Secrecy Performance of Wireless Powered Communication Network

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***Abstract*—In this work, we study a multi-user wireless powered communication network (WPCN) with an energy harvesting (EH) jammer. In the presence of an eavesdropper, a hybrid access-point (H-AP) first broadcasts an energy signal to EH users in an energy transmission (ET) phase, while each of them subsequently transmits its individual message to the H-AP in a time division multiple access manner during an information transmission (IT) phase. At the same time, the EH jammer simultaneously generates artificial noises to keep the messages confidential. We propose an efficient time allocation method for the ET and the IT phases so as to minimize the secrecy outage probability in the absence of the eavesdropper's instantaneous channel state information. Finally, we evaluate the performance of our proposed solutions through simulations.**

***Index Terms*—Physical-layer security, cooepartive jammer, artificial noise (AN), energy harvesting (EH), wireless powered communication networks (WPCN).**

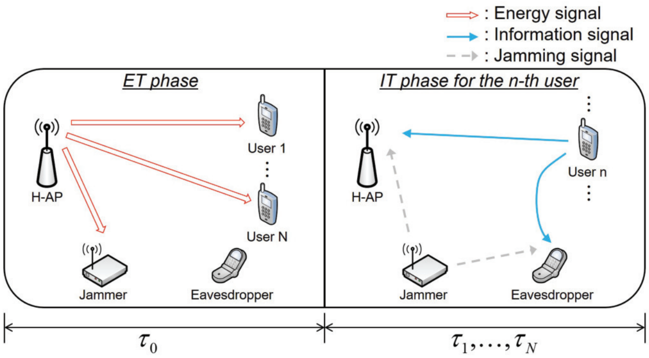

Fig. 1. Schematic diagram for the two-phase WPCN

I. Introduction

In recent years, energy harvesting (EH) utilizing wireless radio frequency signals has been regarded as a promising alternative to providing energy sources in communication networks [1]. Specifically, simultaneous wireless information and power transfer (SWIPT) and wireless powered communication networks (WPCN) are two main branches of EH systems that have drawn a lot of attentions [2]. In the SWIPT, transmitted signals convey both information and energy to simultaneously achieve information delivery and wireless energy recharging [3]–[6]. In contrast, for the WPCN, a hybrid access-point (H-AP) first broadcasts energy-carrying signals to recharge EH nodes in an energy transfer (ET) phase, and then the EH nodes transmit information signals in a subsequent information transfer (IT) phase by utilizing the energy harvested in the previous ET phase [7]–[9].

Meanwhile, physical-layer security in communications have always been important issues for many years [10]. One of the technologies for enhancing the secrecy performance is to transmit artificial noises (AN) on top of the transmitted signals to interfere eavesdroppers [11]. In line with this, the wireless security issues were comprehensively dealt in EH communications systems as well [12]–[14]. In all the aforementioned works, however, the trade-off between the ET and the IT durations for a wiretap WPCN was not explicitly studied.

To reveal the effect of time allocation in wiretap WPCN, [15] recently studied a WPCN with an EH jammer and an eavesdropper which tries to wiretap the communication between an EH user and an H-AP. Since this work was confined to a single user scenario, in this work, we extend the system setting to a multi-user case for a more practical usefulness. In the presence of an eavesdropper, an H-AP first broadcasts an energy signal to EH users in the ET phase, while each of them subsequently transmits its individual message to the H-AP in a time division multiple access (TDMA) manner during the IT phase. At the same time, the EH jammer simultaneously generates AN to keep the messages confidential.

We consider a case where only channel distribution information (CDI) and the location of the eavesdropper are available at the legitimate nodes. Then, an efficient time allocation for ET and IT phases that minimizes the maximum secrecy outage probability (SOP) among the users is proposed through an alternating optimization method. Simulation results at the end evaluate the secrecy performance of our proposed schemes by comparing with conventional ones.

Notations: We use $\mathbb{R}$, $\mathbb{C}$ as sets of real and complex numbers, respectively, and Pr(ν) stands for the probability of an event ν. Moreover, $|\cdot|$, $(\cdot)^*$ and $\mathbb{E}[\cdot]$ are the absolute value, complex conjugate and the expectation operation, respectively. We define $[x]^+ \triangleq \max(0, x)$, and $\mathcal{CN}(m, \sigma^2)$ denotes a circularly symmetric complex Gaussian distribution with mean m and variance σ^2.

II. System Model

In Fig. 1, we describe the system model for the WPCN where an H-AP S, EH users U_n for $n = 1, ..., N$, an EH jammer J and an eavesdropper E are equipped with a single antenna. It is assumed that the H-AP operates with a constant power supply, while the users and the jammer utilize the harvested energy from the energy signals transmitted from the H-AP. We employ the two-phase WPCN protocol in [7], where the H-AP first broadcasts the energy-carrying signals in the ET phase for a τ_0 proportion of the total time block, and then each user and the jammer transmit information and AN, respectively, during the IT phase. To avoid co-channel

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interferences, we assume that each user occupies the uplink channel one at a time in a TDMA manner, and thus the n-th user is assigned a τ_n portion of the time block. Without loss of generality, we assume that the time block length equals one.

Throughout the paper, we denote the path-loss effect and the channel coefficient from node X to Y by $L_{\mathsf{XY}} \in \mathbb{R}$ and $h_{\mathsf{XY}} \in \mathbb{C}$, respectively, where $\mathsf{X},\mathsf{Y} \in \{S, J, U_n \forall n, E\}$. Assuming quasi-static flat-fading, all channel gains stay constant during each time block. It is also assumed that both h_{SU} and h_{SJ} are perfectly known at the H-AP and the users, since channel reciprocity holds for both the ET and IT phases. The eavesdropper is temporarily regarded as an inactive user that may participate in communications in the future [14], in which the location information of the eavesdropper and CDI of h_{JE} and h_{UE} are available to the network. In this work, we particularly consider Rayleigh distributions of $|h_{JE}|$ and $|h_{UE}|$.

During the ET phase, the received signal at the energy receiving node $\mathsf{X}_e \in \{U_n \forall n, J\}$ is

$$y_{\mathsf{X}_e} = \sqrt{P_S L_{S\mathsf{X}_e}} h_{S\mathsf{X}_e} x_S + z_{\mathsf{X}_e}, \tag{1}$$

where P_S stands for the transmit power at the H-AP, $x_S \sim \mathcal{CN}(0,1)$ equals the transmitted symbol from the H-AP, and $z_{\mathsf{X}_e} \sim \mathcal{CN}(0, \sigma^2_{\mathsf{X}_e})$ indicates the complex Gaussian noise at node X_e. Then, the harvested energy at node X_e can be written by [4]

$$\mathcal{E}_{\mathsf{X}_e} = \eta_{\mathsf{X}_e} \mathbb{E}[|y_{\mathsf{X}_e}|^2]\tau_0 = \eta_{\mathsf{X}_e} P_S L_{S\mathsf{X}_e} |h_{S\mathsf{X}_e}|^2 \tau_0, \tag{2}$$

where $\eta_{\mathsf{X}_e} \in (0,1]$ represents the EH efficiency at node X_e.

In the IT phase, the n-th user transmits its information signal $x_{U_n} \sim \mathcal{CN}(0,1)$ to the H-AP by utilizing the harvested energy $\mathcal{E}_{U_n}$. In our system, a security problem arises due to the presence of the eavesdropper. To combat this security issue, the jammer simultaneously generates an AN $x_J[n] \sim \mathcal{CN}(0,1)$ at each time slot n of duration τ_n to reduce the eavesdropper's decoding capacity.

Then, the received signal at the information receiving node $\mathsf{X}_I \in \{S, E\}$ in the n-th time slot is given by

$$\begin{aligned} y_{\mathsf{X}_I}[n] = \sqrt{P_{U_n} L_{\mathsf{X}_I U_n}} h^*_{\mathsf{X}_I U_n} x_{U_n} \\ + \sqrt{P_J[n] L_{\mathsf{X}_I J}} h^*_{\mathsf{X}_I J} x_J[n] + z_{\mathsf{X}_I}, \end{aligned} \tag{3}$$

where $P_{U_n} \triangleq \frac{\zeta_{U_n} \mathcal{E}_{U_n}}{\tau_n}$ and $P_J[n] \triangleq \frac{\zeta_J[n] \mathcal{E}_J}{\tau_n}$ represent the transmit power with $\zeta_{U_n} \in (0,1]$ and $\zeta_J[n] \in (0,1]$ being a portion of the harvested energy used for signal transmission from node U_n and J, respectively, at the n-th time slot.

We assume that the AN $x_J[n]$ is known at the H-AP, which means that the interference $\sqrt{P_J[n] L_{SJ}} h^*_{SJ} x_J[n]$ in (3) can be removed at the H-AP [13]. Then, the throughput $R_S[n]$ and $R_{E_m}[n]$ at the H-AP and the eavesdropper, respectively, are given by

$$R_S[n] = W\tau_n \log_2 \left(1 + A[n]\frac{\tau_0}{\tau_n}\right), \tag{4}$$

$$R_E[n] = W\tau_n \log_2 \left(1 + \frac{B[n]\, |h_{U_n E}|^2\, \frac{\tau_0}{\tau_n}}{C\, |h_{JE}|^2\, \zeta_J[n]\, \frac{\tau_0}{\tau_n} + 1}\right), \tag{5}$$

where W is the system bandwidth, $A[n] \triangleq \zeta_{U_n} \eta_{U_n} P_S L^2_{SU_n} |h_{SU_n}|^4 / \sigma^2_S$, $B[n] \triangleq \zeta_{U_n} \eta_{U_n} P_S L_{SU_n} L_{U_n E} |h_{SU_n}|^2 / \sigma^2_E$, and $C \triangleq \eta_J P_S L_{SJ} L_{JE} |h_{SJ}|^2 / \sigma^2_E$.

From (4) and (5), the secrecy rate during the n-th time slot equals $r[n] = [R_S[n] - R_E[n]]^+$ [12], and accordingly, the SOP for each time slot duration τ_n is defined by the probability that the secrecy rate $r[n]$ falls below a certain positive threshold r_{th} as [16]

$$P_{out}[n] = \Pr(r[n] \le r_{th}). \tag{6}$$

This leads to a maximum SOP minimization problem as

$$\text{(P1)}: \min_{\{\tau_n\},\{\zeta_J[n]\}} \ \max_n \ P_{out}[n] \tag{7a}$$

$$\text{s.t.} \quad \sum_{n=1}^{N} \zeta_J[n] \le \zeta_{J,\max}, \ \sum_{n=0}^{N} \tau_n \le 1. \tag{7b}$$

where $\zeta_{J,\max} \in (0,1]$ indicates the maximum allowed proportion of the harvested energy for transmission in one time block. In (P1), we jointly optimize the jammer's power allocation $\{\zeta_J[n]\}$ and the time allocation $\{\tau_n\}$ to minimize the maximum SOP among the users. The constraint (7b) ensures that the total jammer's transmit power does not exceed its previously harvested power.

Unfortunately, (P1) is non-convex in general mainly due to (7a). Since it is not trivial to obtain globally optimal solutions, we resort to an alternating optimization approach between the time durations $\{\tau_n\}$ and the power allocation $\{\zeta_J[n]\}$ in the following section. It will also be shown that the proposed algorithm for (P1) guarantees at least local optimality.

III. SOP Minimization of the Multi-user Wiretap WPCN

First, we can exploit the fact that each of $|h_{UE}|^2$ and $|h_{JE}|^2$ independently follows an exponential distribution with unit mean to obtain an abalytical expression of (6) as

$$P_{out}[n] = \begin{cases} \frac{\tilde{G}[n]}{1+\tilde{G}[n]} e^{-\frac{\tilde{V}[n]}{\tilde{G}[n]}} & , \ \text{if } \tau_n \in \mathcal{T}[n], \\ 1 & , \ \text{otherwise}, \end{cases} \tag{8}$$

where $\tilde{G}[n] \triangleq \tilde{D}[n] 2^{\frac{r_{th}}{W\tau_n}} / (1 + A[n]\frac{\tau_0}{\tau_n} - 2^{\frac{r_{th}}{W\tau_n}})$, $\tilde{D}[n] \triangleq \frac{\zeta_{U_n} \eta_{U_n} L_{SU_n} L_{U_n E} |h_{SU_n}|^2}{\zeta_J[n] \eta_J L_{SJ} L_{JE} |h_{SJ}|^2}$, $\tilde{V}[n] \triangleq 1/(\tilde{F}\zeta_J[n]\frac{\tau_0}{\tau_n})$, $\tilde{F} \triangleq \eta_J P_S L_{SJ} L_{JE} |h_{SJ}|^2/\sigma^2_E$, and $\mathcal{T}[n] \triangleq \{\tau_n \in \mathbb{R} | 1 + A[n]\frac{\tau_0}{\tau_n} - 2^{\frac{r_{th}}{W\tau_n}} > 0\}$ for $n = 1, ..., N$. In fact, the condition $1 + A[n]\frac{\tau_0}{\tau_n} - 2^{\frac{r_{th}}{W\tau_n}} \le 0$ indicates instances where the channel capacity from the user to the H-AP is smaller than the threshold r_{th} such that a secrecy outage occurs for sure.

Still, $P_{out}[n]$ in (8) is generally non-convex and thus difficult to handle. To make the problem more tractable, we apply the worst case approximation where the noise at the eavesdroppers is assumed negligible [11] [14]. Then, an upper bound of SOP for $n = 1, ..., N$ becomes

$$P_{out,\text{UB}}[n] = \begin{cases} \frac{\tilde{G}[n]}{1+\tilde{G}[n]} & , \ \text{if } \tau_n \in \mathcal{T}[n], \\ 1 & , \ \text{otherwise}. \end{cases} \tag{9}$$

Finally, we can construct a problem for minimizing the maximum value of (9) as

$$\text{(P1.1)} \quad \min_{\{\tau_n\},\{\zeta_J[n]\}} \max_n \ P_{out,\text{UB}}[n] \tag{10a}$$

$$\text{s.t.} \quad \tau_n \in \mathcal{T}[n], \ \forall n, \tag{10b}$$

$$\sum_{n=1}^{N} \zeta_J[n] \leq \zeta_{J,\max}, \ \sum_{n=0}^{N} \tau_n \leq 1. \tag{10c}$$

In the following, we propose an alternating optimization procedure which yields a local optimal solution.

1) Time allocation: For a given power allocation $\{\zeta_J[n]\}$, we can reformulate (P1.1) into an equivalent form with a new variable $0 \leq \lambda_T < 1$ as

$$\text{(P1.2)} \quad \min_{\{\tau_n\},\lambda_T} \quad \lambda_T \tag{11a}$$

$$\text{s.t.} \quad P_{out,\text{UB}}[n] \leq \lambda_T, \forall n, \tag{11b}$$

$$\sum_{n=0}^{N} \tau_n \leq 1, \ \tau_n \in \mathcal{T}[n], \ \forall n. \tag{11c}$$

In (P1.2), an optimal λ_T can be found by a line search method in the outer loop, and for each λ_T, its feasibility is examined by solving the following problem:

$$\text{(P1.3)} \quad \min_{\{\tau_n\}} \quad \sum_{n=0}^{N} \tau_n \tag{12a}$$

$$\text{s.t.} \quad 1 + A[n]\frac{\tau_0}{\tau_n} - 2^{\frac{r_{th}}{W\tau_n}} > 0, \forall n, \tag{12b}$$

$$P_{out,\text{UB}}[n] \leq \lambda_T, \forall n. \tag{12c}$$

To efficiently solve (P1.3), we first fix τ_0 and define $s_n \triangleq \frac{1}{\tau_n}$ for $n = 1, ..., N$. Then, it can be observed that the left-hand side of (12b) is concave in terms of s_n. Thus, the constraint in (12b) can be rewritten as $s_{n,L} < s_n < s_{n,U}$, where

$$s_{n,L} = -\frac{W}{r_{th}\ln 2}\mathcal{W}_{L,0}(\phi) - \frac{1}{A[n]\tau_0}, \tag{13}$$

$$s_{n,U} = -\frac{W}{r_{th}\ln 2}\mathcal{W}_{L,-1}(\phi) - \frac{1}{A[n]\tau_0}, \tag{14}$$

with $\phi = -\frac{r_{th}}{WA[n]\tau_0}\ln 2 \cdot 2^{-\frac{r_{th}}{WA[n]\tau_0}} < 0$. Here, $\mathcal{W}_{L,k}(\cdot)$ stands for the Lambert W function with branch k [17].

For (12c), one can see that $\tilde{G}[n]$ in $P_{out,\text{UB}}[n]$ is quasi-convex in terms of s_n since the numerator is convex while the denominator is concave [18]. Also, a unique minimizer of $\tilde{G}[n]$ is given by a stationary point $s_{n,C} = \frac{W}{r_{th}\ln 2} - \frac{1}{A[n]\tau_0}$, which lies in $(s_{n,L}, s_{n,U})$ since $0 < -\mathcal{W}_{L,0}(\phi) < 1$ in (13) and $1 < -\mathcal{W}_{L,-1}(\phi)$ in (14) for $\phi < 0$. Therefore, $P_{out,\text{UB}}[n]$ of (12c) increases for $s_n \in [s_{n,C}, s_{n,U})$ due to the fact that $P_{out,\text{UB}}[n]$ is an increasing function of $\tilde{G}[n]$.

If $P_{out,\text{UB}}[n]$ equals λ_T at $s_n = s_{n,C}$, it is obvious that the optimal solution is $\tau_{n,\text{SOP}} = \frac{1}{s_{n,C}}$ for $n = 1, ..., N$. On the other hand, when $P_{out,\text{UB}}[n] < \lambda_T$ at $s_n = s_{n,C}$, the objective function in (12a) can be further minimized by finding $s_n > s_{n,C}$ (hence smaller τ_n), since $P_{out,\text{UB}}$ is an increasing function for $s_n \in (s_{n,C}, s_{n,U})$. In this case, the optimal solution $\tau_{n,\text{SOP}}$ for $n = 1, ..., N$ is expressed as

$$\tau_{n,\text{SOP}} = \frac{1}{s_{n,\lambda_T}}, \tag{15}$$

where s_{n,λ_T} is chosen to satisfy $P_{out,\text{UB}}[n] = \lambda_T$, which can be easily determined by the bisection method.

To summarize, the optimal ET phase duration $\tau_{0,\text{SOP}}$ can be found by a simple one-dimensional search in a bounded region $(0, 1)$, while $\{\tau_{n,\text{SOP}}\}_{n=1}^{N}$ for (P1.3) are calculated by (15). Therefore, if (P1.3) is feasible and $\sum_{n=0}^{N} \tau_{n,\text{SOP}} \leq 1$, we decrease λ_T and increase otherwise in the outer loop.

2) Power allocation: With the given $\{\tau_{n,\text{SOP}}\}$, we formulate the power allocation problem by introducing a new variable $0 \leq \lambda_J < 1$ as

$$\text{(P1.4)} \quad \min_{\{\zeta_J[n]\},\lambda_J} \quad \lambda_J \tag{16a}$$

$$\text{s.t.} \quad P_{out,\text{UB}}[n] \leq \lambda_J, \forall n, \tag{16b}$$

$$\sum_{n=1}^{N} \zeta_J[n] \leq \zeta_{J,\max}. \tag{16c}$$

Then, the following problem is considered to check the feasibility for each value of λ_J as

$$\text{(P1.5)} \quad \min_{\{\zeta_J[n]\}} \quad \sum_{n=1}^{N} \zeta_J[n] \tag{17a}$$

$$\text{s.t.} \quad P_{out,\text{UB}}[n] \leq \lambda_J, \forall n. \tag{17b}$$

One can show from (9) that $P_{out,\text{UB}}[n]$ in (17b) is a decreasing function of $\zeta_J[n]$. Therefore, we can rewrite (17b) as $\zeta_J[n] \geq \delta_J[n]$ where the constant $\delta_J[n]$ satisfies $P_{out,\text{UB}}[n] = \lambda_J$ at $\zeta_J[n] = \delta_J[n]$. Hence, a solution $\zeta_{J,\text{SOP}}[n]$ of (P1.5) is given by $\zeta_{J,\text{SOP}}[n] = \delta_J[n]$ for $n = 1, ..., N$, which can be readily determined by the bisection method due to monotonicity of $P_{out,\text{UB}}[n]$. Finally, we decrease λ_J in the outer loop if solutions of the inner problem (P1.5) satisfy $\sum_{n=1}^{N} \zeta_{J,\text{SOP}}[n] \leq \zeta_{J,\max}$ and increase otherwise. The overall optimization procedure is summarized in Algorithm 1.

Algorithm 1. SOP minimization for multi-user WPCN

Initialize $\{\zeta_{J,\text{SOP}}[n]\}$ and $\lambda_J = 1$.
Repeat
  Set $\lambda_{T,\max} = \lambda_J$ and $\lambda_{T,\min} = 0$.
  Repeat
    Set $\lambda_T = \frac{\lambda_{T,\max} + \lambda_{T,\min}}{2}$.
    For $\tau_0 \in (0, 1)$, solve (P1.3) to obtain $\{\tau_n\}_{n=1}^{N}$.
    Set $\{\tau_{n,\text{SOP}}\}_{n=0}^{N}$ such that $\sum_{n=0}^{N} \tau_{n,\text{SOP}}$ is minimum.
    If $\sum_{n=0}^{N} \tau_{n,\text{SOP}} \leq 1$, $\lambda_{T,\max} = \lambda_T$; otherwise, $\lambda_{T,\min} = \lambda_T$.
  Until $|\lambda_{T,\max} - \lambda_{T,\min}|$ converges.
  Set $\lambda_{J,\max} = \lambda_T$ and $\lambda_{J,\min} = 0$.
  Repeat
    Set $\lambda_J = \frac{\lambda_{J,\max} + \lambda_{J,\min}}{2}$ and $\zeta_{J,\text{SOP}}[n] = \delta_J[n], \forall n$.
    If $\sum_{n=1}^{N} \zeta_{J,\text{SOP}}[n] \leq \zeta_{J,\max}$, $\lambda_{J,\max} = \lambda_J$; otherwise, $\lambda_{J,\min} = \lambda_J$.
  Until $|\lambda_{J,\max} - \lambda_{J,\min}|$ converges.
Until $\max_n P_{out,\text{UB}}[n]$ converges.

At each iteration, the maximum SOP $\max_n P_{out,\text{UB}}[n]$ monotonically decreases, since solutions for (P1.2) and (P1.4) are the Karush-Kuhn-Tucker stationary points of (P1), provided that (P1.2) and (P1.4) are optimally solved. It is also obvious that $\max_n P_{out,\text{UB}}[n]$ is lower bounded by 0. Hence,

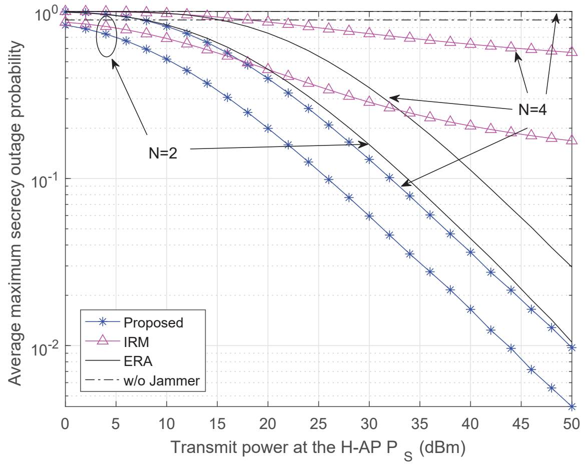

Fig. 2. Average maximum secrecy outage probability where $d_{SU_n} = 5$ m, $d_{SJ} = 5$ m and $d_{SE} = 5$ m

this guarantees Algorithm 1 converges to at least a local optimal point.

IV. Simulation Results

In this section, we provide numerical examples of the secrecy performance in the WPCN with an EH jammer. We adopt the distance-dependent path loss model such that $L_{\mathsf{XY}} = 10^{-3} d_{\mathsf{XY}}^{-3}$, $\forall \mathsf{X},\mathsf{Y} \in \{S, J, U_n \forall n, E\}$, where d_{XY} is the distance between node X and Y as in [7] and [13]. The bandwidth, the EH efficiency and the portion of the harvested energy for transmission of users are fixed as $W = 1$ MHz, $\eta_{\mathsf{X}} = 0.5, \forall \mathsf{X}$ and $\zeta_{U_n} = 0.7, \forall n$, respectively. Furthermore, we set the noise power $\sigma_{\mathsf{X}}^2 = -160$ dBm/Hz, $\forall \mathsf{X}$ unless otherwise stated. The threshold secrecy rate is fixed as $r_{th} = 100$ kbps, and the jammer, users and the eavesdropper are randomly placed from the H-AP with the same distance of 5 m. We set $\zeta_{J,\max} = 1$. Throughout this section, the secrecy performance is averaged over both channel realizations and the locations of the nodes. We compare our proposed solution with the following schemes.

- *Information rate maximization scheme (IRM)*: The sum throughput at the H-AP is maximized without consideration of the eavesdroppers [7].
- *Equal resource allocation (ERA)*: Both power and time resources are equally allocated.
- *Without jammer*: The WPCN with no EH jammer is employed as $\eta_J = 0$.

In Fig. 2, we evaluate the proposed algorithm as a function of P_S. Our proposed scheme is indeed superior to others for all P_S ranges. Specifically, there is approximately 8 dB gain at the SOP of 0.1 with 2 users when compared with the ERA. Note that the performance gain grows as the number of users increases in both figures, whereas the secrecy performance of IRM dramatically drops when multiple users are considered. From the figure, we can thus conclude that the proposed scheme significantly improves the secrecy performance, and the gain becomes more pronounced with the increased number of users compared to other schemes.

V. Conclusion

In this paper, we have investigated the secrecy performance of wiretap WPCN with the aid of an EH jammer. We have considered a meaningful scenario where only the location information and CDI of the eavesdroppers are known. We have derived an analytic expression for SOP and minimized the maximum SOP among users. The numerical examples have validated the proposed method's outstanding performance and confirmed the effect of the EH jammer on the secrecy performance.

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