On Outage Minimization in SWIPT Based Two-way Communications

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***Abstract*—The aim of this paper is to minimize the outage probability of the system to enhance the reliability of the communication between two devices via an energy constrained cooperative relay nodes. The relay node is able to harvest energy from the information bearing radio frequency (RF) signal applying hybrid power-time switching (HPTS) scheme of simultaneous wireless information and power transfer (SWIPT) principle. The devices are enabled through existing battery back-up and they also harvest energy from the energy transmission from the nearest power transmitters. The dual natures of co-channel interference is also considered at relay node. First, we derive the outage expression and then optimize both the power allocation factor and time allocation factor to obtain the minimum value of outage probability. Gradient descent algorithm is also applied to validate the obtained result of the minimum value of outage probability. The results are presented in terms of various parameters like interference-to-noise ratio, distance, transmit power etc.**

***Index Terms*—Energy harvesting, co-channel interference, outage probability, device-to-device communication.**

I. Introduction

Over the last decade, the important issue for the research on 5G or upcoming 6G wireless communication [1], [2] is spectrum efficient and energy efficient self-sustainable operation. Spectrum efficiency along with the area of coverage [3] and robustness is possible to enhance many folds for a wireless network applying cooperative communication technique using relaying approach. Relaying technique [4] is realizable using amplify-and-forward (AF) or decode-and-forward (DF) [5] to fulfill the demand of either power consumption minimization or the error minimization, respectively.

However, the relay nodes are connected with multiple devices or transmitters to grow-up the area of coverage along with spectrum efficiency [6]. Therefore, the interference may affect the transmission from or reception at relay node. The effect of interference is responsible for the deterioration of signal-to-interference and noise ratio (SINR) of the system and corresponding achievable rate of the system [7]. Poor achievable rate is failed to fulfil the target rate of the recent trend of wireless communication. Thus, it is the primary requirement of a transmitter of communication system to send the signal with sufficiently high transmit power. Since, the power back-up of the various small transmitters and relay nodes are limited, therefore, all those transmitting nodes require additional power back-up. However, due to limited energy back-up resources, it is not possible to obtain the stable power supply at small transmitting nodes from additional energy sources and the alternate solution of this problem can be eliminated applying energy harvesting (EH) techniques [8], [9]. Although, EH from environment dependent sources like, solar, vibration etc are not always stable energy supply and therefore, EH from radio frequency (RF) signal is an alternate way to provide sustainable stable energy supply. Typically, EH from RF signal from power transmitter is accomplished using wireless energy transfer (WET) mechanism following simultaneous wireless information and power transfer (SWIPT) protocol [10], [11]. The typical value of harvesting energy from RF signal is varied between some μW level and it is sufficient for small packet transmission in Internet-of-Things (IoT) communication [12]. SWIPT is possible to realize using power splitting (PS) and time switching (TS) protocol for various wireless applications (e.g. V2V, health support system applications etc).

In recent studies on SWIPT based wireless communication was highlighted in [4], [5], [13], [14]. TS-based relaying approach was introduced in [5] to analyze throughput performance of one-way communication. In [13], RF-EH aided two-way communications between two nodes by applying DF relay was considered to show the end-to-end reliability performance in terms of outage probability is derived and numerical results are presented. Both AF and DF relaying performances was compared for PS protocol in [4]. The dual effects of interference both in terms of good and adverse on system outage performances was illustrated in [14] and PS relaying (PSR) was found as better compared to TS relaying (TSR). However, the combined effect of both PS and TS based EH is more useful than individual effect of PS and TS and the integrated form of these protocols is known as hybrid power time switching (HPTS) protocol [13]. The relaying approach using HPTS protocol was recently reported for healthcare application in [15] and optimization problem on energy efficiency was investigated. Moreover, the previous works on EH were done either considering PS or, TS protocol along with co-channel interference (CCI) or considering HPTS protocol without considering CCI. In addition to that, optimization problem was not also formulated in [14] to improve system outage performance in presence of CCI.

Motivated by all the above issues, in this work, we propose a HPTS-based two-communications system model where two devices can communicate with each other via EH relay (EHR). EHR can harvest energy based on the received from two devices and CCI. The novel contributions of the work are listed below:

- We adopt the system model where all the nodes are harvesting energy from RF signal and also formulate an optimization problem to minimize outage probability by controlling both both PS and TS factor.
- Previous work in [14] considered the EH only at relay node. However, in case of this work, we consider EH not only at relay node but also for frequent energy transmission from transmitters, we consider EH also at small transmitters from nearest power transmitters. However, EH based on HPTSR protocol is followed only at relay node.
- Furthermore, analytical results are presented with respect to various parameters like, distance between two devices, power transmission from the devices, interference-to-noise ratio (INR).

II. System Model and Signal Model

A. System model

The system model considered for this work, is given in Figure 1. It consists of cooperative DF relaying system, two-way and half-duplex system, where 2 devices, i.e, device$_1$ and device$_2$; communicate through a energy constrained relay node and relay node is able to harvest steady energy from RF signal to serve sustainable communication between two devices. However, the devices are enabled through the sufficient existing battery back-up and they can also harvest energy from the power transmission from power beacon or power transmitter. Total time frame is split into four distinguished slots. over the first slot duration τT (τ is TS factor), devices harvest energy from power transmitter; the second (τT) and third (τT) slot duration signals are transmitted from devices to the EHR node. It is assumed that the devices and EHR are associated with single antenna for their necessary communication. Furthermore, it is assumed that the channel between device$_k$ and EHR experience Rayleigh fading. The channel conditions are considered to be fixed over the transmission time interval. More practical and relevant effect of CCI is considered at EHR. Channel gains between device$_k$ $\rightarrow$ EHR and EHR $\rightarrow$ device$_k$ ($k \in 1,2$) are defined as h_k and g_k, respectively. The link coefficient between interferer and EHR is considered as β. EHR is considered to be placed at the middle between two devices.

B. Signal Modelling

The received message at EHR from device$_k$ is expressed as

$$y_k = \frac{\sqrt{\alpha(P_t+P_e)}hs_k}{\sqrt{d_k^{\nu}}} + \frac{\sqrt{\alpha p}\beta s_I}{\sqrt{d_I^{\nu}}} + n_r, \ (k \in 1,2), \tag{1}$$

where α is used to indicate the PS factor. P_t and P_e are the transmission power from device$_k$ and the harvested power at devices$_k$ from power transmitter, respectively. p is the transmission power of device$_k$. s_k and s_I are the signal from the device$_k$ and interferer, respectively. d_k and d_I are the distance between the device$_k$-EHR and interferer-EHR, respectively. n_r is the additive white gaussian noise (AWGN).

The received data rate at EHR from device$_k$ is

$$R_k = \tau \log_2\left(1 + \frac{\alpha(P_t+P_e) \mid h_k \mid^2}{d_k^{\nu}\big(\sigma^2 + \alpha p \frac{|\beta|^2}{d_I^{\nu}}\big)}\right), \ (k \in 1,2). \tag{2}$$

EHR can harvest from the received power from device$_k$ and interferer. Energy harvested at EHR through transmissions in the considered slots is written as

$$E_{k,r} = \eta(1-\alpha)\left(\frac{(P_t+P_e) \mid h_k \mid^2}{d_k^{\nu}} + \frac{p \mid \beta \mid^2}{d_I^{\nu}}\right)\tau T, \quad (k \in 1,2), \tag{3}$$

where η is the energy conversion efficiency, $0 < \eta \leq 1$.

In third slot, the received signal at device$_k$ from EHR is expressed as

$$y_{r,k} = \frac{\sqrt{P_r}g_k(s_1 \bigoplus s_2)}{\sqrt{d_k^{\nu}}} + n_k, \ (k \in 1,2), \tag{4}$$

where mean harvesting power P_r is the broadcasting power of the EHR during interval $(1-3\tau)T$ and it can be expressed as

$$\begin{aligned} P_r =& \frac{\sum_{k=1}^{2} E_{k,r}}{(1-3\tau)T} \\ =& \frac{\eta(1-\alpha)}{1-3\tau}\Bigg[(P_t+P_e)\bigg(\frac{\mid \sigma_{h_1} \mid^2}{d_1^{\nu}} + \frac{\mid \sigma_{h_2} \mid^2}{d_2^{\nu}}\bigg) \\ & + 2\frac{p \mid \sigma_{\beta} \mid^2}{d_I^{\nu}}\Bigg]\tau, \end{aligned} \tag{5}$$

where $\mid \sigma_{h_k} \mid^2$ and $\mid \sigma_{\beta} \mid^2$ are the statistical mean of channel h_k and channel β, respectively.

The received data rate at device$_k$ from EHR is written as

$$R_{r,k} = (1-3\tau)\log_2\left(1 + \frac{P_r \mid g_k \mid^2}{d_k^{\nu}\sigma^2}\right), \ (k \in 1,2). \tag{6}$$

III. Infinite Block Length Analysis: Outage Probability Analysis

As we consider SWIPT-enabled NC-based two-way EHR based transmission network over 4 different

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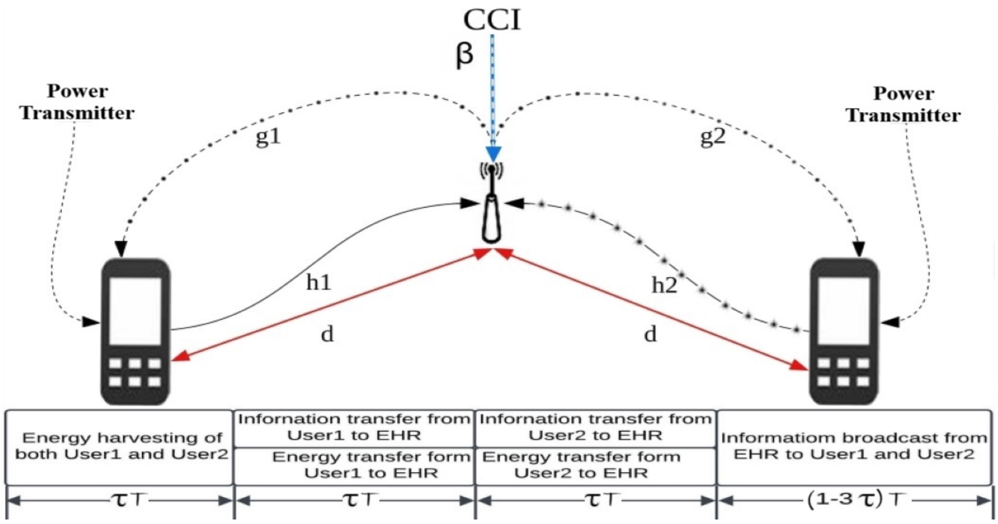

Fig. 1: System Model and time frame structure

transmission links, i.e, $device_1 \rightarrow$EHR, $device_2 \rightarrow$EHR and broadcast links of EHR, therefore, system outage probability depends on the failure of any one of the these links. Hence, the outage probability can be defined as

$$P_{out} = 1 - (1 - P_{out_{D_1,R}})(1 - P_{out_{D_2,R}})(1 - P_{out_{BC}}). \tag{7}$$

Based on (2), the outage probability between $User_k$ to EHR can be expressed as

$$\begin{aligned} P_{out_{D_k,R}} &= 1 - Pr[R_k \geq R_t] \qquad (8)\\ &= 1 - \exp\left[- \frac{(2^{\frac{R_t}{\tau}} - 1) d_k^{\nu} \sigma^2 \Big(1 + \frac{\alpha p \sigma_\beta^2}{\sigma^2 d_I^{\nu}}\Big)}{\alpha (P_t + P_e)} \right], (k \in 1, 2), \end{aligned}$$

where R_t is the target rate of information transmission.

Now, the outage probability between EHR to $User_k$ is written as

$$\begin{aligned} P_{out_{BC}} &= 1 - Pr[R_{BC} \geq R_t] \qquad (9)\\ &= 1 - Pr[R_{r,1} \geq R_t] \times Pr[R_{r,2} \geq R_t]. \end{aligned}$$

Now $Pr[R_{r,k} \geq R_t]$ is given as

$$Pr\left[R_{r,k} \geq R_t\right] = \exp\left[- \frac{(2^{\frac{R_t}{1-3\tau}} - 1) d_k^{\nu} \sigma^2}{P_r} \right]. \tag{10}$$

Finally the system outage probability is expressed as

$$\begin{aligned} P_{out} = 1 - \exp\Bigg[&- \frac{(2^{\frac{R_t}{\tau}} - 1)(d_1^{\nu} + d_2^{\nu}) \sigma^2 \Big(1 + \frac{\alpha p \sigma_\beta^2}{\sigma^2 d_I^{\nu}}\Big)}{\alpha (P_t + P_e)} \qquad (11)\\ &- \frac{(2^{\frac{R_t}{1-3\tau}} - 1)(d_1^{\nu} + d_2^{\nu}) \sigma^2}{P_r} \Bigg]. \end{aligned}$$

IV. Optimization Problem

The objective is to minimize the derived outage probability found in (11) of the proposed system considering the following constraints : i) harvesting energy at $device_k$ from power transmitter is greater than P_{max} ($P_e \geq P_{max}$), ii) PS factor is non-negative real valued ($0 \leq \alpha \leq 1$) and iii) TS factor is non-negative real valued ($0 \leq \tau \leq 1$), iv) The achievable rate should be greater than certain target rate threshold (R_t).

$$\begin{aligned} \underset{\tau, \alpha}{\text{minimize}} \quad & P_{out}\\ \text{subject to} \quad & P_e \geq P_{max},\\ & 0 \leq \alpha, \tau \leq 1,\\ & \mathcal{P}_{out}^{IoD,Sec} \leq \mathcal{P}_{th,Sec},\\ & R_i \geq R_t, \end{aligned}$$

where $R_i \in R_k, R_{r,k}$.

It is sufficient to minimize the argument of exponential function of (11) to minimize P_{out}. Based on $\frac{dP_{out}}{d\alpha} = 0$, we can compute the optimal value of α^* to determine the minimum value of P_{out}.

The closed form expression of α^* can be expressed as follows.

$$\alpha^* = \frac{1}{1 + \sqrt{\frac{\left(2^{\frac{R_t}{1-3\tau}} - 1\right)\left(\frac{1}{\tau} - 3\right)}{\left(2^{\frac{R_t}{\tau}} - 1\right) \eta E_k (P_t + P_e)}}}, \tag{12}$$

where $E_k = (P_t + P_e)\Big(\frac{|\sigma_{h_1}|^2}{d_1^{\nu}} + \frac{|\sigma_{h_2}|^2}{d_2^{\nu}}\Big) + 2\frac{p|\sigma_\beta|^2}{d_I^{\nu}}$, is the total harvesting energy at EHR.

On the other hand, $\frac{dP_{out}}{d\tau}$ is found in (13) (at the top of the next page). Due to highly non-linear nature of $\frac{dP_{out}}{d\tau}$, it is not possible to find the exact solution of τ. Therefore gradient descent method is applied using machine learning approach to find the specific value τ^*.

V. Numerical Results

In this section, we present the results to validate our analytical results in the last section. The results for the variation in outage probability for the variations

$$\frac{dP_{out}}{d\tau} = -\frac{\left(\frac{R_t \times 2^{\frac{R_t}{\tau}} \log_e 2}{\tau^2}\right)(d_1^\nu + d_2^\nu)\sigma^2\left(1 + \frac{\alpha p \sigma_\beta^2}{\sigma^2 d_I^\nu}\right)}{\alpha(P_t + P_e)} + \left[\frac{(d_1^\nu + d_2^\nu)\sigma^2}{(1-\alpha)\eta\left[(P_t + P_e)\left(\frac{|\sigma_{h_1}|^2}{d_1^\nu} + \frac{|\sigma_{h_2}|^2}{d_2^\nu}\right) + 2\frac{p|\sigma_\beta|^2}{d_I^\nu}\right]} \times \left\{\frac{\{(-3R_t \times \log_e 2)2^{\frac{R_t}{1-3\tau}}\}}{\tau(1-3\tau)} - \frac{2^{\frac{R_t}{1-3\tau}} - 1}{\tau^2}\right\}\right]. \tag{13}$$

TABLE I: Parameter Settings

Parameter	Value
η	0.8
ν	2.7
R_t	1 bps/Hz
τ	$0 - 0.33$
$d_1 + d_2 = 2d$, d_I	14 m, 2 m
σ^2	10 μW
P_t	3 Watt

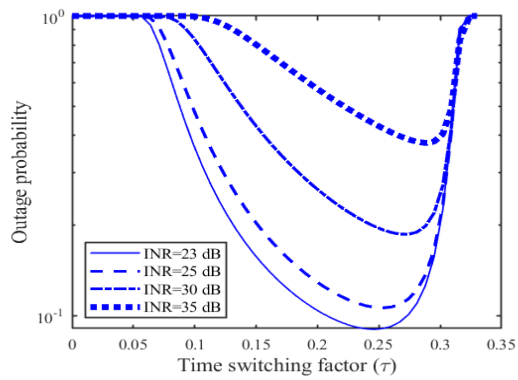

Fig. 2: Outage probability vs τ considering diffent INR.

in system parameters: (i) PS factor and (ii) Distance are also illustrated. The mean value of $|\ \sigma_{h_1}\ |^2$ and $|\ \sigma_{h_2}\ |^2$ are considered to be same as 1 and the mean value of $|\ \sigma_\beta\ |^2$ is considered to be 0.16.

Fig. 2 shows the variation of outage probability versus the TS factor (τ) in HPTSR based SWIPT operation for different scales of INR level. At smaller values of τ the time allocation for information transfer in lesser than time allocation for EH. This results in insufficient slot duration leading to poor achievable rate and thus, it is more likely to fail to achieve the target rate of data transmission. This results in high outage of links from User$_k$ to EHR, as shown in the Figure. With the increase in τ value, the system outage probability decreases due to SNR improvement of the links from User$_k$ ($k \in 1, 2$) to EHR. However, when τ value exceeds the minimum value, then, due to inadequate broadcast time slot leads to gradual increment of the system outage probability with the increasing value of τ. The performance is observed as worst for INR 23 dB.

Fig. 3 illustrates the change of outage variation for

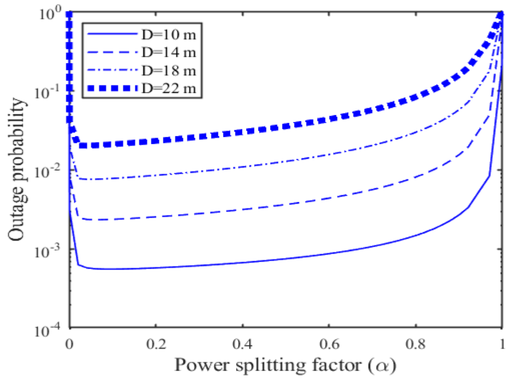

Fig. 3: Outage probability vs α for fixed value of τ considering different distances between two devices.

different values of α for specific optimum value of $\tau = 0.236$, which is found applying gradient descent algorithm and validated through machine learning algorithm. The outage of the system first improves with the increasing value of α (at lower value) and then it deteriorates with increasing value of α and at lowest/highest value of α the outage performance is found to be poor as 1. This may be demonstrated as follows. As α increases, more power is split for data transmission from devices and less power is allocated for EH. This results insufficient harvesting energy which leads to failure of the relay broadcasting rate to meet the target rate for data transfer. The harvesting energy at EHR for α_{opt} is found to be sufficient.

Fig. 4 shows the variation of outage probability with respect to both TS factor (τ) and PS factor (α). The characteristics of the plot can be explained by considering with respect to one of the factors and taking other as constant. The system outage probability is very high when at higher values of τ considering α constant. Similarly the outage probability is high for higher values of α considering τ as constant.

Fig. 5 depicts the different variations of outage probability with respect to total power ($P_t + P_{max}$). As the outage variation is inversely proportional to transmit power, therefore, the outage performance is improved with the increasing power. The performance is observed as relatively 50% better at 17 dB INR compared to 25 dB INR.

VI. Conclusion

This paper considered the impact of CCI and HPTSR based EH on the outage performance of two-

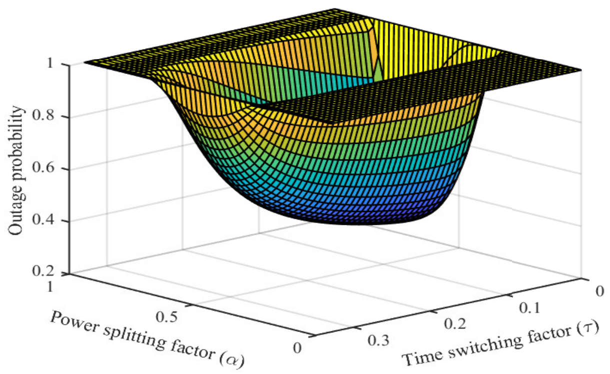

Fig. 4: Outage probability vs α vs τ.

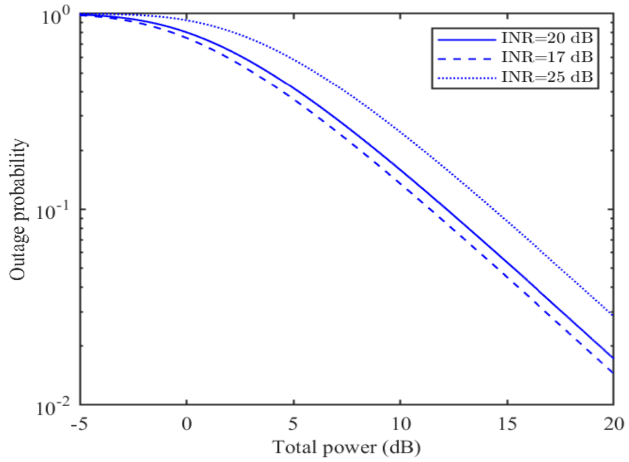

Fig. 5: Outage probability vs total power for INR is considered as 17, 20 and 25 dB.

way communication. The optimization problem was introduced to obtain the minimum value of outage probability with respect to both PS and TS factors. Based on the different distances, the performance results were also shown through the perspective of PS factor of HPTSR protocol based on optimum value of TS factor. It was observed that the performance is found to be less for relatively lower value of INR. The work is possible to extend for multi-user communications via multiple relays using different EH protocols and multiple access techniques in existence of multiple CCI.

TABLE II: The optimal harvesting slot τ^* and α^* to obtain the minimum value of outage probability based on gradient descent algorithm.

α^*	τ^*
0.1	0.23

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