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Secure energy efficiency: Power allocation and outage analysis for SWIPT-in-DAS based IoT

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Abstract

In this paper, we study secure energy efficiency (SEE) for simultaneous wireless information and power transfer (SWIPT) in a distributed antenna system (DAS) based IoT network. We consider a system in which both the legitimate user (Bob) and the eavesdropper (Eve) rely on the energy harvested from the received radio signal. Firstly, with perfect channel state information (CSI), we formulate the maximization of SEE as a constrained optimization problem. In this problem, we aim to highlight the advantage of SWIPT in exploiting the Eve's energy harvesting requirement. This is achieved by defining a charge constraint in the SEE optimization problem which ensures that the Eve is deprived of its only energy source. Next, considering the fact that perfect CSI is hard to achieve in practice, we characterize the system performance in terms of the outage probability (OP) of SEE. For the given SWIPT-in-DAS setup, we derive the closed form expression for the OP of SEE and with the help of numerical results, we study the effect of transmit power levels, number of distributed antenna (DA) ports and the PS ratio of devices. To the best of our knowledge, this is the first attempt to define the OP of SEE for SWIPT-in-DAS.

Keywords: DAS; SWIPT; Energy efficiency; Physical layer security; Outage probability

1. Introduction

In the evolving ubiquitous IoT network, energy efficiency has emerged as a major research issue. This is primarily due to the exponential rise in the number of devices and demand for quality of service [1].

Distributed antenna system (DAS) technology, primarily designed for increasing network coverage and data rates, is now being studied in the field of energy efficient wireless communication [2]. Since DAS reduces the transmitter–receiver access distance, it can significantly help in SWIPT, which is expected to be an energy efficient alternative to facilitate the battery-less operation of IoT devices. The optimal transmission scheme for energy efficient SWIPT in DAS was discussed in [3]. Further, physical layer (PHY) security is also being widely studied alongside energy efficient wireless communication [4].

In this paper, we study SEE for SWIPT-in-DAS based IoT network with energy harvesting eavesdropper (EHE). We define SEE as ratio of the achievable secrecy rate [5] to the total power consumed at DA-ports. The main contributions of this paper are summarized as follows:

Case 1: [Perfect CSI] In this case, our goal is to maximize SEE with respect to the transmit power of DA-ports. We formulate the maximization of SEE as a constrained fractional optimization problem and obtain the optimal solution by solving KKT conditions. However, in contrast to the usual constraints [6], we exploit the EHE's dependence on wireless power transfer as a charge constraint in the optimization problem. While, this novel constraint highlights another advantage of SWIPT, we study the corresponding trade-offs as well.

Case 2: [Statistical CSI] The major part of this work focuses over a more practical scenario, wherein, the CSI is not available at the transmitter. Moreover, different from the conventional methods [7], we adopt a novel approach to characterize the system performance by the OP of SEE. Considering the blanket transmission scheme, wherein all the DA ports are active, we derive the closed form expression for the OP of

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SEE. Further, we also study a more general case, wherein, multiple Eves are present in the system and we evaluate the OP of SEE corresponding to the worst case secrecy rate achievable for the given IoT device.

The rest of the paper is organized as follows: In Section 2, we discuss the system model and problem formulation of the optimal power allocation with perfect CSI. In Section 3 we study the outage probability of SEE. The numerical results are discussed in Section 4. Finally, Section 5 concludes the paper.

2. Optimal power allocation with perfect CSI

2.1. System model

Let us consider a downlink DAS with N centrally controlled DA ports serving K_b number of users in presence of an EHE, all equipped with single antennas. The signal received by a given device in such a setup is written as; $y = \sum_{i=1}^{N} \sqrt{p_i}\zeta_i x_i + n$ [2], where, for ith DA-port, p_i is the transmit power, x_i denotes the transmitted symbol with average power $E[|x_i|^2] = 1$ and ζ_i is the corresponding fading co-efficient. Also, n denotes the additive white Gaussian noise (AWGN) at the receiver. In the given system, each IoT device has a power splitter which splits the received signal power according to a power splitting (PS) ratio (Δ for information decoding and $1-\Delta$ for energy harvesting). We use OFDMA to support the multi-user transmission and assume that the entire bandwidth B is equally segmented into K_b non-overlapping channels to avoid interference. Further, in presence of Eve, the transmitter at each DA port uses Wyner's wiretap coding [5] and hence the achievable secrecy rate (in bits/s/Hz) over sub-carrier k having bandwidth $\frac{B}{K_b}$ is given by :

$$R_s^k = \frac{1}{K_b}\left[\log_2\left(1+\Delta_k^b\Gamma_k^b\right) - \log_2\left(1+\Delta^e\Gamma_k^e\right)\right] \tag{1}$$

In Eq. (1), $\Gamma_k^b = \sum_{j=1}^{N}\gamma_{j,k}^b p_{j,k}$ and $\Gamma_k^e = \sum_{j=1}^{N}\gamma_{j,k}^e p_{j,k}$, where, for kth Bob and Eve respectively, $\gamma_{j,k}^b$ and $\gamma_{j,k}^e$ are the effective channel gain to noise power ratios over sub-carrier k and Δ_k^b, Δ^e denote the corresponding PS ratios. Also, $p_{j,k}$ is the transmit power from jth port over sub-carrier k.

Now, SEE (in bits/Hz/J) is defined as:

$$\eta_{SEE} = \frac{R_{total}}{P_{total}} = \frac{\sum_{k=1}^{K_b} R_s^k}{\sum_{k=1}^{K_b}\sum_{i=1}^{N} p_{i,k} + p_c} \tag{2}$$

where p_c is the power consumed in DA-ports during various signal processing operations. Since each IoT device can decode the information from a given channel, but can harvest energy from all the available channels, the energy harvested by kth Bob can be expressed as: $E_k^b = \tau_k^b(1-\Delta_k^b)\sum_{i=1}^{N}\gamma_{i,k}^b\sum_{j=1}^{K_b} p_{i,j}$ where, τ_k is the linear energy conversion efficiency of kth Bob. Similarly, the energy harvested by the Eve is given by $E^e = \tau^e(1-\Delta^e)\sum_{i=1}^{N}\gamma_i^e\sum_{j=1}^{K_b} p_{i,j}$ where, τ^e is the corresponding energy conversion efficiency of the Eve.

2.2. Problem formulation

Our objective is to optimally allocate power to the DA-ports in order to maximize η_{SEE} in (2). To this end, we formulate the maximization of η_{SEE} as a constrained fractional optimization problem as follows:

$$\begin{aligned} &P1: \max_{\{P_{i,k}\}} \eta_{SEE} \\ &\text{s.t: C1: } \sum_{k=1}^{K_b} p_{i,k} \le P_{max,i},\ \text{ C2: } p_{i,k} \ge 0 \\ &\quad\ \text{C3: } E_k^b \ge E_{k,min}^b \text{ and C4: } E^e \le E_{min}^e \\ &\quad\ \text{for } k = 1,\ldots,K_b,\ i = 1,\ldots,N \end{aligned} \tag{3}$$

where, C1 and C2 correspond to the maximum and minimum transmit power constraints respectively, C3 is the constraint of minimum harvested energy ($E_{k,min}^b$) for kth Bob and the novel constraint C4 limits the energy harvested by the Eve. We introduce the constraint C4 in the problem in order to restrain the Eve from harvesting energy from the received signal. With this, we can restrict it's battery charge, thereby, depriving it of its only energy source. Now, for $\Delta_k^b\Gamma_k^b > \Delta^e\Gamma_k^e$, R_s^k in (1) is a concave function. Thus, it is easy to verify that P1 is a concave linear fractional problem with pseudo-concave objective function [8]. Hence, each stationary point is the global maximizer and KKT conditions are necessary and sufficient for optimality. For detailed proof refer to [8]. Since, η_{SEE} in (3) is twice differentiable, we use Sequential Quadratic Programming (SQP) to solve the KKT conditions for the optimal solution [9]. The numerical results are discussed in Section 4.

3. Outage probability of SEE

Now, considering the fact that perfect CSI is difficult to achieve in practice, we characterize the system performance by the OP of SEE. We consider the blanket transmission scheme, with all DA-ports transmitting at same power level (p). Let h_i and g_i denote the independent and identically distributed (IID) circularly symmetric complex Gaussian (CSCG) channel coefficients (of Bob and Eve respectively) with zero mean and unit variance. Also, let σ_b^2 and σ_e^2 denote the noise variances at Bob and Eve respectively. Therefore, instantaneous SNRs at Bob and Eve are given by $X' = \Delta^b\sum_{i=1}^{N}|h_i|^2 p_i/\sigma_b^2 = \Delta^b(p/\sigma_b^2)\sum_{i=1}^{N}|h_i|^2$ and $Y' = \Delta^e\sum_{i=1}^{N}|g_i|^2 p_i/\sigma_e^2 = \Delta^e(p/\sigma_e^2)\sum_{i=1}^{N}|g_i|^2$ respectively. Let $w^b = \Delta^b(p/\sigma_b^2)$, $X'' = \sum_{i=1}^{N}|h_i|^2$, $w^e = \Delta^e(p/\sigma_e^2)$ and $Y'' = \sum_{i=1}^{N}|g_i|^2$. The OP of SEE corresponding to a given threshold (η_{th}) is hence given by:

$$\begin{aligned} &P_{out}(\eta_{th}) \\ &\quad = P(\eta_{SEE} < \eta_{th}) \\ &\quad = P\left[\frac{\log_2\left(1+w^bX''\right) - \log_2\left(1+w^eY''\right)}{Np+p_c} < \eta_{th}\right] \\ &\quad = P\left(w^bX'' < \{1+w^eY''\}\{2^{(Np+P_c)\eta_{th}}\} - 1 \triangleq Q\right) \end{aligned} \tag{4}$$

Theorem 1. *For the given SWIPT-in-DAS setup $P_{out}(\eta_{th})$ is given by Eq. (5).*

Proof. Since h_i and g_i are IID-CSCG random variables, $|h_i|^2$ and $|g_i|^2$ will be exponentially distributed and hence X'' and Y'', being the sum of N independent exponential random variables, will both follow Erlang distribution. Let $X = w^b X'' \sim f_X(x) = \frac{x^{N-1} e^{\frac{x}{w^b}}}{(w^b)^N (N-1)!} = \frac{\alpha^N x^{N-1} e^{-\alpha x}}{(N-1)!}$ and $Y = w^e Y'' \sim f_Y(y) = \frac{y^N e^{\frac{y}{w^e}}}{(w^e)^N (N-1)!} = \frac{\beta^N y^{N-1} e^{-\beta y}}{(N-1)!}$, where $\alpha = \frac{1}{w^b}$ and $\beta = \frac{1}{w^e}$. Therefore we have:

$$P(X \le Q) = \int_0^\infty \int_o^Q f_X(x) f_Y(y) dx dy$$
$$= \int_0^\infty \int_o^Q \frac{\alpha^N x^{N-1} e^{-\alpha x}}{(N-1)!} f_Y(y) dx dy$$
$$= \int_0^\infty \left(1 - \sum_{n=0}^{N-1} \frac{(\alpha Q)^n e^{(-\alpha Q)}}{n!}\right) f_Y(y) dy$$

Let $z = \{Np + P_c\}\eta_{th}$, therefore;

$$P_{out}(\eta_{th}) = 1 - \sum_{n=0}^{N-1} \int_0^\infty \left[\frac{(\alpha^n)(2^z + 2^z y - 1)^n}{\{e^{\alpha(2^z-1)} e^{\alpha 2^z y}\} n!}\right] f_Y(y) dy$$
$$= 1 - K \sum_{n=0}^{N-1} \frac{\alpha^n}{n!} \left[\int_0^\infty (ay+b)^n e^{-(a\alpha+\beta)y} y^{N-1} dy\right]$$
$$\text{where, } K = \frac{\beta^N e^{\alpha(1-2^z)}}{(N-1)!}, \quad a = 2^z, \quad b = 2^z - 1$$
$$= 1 - K \sum_{n=0}^{N-1} \frac{\alpha^n}{n!} \left[\int_0^\infty \sum_{j=0}^{n} \binom{n}{j} \frac{(ay)^j b^{n-j}}{e^{(a\alpha+\beta)y}} y^{N-1} dy\right]$$
$$= 1 - K \sum_{n=0}^{N-1} \frac{\alpha^n}{n!} \left\{\sum_{j=0}^{n} \binom{n}{j} b^{n-j} a^j\right\} \int_0^\infty \frac{y^{j+N-1}}{e^{(a\alpha+\beta)x}} dx$$
$$= 1 - K \sum_{n=0}^{N-1} \frac{\alpha^n}{n!} \left\{\sum_{j=0}^{n} \binom{n}{j} b^{n-j} a^j\right\} \left\{\frac{(j+N-1)!}{(a\alpha+\beta)^{j+N}}\right\}$$

Using K, a, b and z defined above, we get Eq. (5).

$$P_{out}(\eta_{th}) = 1 - \frac{e^{\alpha\{1-2^{(N.p+Pc)\eta_{th}}\}}}{\beta^{-N}(N-1)!} \sum_{n=0}^{N-1} \frac{\alpha^n}{n!} \left[\sum_{j=0}^{n} \binom{n}{j} \left(2^{(N.p+Pc)\eta_{th}} - 1\right)^{n-j} \times \frac{\left(2^{(N.p+Pc)\eta_{th}}\right)^j (j+N-1)!}{\{\alpha.2^{(N.p+Pc)\eta_{th}} + \beta\}^{j+N}}\right] \quad \blacksquare \tag{5}$$

If only the Eve's CSI is unknown, we can have a special case for the OP of SEE as given below:

$$P_{out}(\eta_{th}) = P\left(Y > \frac{(1 + w^b X'')}{2^{(Np+p_c)\eta_{th}}} - 1 \triangleq Q'\right)$$
$$= 1 - \int_0^{Q'} \frac{\beta^N y^{N-1} e^{-\beta y}}{(N-1)!} dy = 1 - \frac{\gamma_{inc}(N, \beta Q')}{(N-1)!}$$

$$\implies P_{out}(\eta_{th}) = 1 - \frac{\gamma_{inc}\{N, \frac{1}{w^e} \frac{(1+w^b \sum_{i=1}^N |h_i|^2)}{(2^{(Np+P_c)\eta_{th}})} - 1\}}{(N-1)!} \tag{6}$$

where, $\gamma_{inc}(N, x)$ represents the lower incomplete gamma function.

3.1. Outage probability of worst case SEE

If there are M eavesdroppers in the system, the overall performance of the system is determined by the worst case secrecy rate achievable for the given user.

Corollary 1. *The OP of worst case SEE is given by* $P_{out}(\eta_{th}) = 1 - \prod_{m=1}^{M} P\left(Y_m < Q''\right)$

Proof. Considering the secrecy rate corresponding to the maximum of M eavesdroppers, we have: $P_{out}(\eta_{th}) = P(\eta_{SEE} < \eta_{th})$

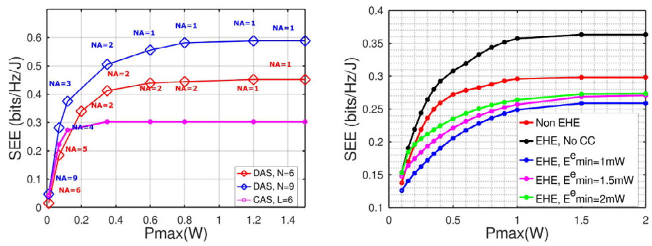
$$= P\left[\frac{\log_2(1+X) - \max_{m\in M} \log_2(1+Y_m)}{Np + p_c} < \eta_{th}\right]$$
$$= P\left[\max_{m\in M} Y_m > \frac{(1+X)}{2^{(Np+p_c)\eta_{th}}} - 1 \triangleq Q''\right]$$
$$= 1 - P\left(\max_{m\in M} Y_m < Q''\right) = 1 - \prod_{m=1}^{M} P\left(Y_m < Q''\right)$$

where, $Y_m's$ are assumed independent. $P\left(Y_m < Q''\right) = \int_0^\infty \int_0^{Q''} f_{Y_m}(y) f_X(x) dy dx$, can be evaluated in closed form similar to proof of Theorem 1 and is given by Eq. (7).

$$P\left(Y_m < Q''\right) = 1 - \frac{e^{\beta\{1-2^{-(N.p+Pc)\eta_{th}}\}}}{\alpha^{-N}(N-1)!} \sum_{n=0}^{N-1} \frac{\beta^n}{n!} \times \left[\sum_{j=0}^{n} \binom{n}{j} \left(2^{-(N.p+Pc)\eta_{th}} - 1\right)^{n-j} \times \frac{\left(2^{-(N.p+Pc)\eta_{th}}\right)^j (j+N-1)!}{\{\beta.2^{-(N.p+Pc)\eta_{th}} + \alpha\}^{j+N}}\right] \quad \blacksquare \tag{7}$$

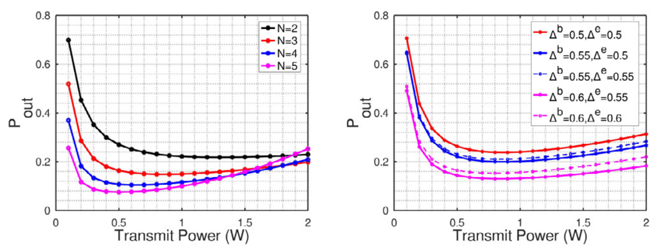
4. Results and discussion

In this section, we present the numerical results of the optimization problem discussed in Section 2 and the OP of SEE discussed in Section 3. In Fig. 1(a), to highlight the advantage of DAS over a conventional antenna system (CAS), we plot SEE as a function of P_{max} with $\Delta_k^b = \Delta^e = 0.5$ and $\tau_k^b = \tau^e = 0.75\ \forall k$. We observe that SEE of the system initially increases with P_{max} but eventually gets saturated. However, with the same total transmit power, the DAS (with $N = 6$) performs significantly better than a CAS with equal number of antennas (L). This is due to the reduced access distances in DAS. Also, as evident in Fig. 1(a), lesser number of DA-ports are active (NA) for higher values of P_{max}. In Fig. 1(b), we have the results corresponding to the charge constraint (CC) of EHE, with $E_{k,min}^b = 1mW\ \forall k$. It is evident that the Eve's dependence on harvested energy is actually beneficial in context of SEE. This also gives an opportunity to prevent other unpredictable attacks of the Eve by depriving it of its only energy source. However, we note that there is



(a) (b)

Fig. 1. (a) SEE w.r.t P_{max} in DAS and CAS (b) SEE w.r.t P_{max} in case of an EHE.



(a) (b)

Fig. 2. (a) OP of SEE w.r.t transmit power for increasing N (b) OP of SEE w.r.t transmit power for increasing Δ^b and Δ^e.

trade-off with the energy efficiency. In Fig. 2, we plot OP of SEE w.r.t transmit power of DA-ports, with σ_b^2=-20dBm and σ_e^2=-10dBm. Transmit power and number of DA-ports play a significant role in the overall system performance. In Fig. 2(a), we observe that $P_{out}(\eta_{th})$ reduces significantly as the transmit power is increased and initially, a similar trend is observed with the number of DA-ports. However, this behaviour changes at higher power levels. In fact, the results reveal that in order to minimize the OP, lesser number of DA-ports need to be active for higher values of P_{max}. Further, in Fig. 2(b), it can be observed that $P_{out}(\eta_{th})$ also decreases when PS ratios of Bob and Eve are increased. Moreover, the system performs better when the PS ratio of Bob is higher in magnitude than that of the Eve.

5. Conclusion

In this paper, we studied SEE for SWIPT-in-DAS based IoT network. For the case of perfect CSI, we discussed an approach to exploit the EHE's charge constraint in the optimal power allocation scheme. Further, in an unknown CSI scenario, we characterized the system performance by the OP of SEE. For the blanket transmission scheme, we obtained a closed form expression for the OP of SEE. The theoretical results obtained were supported with the numerical computations.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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