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Physical Layer Security and Optimal Multi-Time-Slot Power Allocation of SWIPT System Powered by Hybrid Energy

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Abstract: In this paper, a new approach is proposed to solve the constrained optimization problem of saving grid energy and increasing safety in a simultaneous wireless information and power transfer (SWIPT) system. The traditional grid energy is combined with the renewable energy to form a hybrid energy, which provides power for the system to achieve green wireless transmission. The transfer process of SWIPT system is divided into multiple time slots. The renewable energy is harvested and stored in battery at each time slot. A multi-time-slot artificial noise-assisted transmission strategy is proposed to reduce the signal to noise ratio (SNR) of eavesdropping link. A power allocation algorithm based on multi-time-slot golden section is given, which performs one-dimensional search on the power ratio of artificial noise to determine the transmit power of source node. And then the allocation algorithm is utilized to dynamically configure the harvested renewable energy for each time slot. When the battery capacity is constant, the maximum renewable energy is being used to reduce the grid power consumption. Finally, the performances of proposed schemes are evaluated by simulations in terms of various tradeoffs.

Keywords: renewable energy; multi-slot artificial noise; SWIPT; time slots division; power allocation

1. Introduction

Exploiting new energy and transmission mode for wireless communication to reduce the grid power consumption and improve the physical layer security (PLS) is the main issue faced by the next generation (5G) of mobile communication [1,2], and is considered as a problem of wide concern. Based on the above analysis, we consider a simultaneous wireless information and power transfer (SWIPT) system powered by the hybrid energy to save grid resource, and utilize artificial noise (AN) to interference eavesdropper.

The SWIPT technology received extensive attention with separation of destination nodes and carrying energy transmission [3–5]. But the energy receiver (ER) is easy to eavesdrop the information transmitted to the information receiver (IR) from source (S) in the SWIPT system [6,7]. And then ER is seen as a potential eavesdropper that will affect physical layer security. Besides, according to the lower energy conversion efficiency at ER, the high energy consumption is caused in the SWIPT system. In terms of the security issue, the authors in [8] designed a secure beamforming scheme in a SWIPT system, which can minimize the whole transmit power while maintaining the secrecy rate and energy harvesting at ER. Meanwhile, one of the technologies for enhancing the secrecy performance is to transmit artificial noise by jammers to interfere eavesdroppers [9]. The authors in [10,11] recently considered the PLS with the AN by treating energy harvesting (EH) receivers as potential eavesdroppers. A secure MISO SWIPT system was proposed in [12], where an artificial noise is embedded to the information bearing signal to interfere the eavesdroppers and to harvest power by all receivers. However, these security schemes are only suitable for single time slot. Besides, in order to save power consumption, the paper [13] proposed the use of green renewable energy to mobile receivers in a multiple-antenna SWIPT system. The receivers obtain the renewable energy, which cannot be controlled and are not always available [14,15]. The authors in [16] proposed a using renewable energy scheme which divides time slots to allocate the dynamic renewable energy, and gave a power allocation algorithm based on two-stage filling water. In the literature [17–19], using the directional water-filling algorithm in different channel models is considered to allocate the harvesting energy, including the Gaussian fading channel [17], the broadcast channel [18], and the multiple-access channel [19] to maximize the throughput in finite time horizon. However, these algorithms cannot guarantee optimal resource allocation for multi-time-slot. Although many studies have investigated the performance in SWIPT, relatively less work has been done on multi-time-slot wireless transmission.

In this paper, a SWIPT model based on the renewable energy and multi-slot artificial noise-assisted transmission is proposed. According to the dynamic arrival characteristics of renewable energy, the power splitting ratio and the transmitted power are determined at source node. A part of the transmitted power is used to transmit the signal to IR, and the source served as a jammer utilizes the rest power to transmit AN to ER. Meanwhile, ER utilizes the AN to harvest energy to satisfy collection demand. Besides, we propose a power allocation algorithm which can fully utilize renewable energy and guarantee secure transmission under the minimum grid consumption.

2. The System Model and Mathematical Modeling

2.1. The System Model

We consider an energy cooperative network model as shown in Figure 1, which consists of a source, an information receiver, an energy receiver and a battery with a storage limit of $E_{\max}$ at the source. The entire transmission process of the system is divided into N time slots and the size of each slot is t_f. All channels are assumed to undergo blocking fading. $f_i, i \in 1, \ldots, N$ represents the i-th slot channel gain of the S-IR link and $g_i, i \in 1, \ldots, N$ represents the i-th slot channel gain of the S-ER link. The transmit power splitting ratio is defined as $\alpha_i, i \in 1, \ldots 1, N$ and the transmit power at S is defined as $p_i, i \in 1, \ldots, N$.

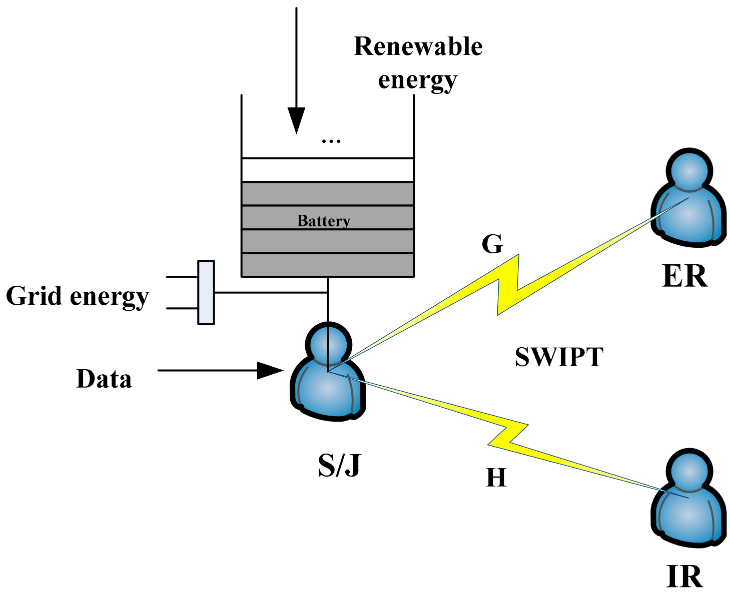

Figure 1. The system model.

2.2. The Mathematical Modeling

In this considered network, assuming that source is powered by hybrid energy consisted of the traditional power grid and the renewable energy. Therefore, the mixed transmit signal at source should be

$$x_i = \sqrt{(1-\alpha_i)p_i}s_{0,i} + \sqrt{\alpha_i p_i}s_{1,i}, \tag{1}$$

where $s_{0,i}, s_{1,i}$ respectively represent the i-th information signal and AN signal at S, they are independent circular symmetric complex Gaussian random variables with zero mean and unit variance.

The received signal expression of IR and ER are formulated as

$$y_{ER,i} = g_i x_i + n_{ER,i}, \tag{2}$$

$$y_{IR,i} = f_i x_i + n_{IR,i}, \tag{3}$$

where $n_{ER,i}$ and $n_{IR,i}$ respectively represent the additive white Gaussian noise (AWGN) at ER and IR with $n_{ER,i} \sim CN(0, \sigma_{2,i}^2)$ and $n_{IR,i} \sim CN(0, \sigma_{1,i}^2)$. Then the SNR at IR and ER are respectively given by

$$snr_{IRi} = \frac{(1-\alpha_i)f_i p_i}{\sigma_{1,i}^2}, \tag{4}$$

$$snr_{ERi} = \frac{(1-\alpha_i)g_i p_i}{\alpha_i g_i p_i + \sigma_{2,i}^2}, \tag{5}$$

According to Equations (4) and (5), the secrecy rate of i-th slot can be calculated as

$$R_i(a_i, p_i) = [\log_2(1+snr_{IRi}) - \log_2(1+snr_{ERi})]^+, \tag{6}$$

where $[x]^+ = \max(0,x)$. In this scheme, we assume that the system is based on timeslot changing. We introduce the following indicator function for the event of outage with respect to the minimum secrecy rate r_0 at each time slot:

$$X(i) = \begin{cases} 1, & R_i(\alpha_i, p_i) < r_0 \\ 0, & otherwise. \end{cases}, \tag{7}$$

where the outage probability can be expressed as

$$E[X(i)] = \frac{1}{N}\sum_{i=1}^{N} X(i),$$

We consider a harvesting renewable energy plan at source as shown Figure 2, and assume that source is equipped a battery with initial power E_0. When a time slot has just begun, the battery stores the harvested renewable energy, i.e., E_i. During the wireless transmission process, the transmit power consists of two parts, one part of which is provided by the battery, i.e., p_i^r and the other obtains from grid, i.e., p_i^g.

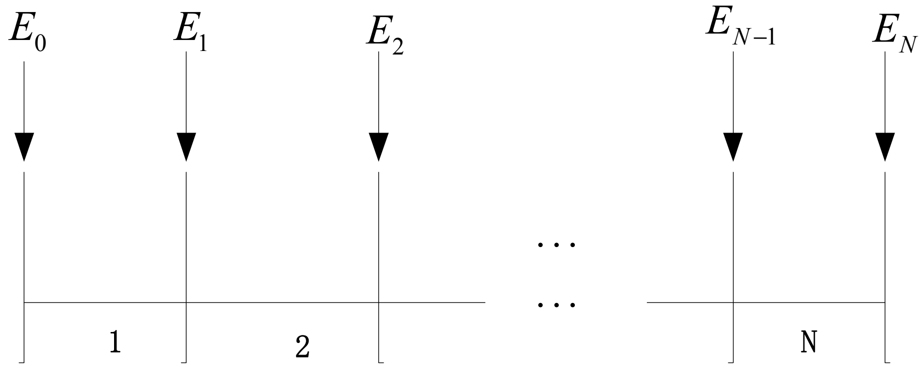

Figure 2. The renewable energy of battery.

After all time slots, the collected energy of ER should satisfy the average collection requirement, i.e.,

$$\frac{1}{N}\sum_{i=1}^{N}\xi\alpha_i p_i g_i \geq p_{ave}, \tag{8}$$

where $\xi \in [0,1]$ is the energy collection efficiency depending on the rectification and energy harvesting circuitry, and p_{ave} represents the need of average collection power. Besides, the collected renewable energy at each time slot must be stored in the battery before it is used, and the causal relationship is shown as

$$\sum_{i=1}^{k} t_f p_i^r \leq \sum_{i=1}^{k-1} E_i, \quad \forall k, \tag{9}$$

Due to the limited battery capacity, the harvesting energy of source in each time slot cannot exceed the maximum limit of the battery, i.e.,

$$\sum_{i=1}^{k-1} E_i - \sum_{i=1}^{k} t_f p_i^r \leq E_{\max}, \quad k < N, \tag{10}$$

where $E_{\max} = MP_{r,ave}t_f$ with $P_{r,ave}$ = 20 dBm. M represents the battery storage capacity coefficient and $P_{r,ave}$ is the average harvesting energy of battery per second. And we define the maximum average energy consumption threshold of the grid in order to limit the actual grid consumption. Therefore, the constraint relation is expressed as

$$\frac{1}{N}\sum_{i=1}^{N}(p_i - p_i^r) \leq p_{ave}^g, \tag{11}$$

where p_{ave}^g represents the average grid consumption. Besides, source is a power-constrained node and the maximum power allowed for transmission is p_{peak}. Therefore, the transmit power of each slot must satisfy the following formula

$$p_k \leq p_{peak}, \quad \forall k, \tag{12}$$

We aim at minimizing the secrecy outage probability for the IR by jointly optimizing α_i and p_i. Based on the definition in Equation (7), the optimization problem can be formulated as

$$\begin{array}{cc} \min\limits_{\alpha_i \in [0,1)} & E[X(i)] \\ s.t. & (8), (9), (10), (11) \text{ and } (12) \\ & p_k^r \leq p_i, \quad \forall \text{k} \\ & p_k^r \geq 0, \quad \forall \text{k} \end{array}, \tag{13}$$

3. The Optimal Power Splitting Ratio and Transmit Power

The above mathematical model involves both α_i and p_i that need to be optimized. We utilize the two-stage optimization strategy in order to solve the above problem [20]. At the first stage, one-dimensional search is performed for the power splitting ratio of each slot based on the golden section principle, and then the minimum required power is obtained. Secondly, we apply the Lagrange duality method to solve Equation (13) based on the ratio solution of the first stage.

3.1. The Power Splitting Ratio

Because of the transmission power of S is constrained, minimizing p_i is also one of the goals [21]. Given any $0 \leq \alpha_{\mathrm{i}} \leq 1$, let $p(\alpha_i)$ denotes the minimum required power to maintain the secrecy rate r_0 allowed for the system, i.e., $R_i(\alpha_i, p_i) = r_0$. It can be shown as

$$\frac{1 + snr_{IRi}}{1 + snr_{ERi}} = 2^{r_0}, \tag{14}$$

By substituting (4) and (5) into (14), and then p_i and α_i should satisfy the condition

$$(1-\alpha_i) f_i \alpha_i g_i p_i^2 + (\alpha_i g_i \sigma_{1,i}^2 + (1-\alpha_i) f_i \sigma_{2,i}^2 - 2^{r_0} g_i \sigma_{1,i}^2) p_i + (1-2^{r_0}) \sigma_{1,i}^2 \sigma_{2,i}^2 = 0, \tag{15}$$

One can show from (15) that it is a quadratic function of p_i. Therefore, the solution of p_i can be expressed as follows

$$\begin{cases} p(\alpha_i) = \frac{-[\alpha_i g_i \sigma_{1,i}^2 + (1-\alpha_i) f_i \sigma_{2,i}^2 - 2^{r_0} g_i \sigma_{1,i}^2] + \sqrt{\Delta}}{2(1-\alpha_i) f_i \alpha_i g_i} & 0 < \alpha_i < 1 \text{and } \Delta > 0 \\ p(\alpha_i) = \begin{cases} \frac{(2^{r_0}-1)\sigma_{1,i}^2 \sigma_{2,i}^2}{f_i \sigma_{2,i}^2 - 2^{r_0} g_i \sigma_{1,i}^2} & p(0) < p_{peak} \\ p_{peak} & p(0) \geq p_{peak} \end{cases} & \alpha_i = 0 \text{ and } f_i \sigma_{2,i}^2 > 2^{r_0} g_i \sigma_{1,i}^2 \end{cases}, \tag{16}$$

where α_i is the independent variable, $p(\alpha_i)$ is the dependent variable. α_i^* is defined as the optimal power splitting ratio. Δ is given by

$$\Delta = (\alpha_i \sigma_{1,i}^2 g_i + \sigma_{2,i}^2 (1-\alpha_i) f_i)^2 + 2^{r_0} (2^{r_0} \sigma_{1,i}^4 g_i{}^2 - 2\alpha_i \sigma_{1,i}^4 g_i{}^2 + (-4\alpha_i^2 + 6\alpha_i - 2) \sigma_{1i}^2 \sigma_{2i}^2 h_i g_i), \tag{17}$$

One-dimensional search is performed for (15), and obtain α_i which satisfies minimum $p(\alpha_i)$. When N is equal to 100, Figure 3 shows the optimal distribution of α_i in i-th time slot with $\sigma_{1,i}^2 = \sigma_{2,i}^2 = 0.01$ and $r_0 = 10$ kbit/s. We see that the optimal distribution is in the range of 0.455 to 0.505, which changes according to the channel state.

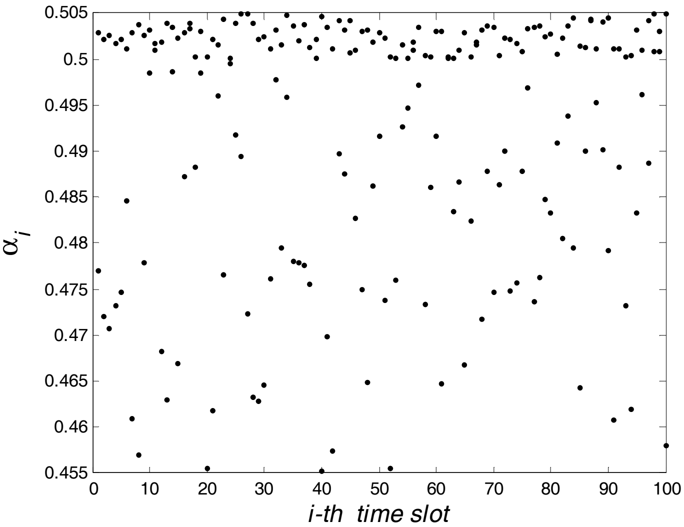

Figure 3. The optimal distribution of α_i with $\sigma_{1,i}^2 = \sigma_{2,i}^2 = 0.01$ and $r_0 = 25$ bps/Hz.

3.2. The Optimal Transmit Power

In the first stage, we obtain the appropriate α_i. In the second stage, the optimization problem is convex about p_i. The Lagrangian function of (13) is expressed as

$$\begin{aligned} L(R,\lambda,\mu_i,\varphi_i,\eta) &= E[X(i)] + \lambda(\frac{1}{N}\sum_{i=1}^{N}\xi p_i g_i - p_{ave}) \\ &- \sum_{k=1}^{N}\mu_k(\sum_{i=1}^{k}t_f p_i^r - \sum_{i=1}^{k-1}E_i) - \sum_{k=1}^{N-1}\varphi_k(\sum_{i=1}^{k-1}E_i - \sum_{i=1}^{k}t_f p_i^r - E_{\max}) \\ &- \sum_{k=1}^{N}\beta_k(p_k^r - p_k) + \sum_{k=1}^{N}\gamma_k p_k^r \\ &- \eta(\frac{1}{N}\sum_{i=1}^{N}(p_i - p_i^r) - p_{ave}^g) \end{aligned}, \quad (18)$$

where λ, u_i, φ_i and η are the dual variables associated with the average collected energy p_{ave} at ER, the harvesting renewable energy E_i at source, the battery capacity $E_{\max}$ and the average grid consumption p_{ave}^g, respectively. Then the partial Lagrange dual function of (18) is expressed as

$$f(\lambda,\mu_i,\varphi_i,\eta) = \min_{\{\mathrm{p}_k \le p_{peak}\},\{\alpha_i \in [0,1]\}} L(R,\lambda,\mu_i,\varphi_i,\eta), \quad (19)$$

The dual problem of (13) is given by

$$\begin{array}{cc} \max & f(\lambda,\mu_i,\varphi_i,\eta) \\ s.t. & p_k \le p_{peak} \\ & \lambda \ge 0, \mu_i \ge 0, \varphi_i \ge, \eta \ge 0. \end{array}, \quad (20)$$

Substituting the optimal power splitting ratio from the first stage into Equation (18), we obtain the expression about the optimal transmit power of per time slot

$$\begin{array}{l} AP_i^3 + Bp_i^2 + Cp_i + D = 0 \\ A = cC_1(C_2^2 + C_2) \\ \mathrm{B} = \left[c\left(C_2^2 + C_2 + 2C_1C_2C_3 + C_1C_3\right) - C_1\left(C_2^2 + C_2\right)\right] \\ C = 2C_2C_3c + cC_3 + cC_1C_3^2 - 2C_1C_2C_3 \\ \mathrm{D} = cC_3^2 - C_1C_3^2 - C_3 \end{array}, \quad (21)$$

where $c = (\eta - \beta_i - \frac{\xi\lambda}{N}\sum_{i=1}^{N}\alpha_i g_i)/\ln 2$, $C_1 = (1-\alpha_i)f_i/\sigma_{1,i}^2$, $C_2 = \alpha_i/(1-\alpha_i)$ and $C_3 = \sigma_{2,i}^2/((1-\alpha_i)g_i)$. Since Equation (21) is a cubic equation and is complex, we utilize MATLAB to solve the cubic equation and obtain the optimal power.

4. A Power Allocation Algorithm

In this paper, we utilize the golden section principle to search the power splitting ratio, and then obtain the optimal transmit power at source based on the Lagrange duality method. Based on the above analysis, a power allocation algorithm structure is proposed. The steps of the algorithm are as follows:

Step1: Initialize the optimization problem and algorithm parameters. We want to minimize the outage probability which includes the variable α_i and p_i. The renewable energy power harvested in the battery of each slot is p_i^r.

Step2: Perform one-dimensional searching on α_i and obtain the transmit power at source.

Step3: The power allocation starts from the i-th slot with $i = N$, and the harvesting renewable energy cannot exceed $E_{\max}$. If $p_i^r > E_{\max}$, set $p_i^r = E_{\max}$.

Step4: In this step, we compare the renewable energy p_i^r and the optimal power p_i in i-th slot. When p_i is greater then p_i^r, an allocation scheme is proposed referring to the model (a) in Figure 4. As shown in the model (a), all of the renewable energy of the i-th time slot is used, the rest of the transmit power is filled by grid, i.e., $p_i = p_i^g + p_i^r$. And then set $i = i - 1$. In contrast, utilize the model (b) to allocate the hybrid power. In the model (b), find the j-th slot with $j < i$ satisfying with $p_i^r - \sum_{m=j}^{i} p_m \le 0$ and $p_i^r - \sum_{m=j+1}^{i} p_m > 0$, and then set $i = j$. During this process, no grid power is used.

Step5: If $i \neq 1$, repeat step 3 and step 4 until $i = 1$.

Step6: If there is still remaining renewable energy at rest of the time slot and $p_i < p_{peak}$, the remaining energy will be directly supplied to the source node of the corresponding time slot to transmit information for IR.

In this algorithm, we build an inverse sequence for the time slot to guarantee all the renewable energy be utilized.

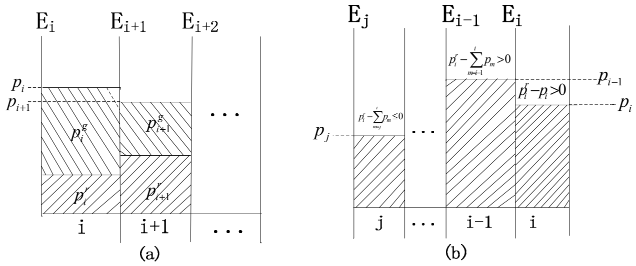

Figure 4. Two types of power allocation model. (**a**) The less renewable energy allocation model; (**b**) The enough renewable energy allocation model.

5. Simulation Results

In this section, we provide simulation results to validate our theoretical analysis and evaluate the performance of the proposed scheme. We run $N = 100$ frames in each simulation and set the maximum transmit power as 30 dBm, i.e., $p_{peak} = 30$ dBm. The harvested energy of ER follows non-negative uniform distribution with mean $p_{ave} = 20$ dBm. The energy conversion efficiency is set as $\xi = 0.8$ [22]. Besides, in order to make fully use of the renewable energy, we set a little average grid consumption power as $p_{ave}^g = 20$ dBm.

Figure 5 shows that the relationship between the power ratio, the outage probability and the transmit power. We define the power splitting ratio vector $\boldsymbol{\alpha} = \{\alpha_1, \alpha_2, \ldots, \alpha_N\}$. Three vector schemes are given: all the elements of vector are 0.1, all the elements of vector are 0.3 and all the elements of vector are the optimal search values. We can see that the transmit power gradually decreases and tends to be stable with the increasing outage probability. Besides, when the outage probability is fixed, the optimal $\boldsymbol{\alpha}$ corresponds to the whole transmit power is minimum. When the difference between the power splitting ratio and the optimal $\boldsymbol{\alpha}$ is larger, the difference of transmit power value will be larger. Therefore, in the case of satisfying a certain outage probability, utilizing the golden section to search the optimal $\boldsymbol{\alpha}$ can effectively reduce the transmit power at source.

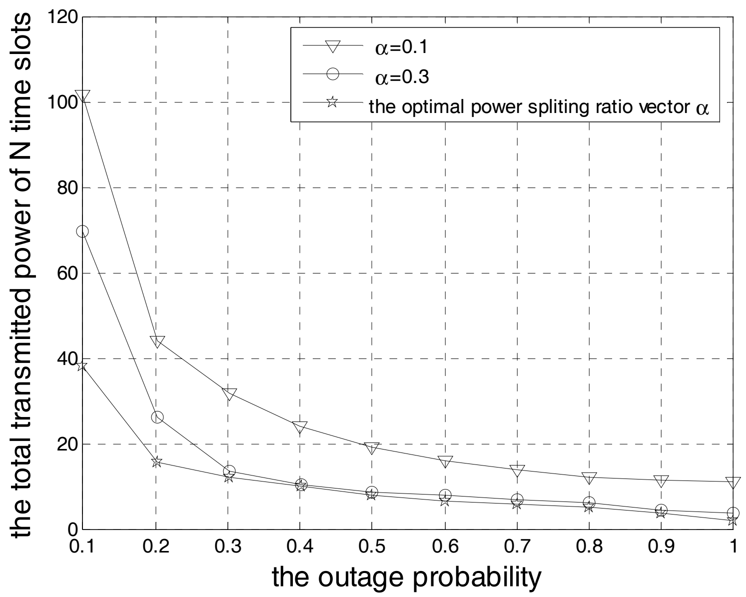

Figure 5. The average transmit power with different α_i, M = 3, $p^g_{ave} = 20$ dBm, $\sigma^2_{1,i} = \sigma^2_{2,i} = 0.01$ and $p_{ave} = 20$ dBm.

From Figure 6, we can see that the grid power consumption is gradually decreasing when the battery capacity increases. The power allocation algorithm which we proposed is better than the directly filling water algorithm and the two-stage filling water algorithm on reducing the consumption of grid. Therefore, fully utilizing renewable energy can improve the capacity, which reduces unnecessary power consumption of the grid as much as possible.

Figure 7 shows that the curve changing of the secrecy rate with the influence of M and α_i. According to the three-dimensional figure, we obtain that the secrecy rate gradually increases and tends to be stable with changing of M, and the curve of the secrecy rate has a peak at around $\alpha_i = 0.5$. Therefore, choosing the appropriate battery capacity and the power splitting ratio can effectively improve the secrecy performance.

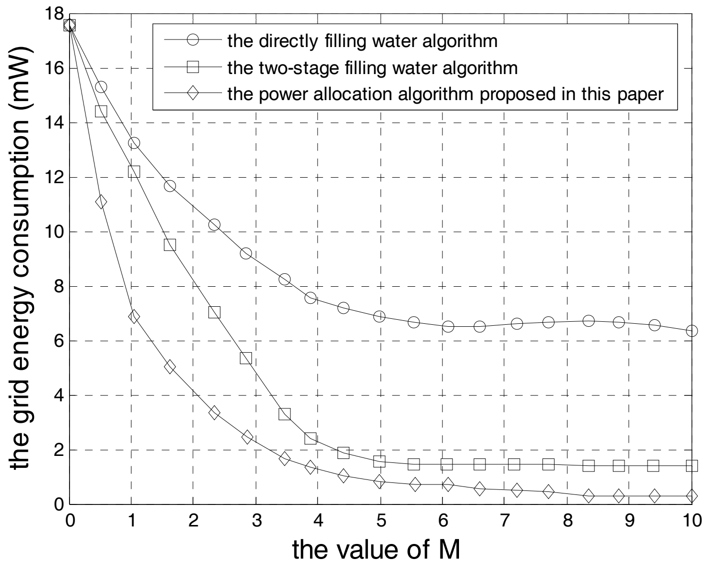

Figure 6. The grid power consumption with different power allocation algorithm. $\alpha_i = \alpha_i^*$, $p_{ave}^g = 20$ dBm, $\sigma_{1,i}^2 = \sigma_{2,i}^2 = 0.01$ and $p_{ave} = 20$ dBm.

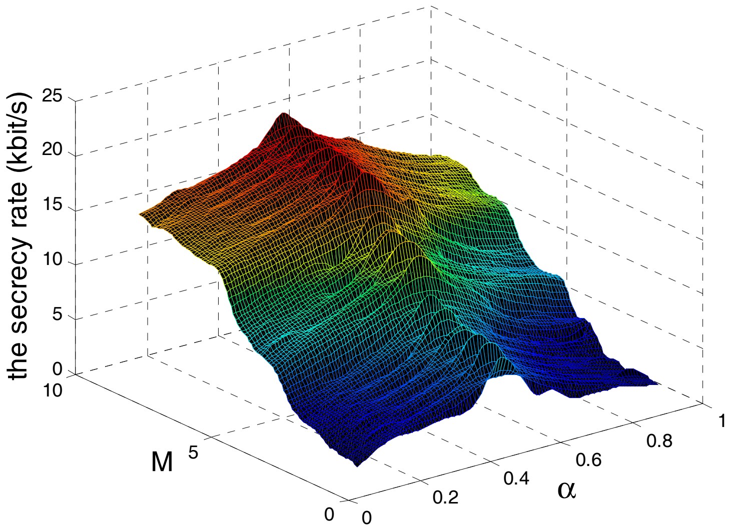

Figure 7. The secrecy rate with the influence of M and α_i. $p_{ave}^g = 20$ dBm, $\sigma_{1,i}^2 = \sigma_{2,i}^2 = 0.01$ and $p_{ave} = 20$ dBm.

6. Conclusions and Future Works

This paper considers the problems of safety and energy in a SWIPT system, in presence of potential eavesdropper, i.e., ER. The paper shows that secure transmission can be achieved by adding AN based on multi-slot. And we have optimized the power splitting ratio and the transmit power at source based on the time domain. Also, we propose a power allocation algorithm for the system to allocate the renewable energy at each time slot to guarantee the minimum grid power consumption. The simulation examples have validated the proposed methods and confirmed the effect on the secrecy performance and grid energy. A system with a full duplex node or IR served as a jammer may be interesting future topic.

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Conflicts of Interest: The authors declare no conflict of interest.

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