2018 IEEE 19th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)

Optimal Simultaneous Wireless Information and Power Transfer with Low-Complexity Receivers

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***Abstract*—Nowadays, a significant goal of technology is to prolong the lifetime of the wireless communication devices. To this end, this paper studies and optimizes the performance of simultaneous wireless information and power transfer with an integrated energy and information receiver, which has the advantage of low complexity and energy cost. Specifically, a tractable expression for the achievable rate is provided, which is then used to describe the achievable harvested energy-rate region. Moreover, the joint harvested energy-rate outage probability is defined and minimized for a point-to-point and multicasting system. Finally, simulation results illustrate the performance of the proposed framework.**

***Index Terms*—Simultaneous wireless information and power transfer (SWIPT), integrated receiver, joint harvested energy-rate outage probability**

I. Introduction

In today's widely used devices and internet-of-things (IoT) applications, such as wearables, and sensor networks, which require connection to the power cord, energy harvesting (EH) can be seen as the final challenge to true mobility. Also, especially in low power devices, e.g., in sensor networks, EH can be applied to replace the traditional batteries with super capacitors [1], which is desirable particularly when replacing or recharging the batteries is inconvenient, costly, or dangerous, such as in remote areas, harsh industrial environments, and healthcare applications. Furthermore, EH can reduce the number of batteries needed for such off grid devices, and, thus, counterbalance the environmental impact.

The main drawback of traditional EH methods is that they rely solely on ambient energy sources, such as solar, wind energy, and vibrations, which are uncontrollable and usually unpredictable. To this end, harvesting energy from sources that intentionally generate radio frequency (RF) signals seems to be an interesting alternative. The potential to use this concept, termed as wireless power transfer (WPT), in communication applications, has received much attention during the last years [2], [3]. WPT creates unique challenges in the design of communication systems, since, in some cases, it conflicts with the information transmission. More specifically, nodes cannot harvest energy and receive information simultaneously, which complicates the design of communication systems with WPT [1], [4], [5]. This is the main challenge of simultaneous wireless information and power transfer (SWIPT), which aims at unifying the information and energy transmission. To achieve this in single-antenna nodes, two fundamental strategies have been proposed, namely power-splitting (PS) and time-switching (TS) [4], [6], [7]. PS is based on the division of the signal power into two streams, while in TS, during a portion of time the received signal is used solely for energy harvesting.

It is noted that existing literature mostly focuses on the investigation of the separated information and energy receiver [8]–[13], which is based on traditional circuits used for communication and energy harvesting purposes. However, in the pioneer work [14], an architecture for the integrated information and energy receiver has been proposed. In this architecture, the rectifier that is used for EH, is also used for RF band to direct current (DC) conversion, substituting the traditional RF band to baseband conversion. This receiver architecture consumes less power by avoiding the use of active devices, which is extremely important for low power consumption. Moreover, the separated receiver can be combined with the integrated one [15], in order to improve symbol error rate at the expense of complexity. The later retains this multi-branch architecture out of the scope of our paper, which focuses on the integrated receiver. However, the investigation and optimization of the performance of this receiver is difficult, e.g., in terms of outage probability, mainly due to the absence of an appropriate expression for the achievable rate. Also, in the integrated receiver, the optimization of the PS factor is affected by the analogue-to-digital conversion noise, which has also not been addressed in existing literature.

To this end, in this paper, we present a novel theoretical framework to facilitate the investigation of performance of the integrated receiver. First, we provide a tractable expression of the achievable rate. Then using this expression, we define the joint harvested energy-rate outage probability, which is calculated for a point-to-point and multicasting system. Also, the PS ratio is optimized, such as to minimize the joint outage probability. Finally, simulation results are provided to illustrate the performance of the considered system, for the optimal PS factor.

II. System Model

We consider the downlink of a communication network that consists of one base station that performs SWIPT to serve the

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assigned EH users. All nodes are assumed to have a single antenna. Two different cases are taken into account, namely:

- point-to-point communication and
- downlink multicasting, where the BS transmits the same information to N users simultaneously.

When referring to downlink multicasting, the notation $(\cdot)_n$ will be used to denote the value of the variable $(\cdot)$ for the n-th user. The path loss factor between the BS and the user is denoted by l, while the small scale fading coefficient is given by the complex random variable $h \sim \mathcal{CN}(0,1)$.

It is assumed that each receiver is equipped with an integrated information and energy receiver, which is shown in Fig. 1 and presented in [14]. In such a receiver, the received RF signal is converted to a DC signal by a rectifier, consisting of a Schottky diode and a passive low pass filter. Then, the DC signal is split into two streams, one proportional to the PS factor $\rho \in [0,1]$ and one proportional to the factor $1-\rho$ for energy harvesting and information decoding (via energy detection [14]), respectively.

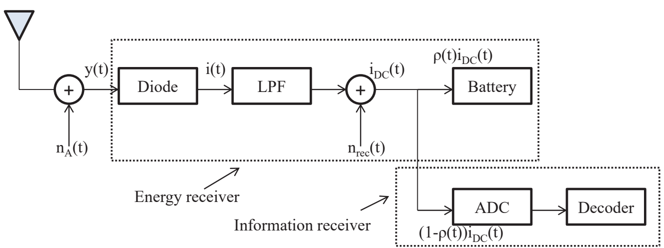

Fig. 1. Architecture of the integrated SWIPT receiver.

The DC signal is given by

$$i_{\mathrm{DC}}(t) = \left| |h|\sqrt{lP}A(t) + n_A(t) \right|^2 + n_{\mathrm{rec}}(t), \quad (1)$$

where $A(t)$ denotes the amplitude of the complex baseband signal at the transmitter side, P denotes the average transmit power, $n_A(t) \sim \mathcal{CN}(0,\sigma_A^2)$ and $n_{\mathrm{rec}} \sim \mathcal{N}(0,\sigma_{\mathrm{rec}}^2)$ denote the additive noise introduced by the antenna and the rectifier, respectively.

As shown in [14], the portion of the DC signal for decoding information is processed by an analog-to-digital converter (ADC). After the noiseless power splitter and the ADC, the output $y[k]$ is given by

$$y[k] = (1-\rho)\left(\left| |h|\sqrt{lP}A[k] + n_A[k] \right|^2 + n_{\mathrm{rec}}[k] \right) + n_{\mathrm{ADC}}[k], \quad (2)$$

where k denotes the discrete time and $n_{\mathrm{ADC}} \sim \mathcal{N}(0,\sigma_{\mathrm{ADC}}^2)$ denotes the additive noise introduced by the ADC.

From (2), considering that the antenna noise is negligible ($\sigma_A^2 \to 0$), the equivalent discrete-time memoryless channel is modeled as

$$Y = l|h|^2 PX + Z, \quad (3)$$

where X denotes the signal power, which is the non-negative channel input, Y denotes the channel output and $Z \sim \mathcal{N}(0, \sigma_{\mathrm{rec}}^2 + \frac{\sigma_{\mathrm{ADC}}^2}{(1-\rho)^2})$ denotes the equivalent processing noise, where $X \geq 0 \in \mathbb{R}$ and $\mathbb{E}[X] \leq 1$.

III. Harvested Energy-Rate Trade-off

In this section, the expressions of the harvested energy and the rate are extracted for the point-to-point system.

A. Harvested Energy

It is assumed that the converted energy in the energy receiver is linearly proportional to i_{DC}, with a conversion efficiency $0 < \zeta \leq 1$. It is also assumed that the harvested energy due to the equivalent processing noise is negligible and thus ignored. Hence, the harvested energy, which coincides with power assuming the symbol period to be one, is given by [14]

$$Q = \rho\zeta l|h|^2 P. \quad (4)$$

B. Achievable Rate

Theorem 1: The achievable rate is given by

$$R = \frac{1}{2}\log_2\left(1 + \frac{e(l|h|^2P)^2}{2\pi\sigma^2}\right), \quad (5)$$

with e being the base of the natural logarithm and $\sigma = \sigma_{\mathrm{rec}}^2 + \frac{\sigma_{\mathrm{ADC}}^2}{(1-\rho)^2}$.

Proof: The channel capacity is related with the mutual information between the input and the output of the channel through the inequality

$$C \geq I(X,Y), \quad (6)$$

where the equality holds for the optimal input distribution. From (6), a capacity lower bound can be obtained, using a random input distribution subject to $X \geq 0$ and $\mathbb{E}[X] \leq 1$.

The mutual information between the input and the output of the channel (3) can be written as

$$I(X,Y) = H(Y) - H(Y|X) \quad (7)$$
$$= H(l|h|^2PX + Z) - H(Z) \quad (8)$$
$$= \frac{1}{2}\log_2\left(2^{2H(l|h|^2PX+Z)}\right) - H(Z), \quad (9)$$

where $H(\cdot)$ denotes the entropy. For the first term in (9), it holds that [16]

$$\frac{1}{2}\log_2\left(2^{2H(l|h|^2PX+Z)}\right) \geq \frac{1}{2}\log_2\left(2^{2H(l|h|^2PX)} + 2^{2H(Z)}\right). \quad (10)$$

Thus, (9) can be written as

$$I(X,Y) \geq \frac{1}{2}\log_2\left(1 + \frac{2^{2H(l|h|^2PX)}}{2^{2H(Z)}}\right). \quad (11)$$

Considering that Z follows normal distribution, the entropy of the equivalent processing noise in bits is

$$H(Z) = \frac{1}{2}\log_2\left(2\pi e\sigma^2\right). \quad (12)$$

Substituting (12) to (11) and using the lower bound of the mutual information, the following expression is derived

$$I(X,Y) = \frac{1}{2}\log_2\left(1 + \frac{2^{2H(l|h|^2PX)}}{2\pi e\sigma^2}\right). \quad (13)$$

The exponent in the numerator in (13) can be rewritten as [16]

$$H(l|h|^2PX) = H(X) + \log_2(|l|h|^2P|) \quad (14)$$
$$= H(X) + \log_2(l|h|^2P), \quad (15)$$

as l, $|h|^2$ and P are positive constants.

The channel (3) is known as optical intensity channel [17]. It has been shown that for this channel a tight capacity lower bound is obtained by mutual information when the input X follows exponential distribution. The rate parameter of the exponential distribution is set to one in order for the restriction $\mathbb{E}[X] \leq 1$ to be satisfied. The entropy of X in bits under this distribution is

$$H(X) = \frac{1}{\ln 2}. \quad (16)$$

From (13), the mutual information is computed, assuming that the input distribution is exponential. This capacity lower bound is considered as the achievable rate and is given by

$$R = \frac{1}{2}\log_2\left(1 + \frac{2^{2(\frac{1}{\ln 2}+\log_2(l|h|^2P))}}{2\pi e\sigma^2}\right), \quad (17)$$

from which, (5) is derived. ■

C. Harvested Energy-Rate Region

Using (4) and (5), for the harvested energy and the rate, respectively, the achievable harvested energy-rate region for the point-to-point system can be obtained, which is presented in Fig. 2. The transmit power, the variance of ADC noise and the harvested energy is normalized to the variance of the rectifier noise.

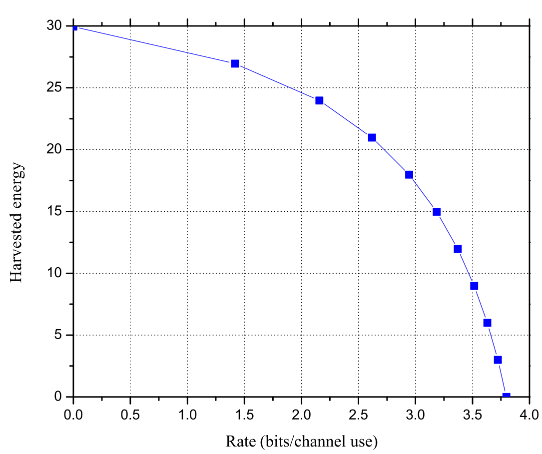

Fig. 2. Harvested energy-rate region with $P = 100$, $h \sim \mathcal{CN}(0,1)$, $\zeta = 0.6$, $l = \frac{1}{2}$, $\sigma^2_{\text{ADC}} = 1$.

IV. Joint Harvested Energy-Rate Outage Probability

A. Point-to-Point System

The joint harvested energy-rate outage probability P_o is defined as the probability that the energy harvested by the user is lower than an energy threshold q_{th} or the rate is lower than a rate threshold r_{th}.

This definition can be expressed as

$$P_o = \Pr\left(Q \leq q_{\text{th}} \cup R \leq r_{\text{th}}\right), \quad (18)$$

where $\Pr(\cdot)$ denotes probability.

Theorem 2: The joint harvested energy-rate outage probability for a point-to-point system is given by

$$P_o = 1 - e^{-\max\left\{\frac{q_{\text{th}}}{\rho\zeta lP},\, \frac{1}{lP}\sqrt{\frac{2\pi\sigma^2}{e}\left(2^{2r_{\text{th}}}-1\right)}\right\}}. \quad (19)$$

Proof: From (4) and (5), (18) can be rewritten as

$$P_o = \Pr\left(\rho\zeta l|h|^2P \leq q_{\text{th}} \cup \frac{1}{2}\log_2\left(1 + \frac{(\sqrt{e}l|h|^2P)^2}{2\pi\sigma^2}\right) \leq r_{\text{th}}\right). \quad (20)$$

The random variable of both events is $|h|^2$, thus the outage probability can be written as

$$P_o = \Pr\left(|h|^2 \leq \frac{q_{\text{th}}}{\rho\zeta lP} \cup |h|^2 \leq \frac{1}{lP}\sqrt{\frac{2\pi\sigma^2}{e}\left(2^{2r_{\text{th}}}-1\right)}\right). \quad (21)$$

It can be observed that the random variable $|h|^2$ is upper bounded in both events. The union of these events occurs when $|h|^2$ is lower than the maximum of these upper bounds. Hence, P_o can be expressed as

$$P_o = \Pr\left(|h|^2 \leq \max\left\{\frac{q_{\text{th}}}{\rho\zeta lP}, \frac{1}{lP}\sqrt{\frac{2\pi\sigma^2}{e}\left(2^{2r_{\text{th}}}-1\right)}\right\}\right), \quad (22)$$

where $\max\{\cdot\}$ denotes the maximum of the two elements.

As it has been mentioned, $h \sim \mathcal{CN}(0,1)$. Consequently, $|h|$ follows Rayleigh distribution with scale parameter $\frac{\sqrt{2}}{2}$ and $|h|^2$ follows exponential distribution with rate parameter 1. The probability density function (PDF) for this distribution is $f(x) = e^{-x}$ and the outage probability is given by

$$P_o = \int_0^{\max\left\{\frac{q_{\text{th}}}{\rho\zeta lP},\, \frac{1}{lP}\sqrt{\frac{2\pi\sigma^2}{e}\left(2^{2r_{\text{th}}}-1\right)}\right\}} e^{-x}dx \quad (23)$$

from which (19) is derived. ■

In a SWIPT system, the aim is to minimize this probability, and, thus, the optimal value of ρ is defined as

$$\rho^* = \arg\max_{\rho} P_o \quad (24)$$

Theorem 3: The optimal value of $\rho \in [0,1]$ is given by the solution of

$$\rho^4 - 2\rho^3 + \left(1 + \frac{\sigma^2_{\text{ADC}}}{\sigma^2_{\text{rec}}} - \frac{A^2}{2\pi e\sigma^2_{\text{rec}}B^2}\right)\rho^2 + \frac{2A^2}{\sigma^2_{\text{rec}}B^2}\rho - \frac{A^2}{\sigma^2_{\text{rec}}B^2} = 0. \quad (25)$$

Proof: As the PS factor ρ increases, the first term in $\max\left\{\frac{q_{\text{th}}}{\rho\zeta lP}, \frac{1}{lP}\sqrt{\frac{2\pi\sigma^2}{e}\left(2^{2r_{\text{th}}}-1\right)}\right\}$ decreases, while the second term increases. Thus, the probability is minimized when the two terms are equal and the optimal PS factor can be extracted from

$$\frac{A^2}{\rho^2} = \left(\sigma_{\text{rec}}^2 + \frac{\sigma_{\text{ADC}}^2}{(1-\rho)^2}\right) B^2, \tag{26}$$

where $A = \frac{q_{\text{th}}}{\zeta lP}$ and $B = \frac{1}{lP}\sqrt{\frac{2\pi}{e}}\sqrt{2^{2r_{\text{th}}}-1}$. Multiplying by $\rho^2(1-\rho)^2$ and dividing by $\sigma_{\text{rec}}^2 B^2$, (26) can be rewritten as in (25). ■

B. Multicasting System

In a multicasting system, the harvested energy by the n-th user is given by

$$Q_n = \rho_n \zeta l_n |h_n|^2 P. \tag{27}$$

Accordingly, from (5), the rate of the n-th user is

$$R_n = \frac{1}{2}\log_2\left(1 + \frac{e(l_n|h_n|^2P)^2}{2\pi\sigma_n^2}\right). \tag{28}$$

Theorem 4: The joint harvested energy-rate outage probability for a multicasting system is given by

$$P_o = 1 - \prod_{n=1}^{N} e^{-\max\left\{\frac{q_{\text{th,n}}}{\rho_n\zeta l_n P}, \frac{1}{l_n P}\sqrt{\frac{2\pi\sigma_n^2}{e}\left(2^{2r_{\text{th}}}-1\right)}\right\}}. \tag{29}$$

Proof: The joint harvested energy-rate outage probability in this system is defined as the probability that at least one uses is in outage. This can be expressed as

$$P_o = \Pr\left(Q_1 \le q_{\text{th,1}} \cup R_1 \le r_{\text{th}} \cup \ldots \right. \tag{30}$$

$$\left. \cup\, Q_N \le q_{\text{th,N}} \cup R_N \le r_{\text{th}}\right). \tag{31}$$

It is assumed that the threshold of harvested energy can be different in each user, but the same does not hold for the rate, due to multicasting principles. Using the complementary event and since $|h_n|^2$ are independent for all values of $n \in \{1, ..., N\}$, (31) can be written as

$$P_o = 1 - \prod_{n=1}^{N} \Pr\left(Q_n \le q_{\text{th,n}} \cup R_n \le r_{\text{th}}\right). \tag{32}$$

Thus, the joint harvested energy-rate outage probability for a multicasting system is given by (29). ■

Finally, the optimal PS factor for each user can be computed from an equation like (25).

V. Simulation and Discussion

For the simulation, the transmit power, the variance of ADC noise and the harvested energy is normalized to the variance of the rectifier noise. Unless stated otherwise, we also assume that $P = 100$, $\sigma_{\text{ADC}}^2 = 1$, and $\zeta = 0.6$ [14]. Also, in all figures, the value of ρ is optimally selected. Moreover, the path loss factor is given by the bounded model [10], [11], i.e., $l = (1 + d^a)^{-1}$, where $a = 2$ is the path loss exponent.

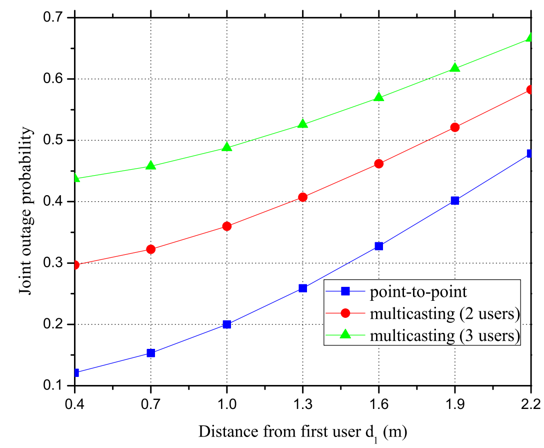

Fig. 3. Outage probability versus distance d_1.

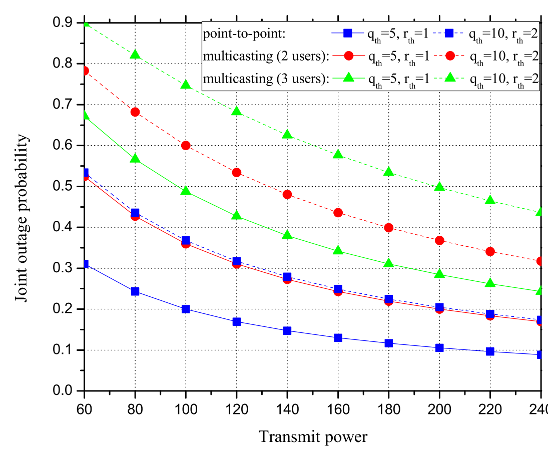

Fig. 4. Outage probability versus transmit power.

In Fig. 3, a point-to-point system, a multicasting system of 2 users, and a multicasting system of 3 users are simulated. The harvested energy threshold is $q_{\text{th}} = 5$ and the rate threshold is $r_{\text{th}} = 1$ bits/channel use. The joint harvested energy-rate outage probabilities of the three systems are compared, when the distance of one of the users increases. As it can be observed, as the users increase, the performance drops, but in long distances the number of users has limited effect on the performance.

In Fig. 4, the performance of the same systems is plotted versus the transmit power, for two different pairs of harvested energy and rate thresholds. The distance for all users is considered $d = 1$m. It is obvious that when the transmit power increases or the thresholds decrease, the joint outage probability decreases. However, as expected, the increase of performance saturates with the increase of transmit power.

In Fig. 5 and 6, the effect of both harvested energy and rate threshold on the joint outage probability and the optimal selection of ρ is illustrated, for $P = 100$ and $d = 1$ m. As the thresholds increase, both the joint outage probability and the optimal value of the PS factor increase. Also, it is observed that $\rho^* \in [0, 1]$ spans in a large range of values, for different thresholds. This is a quite interesting observation

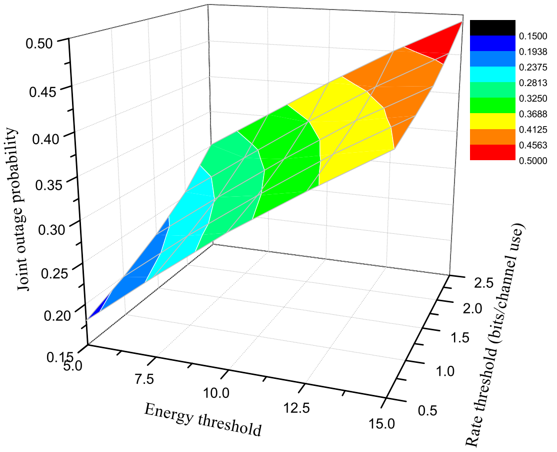

Fig. 5. Outage probability versus energy and rate thresholds in a point-to-point system.

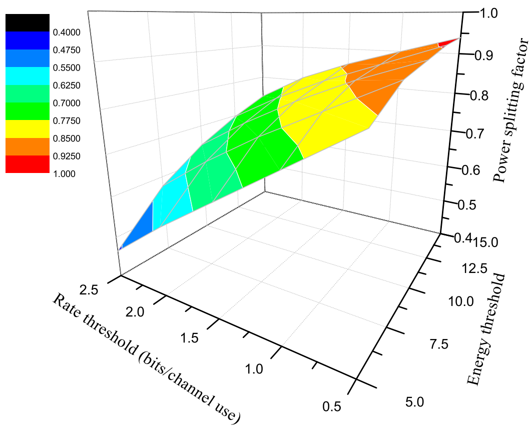

Fig. 6. Optimal PS factor versus energy and rate thresholds in a point-to-point system.

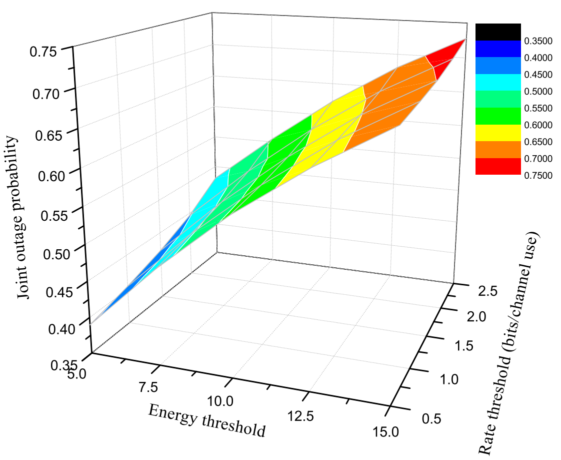

Fig. 7. Outage probability versus energy and rate thresholds in a multicasting system.

and highlights the importance of the ADC noise, since when ignoring this, $\rho^* \to 1$. Similar observation can be made for the multicasting system, the performance of which is illustrated in Fig. (7), for 2 users and $d_n = 1, n \in \{1, 2\}$.

VI. Conclusions

The performance of the integrated energy and information receiver has been investigated, providing a tractable expression for the achievable rate. The trade-off between the harvested energy and the rate has been explored, when PS is used. To balance this trade-off in a point-to-point and a multicasting system, we have defined and minimized the joint harvested energy-rate outage probability. Also, the ADC noise has been considered, which has an important impact on the optimal selection of the PS factor. The proposed theoretical framework facilitates the investigation of performance of the integrated receiver and opens the road for future research on this topic.

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