimize the total power consumption while satisfying the individual quality-of-service (QoS) and EH requirements, as well as the channel estimate error and transmit power constraints. In addition, to ensure the secrecy of the WMN, the signal-to-interference-plus-noise ratio (SINR) of eavesdropper (Eve) was limited to be less than a certain threshold. The formulated problem was non-convex due to the fractional form and logarithmic function, and we first transformed it to a convex one and then obtained the feasible optimal solution by using the semi-definite programming (SDP) relaxation and S-procedure methods. The simulation results indicated the good performance of the proposed schemes compared to non-robust ones. The main contributions of this paper are listed as follows:

• In this paper, both SWIPT and cooperative jamming technics were adopted in the multi-radio WMN to enhance its power consumption and physical layer security performance, respectively. While [20–24] only adopted the SWIPT, [25–27] only adopted the cooperative jamming. Although [28–31] proposed some beamforming method, considering both SWIPT and cooperative jamming, all of them were designed for the cognitive radio system.

• Both imperfect channel state information and non-linear EH model were considered in this paper, making our system model more practical. Moreover, the imperfect channel state information led to the unknown channel estimate error. We utilized the S-procedure method to relax the channel estimate error constraints.

• The transmit power consumption optimization constrained by the SINR threshold, EH threshold, channel estimate error, and total transmit power was a non-convex problem. We transformed it into a standard SDP format, which was a convex problem.

The rest of the paper is organized as follows. In Section 2, the related works are reviewed. The SWIPT-based multi-radio WMN model with cooperative jamming is presented in Section 3. In Section 4, a robust beamforming problem is formulated, and the optimal scheme is elaborated. Section 5 provides numerical results and discussions. Finally, conclusions are presented in Section 6.

Notations: $|\cdot|$, $\|\cdot\|_F$, and $(\cdot)^H$ denote the absolute value, the Frobenius norm, and the Hermitian transpose, respectively. $\text{Tr}(\cdot)$ and $E[\cdot]$ denote the trace expectation operator. $0_N$ is the $N \times 1$ zero vector. The distribution of a circularly symmetric complex Gaussian (CSCG) random variable with zero mean and variance $\sigma^2$ is denoted as $\mathcal{CN}(0, \sigma^2)$. $\langle A, B \rangle = \text{Tr}(A^H B)$ and $[x]^+ = \max\{x, 0\}$. $A \succeq 0$ indicates that matrix $A$ is positive semidefinite, and $\text{rank}(A)$ is the rank of a matrix $A$.

2. Related Works

Simultaneous wireless information and power transfer (SWIPT) in wireless communications has recently attracted considerable attention, and wireless networks are envisioned to be energy
self-sufficient in the future. The concept of SWIPT was first developed in [32], where a trade-off between the rates at which energy and reliable information can be transmitted over a single noisy channel was studied. Later on, this work was extended in [33] to incorporate the effect of frequency-selective channels and additive white Gaussian noise. However, these studies assumed that decoding information and extracting power could be obtained simultaneously from the same received signal, which is unrealistic in practice due to practical circuit design limitations. On the other hand, two practical EH receivers, namely, time switching (TS) and power splitting (PS), were introduced in [34,35]. In the former, the receiver switches between the energy harvester and information receiver, whereas, in the latter scheme, the receiver splits the signal into two streams, one for EH, and the other for information decoding. In this paper, we adopted the PS method in the EH model.

Multi-radio and cooperative communication techniques were exploited to further enhance the performance of SWIPT systems [36]. The capacity of SWIPT was optimized through multiple-input single-output (MISO) and multiple-input multiple-output (MIMO) techniques, which were illustrated in [37,38], respectively. Furthermore, an EH relaying system was studied in [20] for the cases with/without the presence of co-channel interference, where the multiple antennas relay node was powered by the source signal and signals from other sources. Joint optimization of beamforming, transmission power, and harvested energy for the MIMO SWIPT system was investigated in [21]. The broadcasting and interference channel case in the MR SWIPT system with multi-users was analyzed in [22]. An energy efficiency maximization algorithm, considering both the power splitting factor and precoding metric for SWIPT MIMO wireless sensor network, was proposed in [23]. In [24], EH was employed into the MR WMNs, and a minimum power channel assignment and routing algorithm (MP-CACR) was proposed to manage the EH in WMN.

Recently, there has been a growing interest in studying physical layer security in SWIPT systems. The concept of physical layer security was first introduced by Wyner in [25]. It was shown that secret communication was possible when the Eve channel was a degraded version of the destination channel. To counter eavesdropping, a friendly jammer in the network sent out artificial noise (AN) to specifically interfere with Eve’s reception so that the transmitted message could not be decoded. References [26,27] introduced how to choose friendly jammers efficiently. In [28,29], cooperative jamming-aided secure communication for SWIPT networks was studied, where the jammer could help the source to increase the harvested energy by the energy receiver. The authors of [30] proposed a harvest-and-jam (HJ) protocol in a SWIPT cooperative system, consisting of four relay node wiretap channels with multi-antenna HJ helpers to maximize the secrecy rate while subjecting to the relay transmit power and the total harvested energy constraints for each jamming helper. In [31], different secure relay beamforming algorithms for SWIPT non-regenerative relay systems were studied. However, to the best of our knowledge, no investigation or analysis has yet been carried out for the robust beamforming of full duplex SWIPT-based MR WMNs with the cooperative jamming secure method, which motivated the research of this paper.

3. System Model

The model was motivated by the potential of SWIPT and cooperative jamming technic in future wireless communication systems. In this paper, we considered a SWIPT-based MR WMN with cooperative jamming, as shown in Figure 1. The system under consideration consisted of three communication nodes, one Eve, and one cooperative jammer. All the communication nodes consisted of a normal WMN, where all the nodes in the WMN could communicate with any other nodes. To simplify the calculations, we assumed only three communication nodes in our system. A WMN with more communication nodes could be calculated in a similar method. The communication nodes were represented as a, b, and c, while three communication links among them were denoted as $l_{ab}$, $l_{bc}$, and $l_{ca}$, respectively. To improve the energy performance of the WMN system in Figure 1, each communication nodes equipped a power split-based SWIPT model, making the nodes to reuse the energy from the received signal. Due to the lack of the physical layer in WMN, the communication between the WMN
nodes was easy to eavesdrop. In this paper, we assumed that there was an eavesdropper, which was eavesdropping the communication between the node \(c\) and \(a\). The link \(l_{aj}\) was eavesdropped by an eavesdropper with a single antenna. To enhance the security performance of the system, one of the trustworthy WMN nodes was selected to work as a jamming node, which would inject artificial noise signals continuously into the channel to make the eavesdropper incapable of successfully decoding the confidential signals. In this paper, we assumed that the jamming node had been selected and determined, and the procedure of jammer selection was not discussed here because the selection algorithm was out of the research scope of this work, and it could be referred to in literature [37,39]. Each node in the WMN was assumed to be equipped with \(N + 1\) antennas—\(N\) for transmitting and one for receiving. Through a power splitter, the received signal was divided into two parts, one for the information decoder, and another for EH. \(\rho_n\) denotes the PS ratio of the node \(n\), \(n \in \{a,b,c,j\}\), which means that a portion \(\rho_n\) of the signal power was used for signal detection, while the remaining portion \((1 - \rho_n)\) was diverted to EH.

![Figure 1](image-url)  
Figure 1. A system model of the simultaneous wireless information and power transfer (SWIPT)-based multi-radio wireless mesh network (WMN) with cooperative jamming.

In some practical deployments, it is difficult to obtain accurate channel state information (CSI) at the transmitter because of delay, quantization errors, etc. Thus, the channel estimation error was considered in the system model. \(h_{af} \in \mathbb{C}^{N \times 1}\) represents the practical channel response between the node \(a \in \{a,b,c,j\}\) and \(\beta \in \{a,b,c,e\}\), where \(a\) and \(\beta\) denote the transmitter and receiver, respectively. Thus, the actual channel response between two nodes could be expressed as

\[
h_{af} = \tilde{h}_{af} + e_{af}, \quad a \in \{a,b,c,j\}, \; \beta \in \{a,b,c,e\},
\]  

(1)

where \(\tilde{h}_{af} \in \mathbb{C}^{N \times 1}\) is the estimated channel vector, and \(e_{af} \in \mathbb{C}^{N \times 1}\) is the estimation error vector. When \(a = \beta\), \(e_{af}\) was sufficiently small, which was treated as zero in this paper. The channel estimation error was assumed to be within a certain range with the upper limit \(\eta_{af}\), which could be expressed as

\[
\|e_{af}\|_F^2 = \|h_{af} - \tilde{h}_{af}\|_F^2 \leq \eta_{af}, \quad a \in \{a,b,c,j\}, \; \beta \in \{a,b,c,e\}.
\]  

(2)

The signal received by the WMN communication nodes and Eve was expressed as
where $x_a$ is the signal transmitted from the node $a \in \{a,b,c\}$, satisfying $E[|x_a|^2] = 1$. $w_a \in \mathbb{C}^{N \times 1}$ denotes the beamforming vectors of the node $a \in \{a,b,c\}$, and $n_\beta, n_\beta \in \{a,b,c,e\}$ is the additive white Gaussian noise (AWGN) with zero mean and variance of $\sigma^2$.

Due to the nodes having the knowledge of their own code words, and the self-interfering channel estimation errors were ignored as we mentioned above, the self-interference term in Equations (3)–(5) could be cancelled through self-interference cancellation technique [40]. The received signal after self-interference cancellation could be written as

$$
\bar{y}_a = (h_{ab})^H w_a x_a + (h_{ab})^H w_b x_b + (h_{ab})^H w_c x_c + (h_{ja})^H w_j x_j + n_a,
$$

$$
\bar{y}_b = (h_{ab})^H w_a x_a + (h_{jb})^H w_b x_b + (h_{ja})^H w_c x_c + (h_{ja})^H w_j x_j + n_b,
$$

$$
\bar{y}_c = (h_{bc})^H w_a x_a + (h_{bc})^H w_b x_b + (h_{jc})^H w_c x_c + (h_{jc})^H w_j x_j + n_c,
$$

$$
\bar{y}_e = (h_{ae})^H w_a x_a + (h_{ae})^H w_b x_b + (h_{ae})^H w_c x_c + (h_{je})^H w_j x_j + n_e.
$$

According to Equations (7)–(10), the SINR of the WMN nodes and Eve could be calculated as

$$
\text{SINR}_a = \frac{\rho_a \left| (h_{ab})^H w_a \right|^2}{\rho_a \left| (h_{ab})^H w_b \right|^2 + \left| (h_{ab})^H w_c \right|^2 + \sigma^2_a + \left| (h_{ja})^H w_j \right|^2},
$$

$$
\text{SINR}_b = \frac{\rho_b \left| (h_{ab})^H w_a \right|^2}{\rho_b \left| (h_{ab})^H w_c \right|^2 + \left| (h_{ab})^H w_a \right|^2 + \sigma^2_b + \left| (h_{ja})^H w_j \right|^2},
$$

$$
\text{SINR}_c = \frac{\rho_c \left| (h_{bc})^H w_b \right|^2}{\rho_c \left| (h_{bc})^H w_c \right|^2 + \left| (h_{bc})^H w_b \right|^2 + \sigma^2_c + \left| (h_{jc})^H w_j \right|^2},
$$

$$
\text{SINR}_e = \frac{\rho_e \left| (h_{ae})^H w_c \right|^2}{\rho_e \left| (h_{ae})^H w_c \right|^2 + \left| (h_{ae})^H w_c \right|^2 + \sigma^2_e + \left| (h_{je})^H w_j \right|^2}.
$$

The non-linear parametric EH model was adopted here since it is more practical than the linear one [41–44]. After energy harvesting, the power harvested at each WMN node $n \in \{a,b,c\}$ was modeled as

$$
EH_{n}^{\text{out}} = \frac{M_n}{1 + \exp\left(-\Omega_n (EH_{n}^{\text{in}} - \Upsilon_n)\right)} - \frac{M_n}{1 + \exp\left(\Omega_n \Upsilon_n\right)}, \quad n \in \{a,b,c\},
$$

where $M_n$ is a constant denoting the maximum harvested power of node $n$ when the EH circuit is saturated, $\Upsilon_n$ is related to the turn-on voltage threshold of the EH circuit, and $\Omega_n$ reflects the non-linear
charging rate with respect to the input power of the EH circuit $EH_{in}^n$. $EH_{in}^n$ was calculated by the PS ratio $\rho_n$ and the energy harvesting efficiency $\xi_n$, which could be expressed as

$$EH_{in}^n = \xi_n(1 - \rho_n)E[|y_n|^2], \ n \in \{a, b, c\}. \quad (16)$$

4. Robust Beamforming Design

In this paper, we focused on the beamforming design and PS ratio optimization of the system. Our goal was to minimize the total transmitted power while subjecting to the SINR, EH, and power consumption constraints. The optimization problem could be mathematically characterized as

$$\text{P1: min} \sum_{n \in \{a, b, c, j\}} \|w_n\|^2_F$$

subject to:

$$\text{SINR}_n \leq \gamma_n \quad (18)$$
$$\text{SINR}_n \geq \gamma_n, \ n \in \{a, b, c\} \quad (19)$$
$$EH_{out}^n \geq \theta_n, \ n \in \{a, b, c\} \quad (20)$$
$$\|w_n\|^2_F \leq P_{max}, \ n \in \{a, b, c, j\} \quad (21)$$
$$0 \leq \rho_n \leq 1, \ n \in \{a, b, c\} \quad (22)$$

where $\gamma_n$ represents the upper bound SINR threshold of Eve, $\gamma_n, \ n \in \{a, b, c\}$ and $\theta_n, \ n \in \{a, b, c\}$ represent the lower bound SINR and EH threshold of the WMN communication nodes, respectively. $P_{max}$ is the power consumption constraint of each node.

$\text{P1}$ is a non-convex optimization problem and difficult to solve due to the fractional form and logarithmic function in the objective function. To deal with this difficulty, we first introduced a new variable $W_n = w_n(w_n)^H, \ n \in \{a, b, c, j\}$ with $\text{rank}(W_n) = 1$. Then, it was reformulated into an equivalent non-fractional form $\text{P2}$.

$$\text{P2: min} \sum_{n \in \{a, b, c, j\}} \text{Tr}(W_n)$$

subject to:

$$\text{Tr}(W_n) \leq P_{max}, \ n \in \{a, b, c, j\} \quad (26)$$
$$W_n \geq 0, \ n \in \{a, b, c, j\} \quad (27)$$
$$\text{rank}(W_n) = 1, \ n \in \{a, b, c, j\}. \quad (28)$$

In practice, the exact statistical information of the channel estimation errors is generally unknown, which led $\text{P2}$ to be intractable. We adopted the S-procedure [45–47] to transform the constraints that include $e_{\alpha\beta}, \ a \in \{a, b, c, j\}, \ \beta \in \{a, b, c, e\}$, i.e., Equations (18)–(20) into a semi-definite programming (SDP) form [48,49] by utilizing the upper bounds of the channel estimation errors.

In order to transform constraint Equation (18), we first introduced some auxiliary variables as follows.

$$m_{\alpha\theta} = \min_{e_{\alpha\theta}} (\bar{h}_{\alpha\theta} + e_{\alpha\theta})^H W_a (\bar{h}_{\alpha\theta} + e_{\alpha\theta}), \ |e_{\alpha\theta}| \leq \eta_{\alpha\theta} \quad (29)$$
$$m_{\alpha\beta} = \min_{e_{\alpha\beta}} (\bar{h}_{\alpha\beta} + e_{\alpha\beta})^H W_b (\bar{h}_{\alpha\beta} + e_{\alpha\beta}), \ |e_{\alpha\beta}| \leq \eta_{\alpha\beta} \quad (30)$$
\[
m_{ce} = \max_{e_{ce}} \left( h_{ce} + e_{ce} \right)^{H} W_{e} \left( h_{ce} + e_{ce} \right), \|e_{ce}\| \leq \eta_{ce}.
\]  
(31)

Then, Equation (18) could be rewritten as

\[
\gamma \left( h_{je} + e_{je} \right)^{H} W_{j} \left( h_{je} + e_{je} \right) + \gamma e(m_{ae} + m_{be}) - m_{ce} + \gamma e \sigma_{e}^{2} \geq 0,
\]

\[
\|e_{ne}\|^2 \leq \eta_{ne}, n \in \{a, b, c, j\}
\]  
(32)

\[
m_{ae} \leq \left( h_{ae} + e_{ae} \right)^{H} W_{a} \left( h_{ae} + e_{ae} \right), \|e_{ae}\| \leq \eta_{ae},
\]  
(33)

\[
m_{be} \leq \left( h_{be} + e_{be} \right)^{H} W_{b} \left( h_{be} + e_{be} \right), \|e_{be}\| \leq \eta_{be},
\]  
(34)

\[
m_{ce} \geq \left( h_{ce} + e_{ce} \right)^{H} W_{c} \left( h_{ce} + e_{ce} \right), \|e_{ce}\| \leq \eta_{ce}.
\]  
(35)

By applying the S-procedure, Equation (18) could be transformed into the standard SDP form, as shown in Equations (36)–(39).

\[
\begin{pmatrix}
W_{j} + \lambda_{je} I \\
\left( h_{je} \right)^{H} W_{j} \\
\left( h_{je} \right)^{H} W_{j} \left( h_{je} \right) - \gamma e(m_{ae} + m_{be}) - m_{ce} + \gamma e \sigma_{e}^{2} - \lambda_{je} \eta_{je}^{2}
\end{pmatrix} \geq 0,
\]  
(36)

\[
\begin{pmatrix}
W_{a} + \lambda_{ae} I \\
\left( h_{ae} \right)^{H} W_{a} \\
\left( h_{ae} \right)^{H} W_{a} \left( h_{ae} \right) - m_{ae} - \lambda_{ae} \eta_{ae}^{2}
\end{pmatrix} \geq 0,
\]  
(37)

\[
\begin{pmatrix}
W_{b} + \lambda_{be} I \\
\left( h_{be} \right)^{H} W_{b} \\
\left( h_{be} \right)^{H} W_{b} \left( h_{be} \right) - m_{be} - \lambda_{be} \eta_{be}^{2}
\end{pmatrix} \geq 0,
\]  
(38)

\[
\begin{pmatrix}
W_{c} + \lambda_{ce} I \\
\left( h_{ce} \right)^{H} W_{c} \\
\left( h_{ce} \right)^{H} W_{c} \left( h_{ce} \right) - m_{ce} - \lambda_{ce} \eta_{ce}^{2}
\end{pmatrix} \geq 0,
\]  
(39)

Equations (18) and (19) represents the SINR and EH constraints for the WMN communication nodes, respectively. Here, for simplicity, we only took the node a as an example to show the transformation procedure, and the constraints of other nodes could be transformed in the same way. First, several auxiliary variables were introduced as follows

\[
m_{ja} = \min_{e_{ja}} \left( h_{ja} + e_{ja} \right)^{H} W_{j} \left( h_{ja} + e_{ja} \right), \|e_{ja}\| \leq \eta_{ja},
\]  
(40)

\[
m_{ja} = \max_{e_{ja}} \left( h_{ja} + e_{ja} \right)^{H} W_{j} \left( h_{ja} + e_{ja} \right), \|e_{ja}\| \leq \eta_{ja},
\]  
(41)

\[
m_{ba} = \min_{e_{ba}} \left( h_{ba} + e_{ba} \right)^{H} W_{b} \left( h_{ba} + e_{ba} \right), \|e_{ba}\| \leq \eta_{ba},
\]  
(42)

\[
m_{ba} = \max_{e_{ba}} \left( h_{ba} + e_{ba} \right)^{H} W_{b} \left( h_{ba} + e_{ba} \right), \|e_{ba}\| \leq \eta_{ba},
\]  
(43)

\[
m_{ba} = \left( h_{ba} \right)^{H} W_{b} \left( h_{ba} \right),
\]  
(44)

\[
\hat{\Omega}_{n} = \Psi_{n} - \ln \left( \frac{M_{n}}{1 + \exp \left( \Omega_{n} \Psi_{n} \right)} \right) / \Omega_{n}, n \in \{a, b, c, j\},
\]  
(45)
where $\hat{\theta}_a$ is the threshold of the input power of the EH circuit $EH^n_\mu$, which is obtained from the mathematical transformation of Equations (17) and (18). Then, Equation (19) could be rewritten as

$$
\rho_a(h_c + e_c) \cdot W_a(h_c + e_c) - \gamma_a \rho_a(m_{ba} + m_{ja}) - \gamma_a \sigma^2_a \geq 0,
$$

where $\eta_a$ is the channel fading. Then, Equation (19) could be rewritten as

$$
\text{subject to } \|e_{im}\|^2 \leq \eta_{im}, n \in \{b, c, f\}
$$

By substituting Equations (18), (19), and (20) in the objective function and dropping the rank-one constraint, we could obtain the convex optimization problem $P3$ shown below, which could be solved iteratively by the standard convex (CVX) optimization toolbox, a package in Matlab for specifying and solving convex programs [50, 51].

$$
P3: \min_{\mathbf{W}_n, \phi} \sum_{n \in \{a, b, c, f\}} \text{Tr}(\mathbf{W}_n)
$$
subject to:

\[
\begin{align*}
(36),(37),(38),(39), \\
(49),(50),(51), \\
(55),(56),(57), \\
(22),(26),(27), \\
\tilde{m}_{n_1 n_2} &\geq m_{n_1 n_2} \geq 0, \ n_1, n_2 \in \{a, b, c, j, e\}, \\
\lambda_{n_1 n_2} &\geq 0, \ n_1, n_2 \in \{a, b, c, j, e\}, \\
\mu_{n_1 n_2} &\geq 0, \ n_1, n_2 \in \{a, b, c, j, e\}.
\end{align*}
\]

As the rank-one constraint of \(W_n\) is dropped, the resulting \(W_n\) may not satisfy the rank-one constraint Equation (61), in general. In this case, we adopted the randomization technique in [52–54] to obtain the feasible rank-one solution of the result.

Here, we discussed the complexity of the proposed algorithm. The main computational complexity of our algorithm arose from computing the optimal \(w_n\), which was transformed into an SDP problem. The number of arithmetic operations required to solve a standard real-valued SDP problem could be expressed as

\[
\begin{align*}
\min_{x \in \mathbb{R}^n}^T x
\end{align*}
\]

subject to:

\[
\begin{align*}
A_0 + \sum_{i=1}^n x_i A_i \geq 0, ||x||_2 \leq X,
\end{align*}
\]

where \(A_i\) denotes the symmetric block-diagonal matrices with \(P\) diagonal blocks of size \(e_l \times e_l\), \(l = 1 \cdots P\), upper-bounded by [55].

\[
O\left(1 + \sum_{i=1}^n e_i \right)^{\frac{1}{2}} n \left( n^2 + n \sum_{i=1}^P e_i^2 + \sum_{i=1}^P e_i^3 \right).
\]

In computing \(w_n\), the number of diagonal blocks was equal to 40, \(e_i\) was equal to 1. The unknown variables to be determined were of a size \(n = 2N^2 + 1\), where the first and second parts were the real parts of \(W_n\) and the slack variable, respectively.

5. Numerical Results and Performance Analysis

In this section, we numerically investigated the performance of the robust beamforming design for SWIPT-based multi-radio WMN with cooperative jamming. For simplicity, the EH, SINR, and channel estimation error thresholds were assumed to be equal for all the WMN nodes, which were denoted as \(\theta, \gamma, \text{and } \eta\), respectively. All the channels were assumed to be independent of Rayleigh fading, and the channel vectors \(h\) were generated by independent CSCG random variables distributed as \(CN(0, \sigma^2)\).

For the direct communication channels, the variance was set as \(\sigma_{ab}^2 = \sigma_{bc}^2 = \sigma_{ac}^2 = \sigma_{jc}^2 = \sigma_{ce}^2 = 10^{-4}\).

For the inter-user interference channels, the variance was set as \(\sigma_{ba}^2 = \sigma_{cb}^2 = \sigma_{cb}^2 = \sigma_{je}^2 = \sigma_{ce}^2 = 10^{-4}\), \(n \in \{a, b, c\}\), where \(\tau\) is the inter-user interference suppression factor. The variance of the self-interference channels was set as \(\sigma_{mn}^2 = 10^{-3}\), \(n \in \{a, b, c\}\). Unless other stated, we set \(\theta = -5 \text{ dBm}, \gamma = 5 \text{ dBm}, \gamma_e = 2 \text{ dBm}, \eta = 0.05, \tau = 0.1, N = 4\). For the practical nonlinear EH model, we set the circuit parameters as \(M_n = 24 \text{ mW}, \Omega_n = 150\), and \(\Psi_n = 0.014\) [41–44].

In Figures 2–4, a non-robust beamforming method proposed in [46] was taken as the comparison scheme. Figure 2 demonstrates the power consumption versus the EH threshold with different SINR thresholds. It could be seen that the power consumption increased with the increasing of the EH threshold. The increase was non-linear due to the non-linear EH model. In addition, the results in Figure 2 show that the robust beamforming design was much better than the non-robust one.
The variance of the self-interference channels was set as $\sigma^2 = 10$. Unless otherwise stated, we set $\theta = -5$ dBm, $\gamma = -2$ dBm, $\eta = 0.05$, and $\tau = 0.1$. For the practical nonlinear EH model, we set the circuit parameters as $24$ mW, $N = 150$ $\Omega$, and $\Psi = 0.014$.

In Figures 2–4, a non-robust beamforming method proposed in [46] was taken as the comparison scheme. Figure 2 demonstrates the power consumption versus the EH threshold with different SINR thresholds. It could be seen that the power consumption increased with the increasing of the EH threshold. The increase was non-linear due to the non-linear EH model. In addition, the results in Figure 2 show that the robust beamforming design was much better than the non-robust one.

Figure 2. Power consumption versus energy harvesting (EH) threshold with different signal-to-interference-plus-noise ratio (SINR) thresholds.

Figure 3 illustrates the power consumption versus SINR threshold with a different number of transmission antennas. Similar to the relationship with the EH threshold, the power consumption grew non-linearly with the increase in the SINR threshold, and the robust beamforming design had a better power consumption performance than the non-robust one. Meanwhile, it could be observed that with the increase of the number of transmit antennas, the power consumption was also increasing. Although a large number of transmit antennas could improve the capacity, security rate, and bring other benefits to the system, they led a higher total power consumption.

Figure 3. Power consumption versus SINR threshold with a different number of transmit antennas.

Figure 4 demonstrates the impact of different channel estimation error on power consumption with different EH thresholds. The bound of the channel estimation error threshold was set from 0.1 to 0.5. Although the power consumption of both robust and non-robust designs increased with the increase in channel uncertainty, the non-robust beamforming design increased faster than the robust one, which indicated that the non-robust scheme was more sensitive with different channel estimation error.

Figure 4. Power consumption versus channel estimation error with different EH thresholds.
In Figure 5, the effect of value $\tau$ on power consumption with different EH threshold was investigated. The value of $\tau$ represented the channel isolation among the nodes responsible for the inter-user interference. Different channel assignment scheme might lead to a different inter-user interference [7]. It could be seen that the power consumption increased with $\tau$ first, but became flat later. It is worth noting that the inter-user interference was stronger when $\tau$ was small, and the system could harvest more energy from the interference. However, as $\tau$ was increasing, the system could not harvest enough energy from the interference channels.

Figure 6 illustrates the maximum SINR of Eve versus SINR threshold of WMN nodes with different number of transmission antennas and different channel estimation error thresholds. It was seen that the maximum SINR value of Eve was far less than the SINR of WMN nodes. Although the maximum SINR of Eve grew with the increase of $\gamma$, it was always less than 1 dbm. Figure 6 also depicts the impact of the number of transmit antennas and the channel estimation error. It could be observed that a large number of transmit antennas brought some benefit to the physical layer secrecy. When the number of transmit antennas and the SINR threshold were fixed, a larger channel estimation error led to a larger SINR of Eve.
Figure 5. Power consumption versus $\tau$ with different EH thresholds.

Figure 6 illustrates the maximum SINR of Eve versus SINR threshold of WMN nodes with a different number of transmission antennas and different channel estimation error thresholds. It was seen that the maximum SINR value of Eve was far less than the SINR of WMN nodes. Although the maximum SINR of Eve grew with the increase of $\gamma$, it was always less than 1 dbm. Figure 6 also depicts the impact of the number of transmit antennas and the channel estimation error. It could be observed that a large number of transmit antennas brought some benefit to the physical layer secrecy. When the number of transmit antennas and the SINR threshold were fixed, a larger channel estimation error led to a larger SINR of Eve.

In Figures 7 and 8, a comparison beamforming algorithm in [46] was taken to verify the power consumption and security performance. The comparison algorithm applied the SWIPT technic to the IoT devices, and the imperfect channel estimation was taken into consideration as well. However, the comparison algorithm did not consider the problem of physical layer security. Here, we took its MISO scenario, and all the interference caused by the circuits were neglected. As the comparison algorithm did not consider the jamming node, we only compared the power consumption of communication nodes in Figure 7. From Figure 7, we could observe that the comparison algorithm had a slight superiority in power consumption, which was less than 2 dbm. This was because the security strategy slightly reduced energy efficiency. However, our algorithm had a large improvement in security performance, which could be seen in Figure 8. Because the comparison algorithm did not have any security strategy, it could not inhibit eavesdrop behavior.

Figure 6. Maximum SINR of Eve versus SINR threshold of WMN nodes with different number of transmit antennas and channel estimation error thresholds.

Figure 7. Communication nodes’ power consumption comparison with different SINR thresholds.
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Figure 7. Communication nodes' power consumption comparison with different SINR thresholds.

Figure 8. Maximum SINR of Eve comparison with a different number of transmit antennas.

6. Conclusions

In this paper, we proposed a robust beamforming design for a SWIPT-based multi-radio WMN with cooperative jamming under imperfect channel state information. Our goal was to minimize the total power consumption while subjecting to the SINR, EH, and total transmit power constraints. The SINR of Eve was also limited to prevent the physical layer secrecy. The non-linear EH model was adopted to better match the practical EH circuit. To solve the problem, we utilized the SDP technique and S-procedure method to transform the initial non-convex optimization to a convex SDP form. Simulation results indicated the good performance of the proposed schemes compared to non-robust ones.

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