PERFORMANCE ANALYSIS OF GENERAL HYBRID TSR-PSR ENERGY HARVESTING PROTOCOL FOR AMPLIFY-AND-FORWARD HALF-DUPLEX RELAYING NETWORKS

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Abstract. *In this paper, we propose a hybrid protocol for energy harvesting in wireless relay networks, which combines the benefits of both time-switching relaying (TSR) and power-splitting relaying (PSR), which are two main protocols for energy harvesting. In TSR, a dedicated harvesting time in each time slot is allocated for energy harvesting, while the remaining time is used for information transmission. In PSR, a portion of received power is split for energy harvesting. TSR can simplify the hardware compared to PSR, but reduce the throughput or achievable rate of the system. Specifically, we conduct a rigorous analysis to derive the closed-form formulas for performance factors of the system. We deliver the analysis results for various transmission modes: instantaneous transmission, delay-limited transmission, and delay-tolerant transmission, which are different from each other on the availability of statistical information about the channels between source and relay nodes. The results are also confirmed by Monte Carlo simulation.*

Keywords

Energy harvesting, time-switching relaying, power-splitting relaying, half-duplex, ergodic capacity.

1. Introduction

Energy harvesting, which alludes for wireless energy collection from the source devices to the relay nodes without requirements of battery charging or replacement, has been broadly anticipated to be an essential cornerstone to enhance system performance and bolster new amenities beyond 2020 in future 5G systems. Simultaneous wireless information and power transfer (SWIPT) has attracted a lot of research in wireless communication field recently [1], [2]. This is developed as a promising technique, especially for wireless relay networks, in which the source not only transfers the information to the relay nodes, but also supplies its energy to relay nodes so that the relays can forward the information to the destination in the next phase. SWIPT can solve the energy problem at the relay, which is the main obstacle for relay networks to be implemented in practice. Consequently, it can lead to significant gains in terms of spectral efficiency, time delay, energy consumption, and interference management by superposing information and power transfer [3].

The concept of SWIPT was originally proposed in [1]. Later, two practical architectures for energy harvesting in relay networks, namely time-switching (TSR) and power-splitting (PSR) protocols, have been introduced in [2]. In the PSR protocol, the relay splits the received signal from the source into two streams for energy harvesting as well as for information detection, and it processes these two signals simultaneously [4]. In the TSR protocol, a dedicated harvesting time in each time slot is allocated for energy harvesting, while the remaining time slot is used for information transmission. Since the work of Zhang and Ho [2], there have been many works focusing on the performance of these two methods separately. Nasir et al. [5], [6] have analyzed the effect of different system parameters on the throughput performance of amplify-and-forward (AF) and decode-and-forward (DF) relaying systems for both TSR and PSR protocols. In [7], the performance of TSR protocol in full-duplex relaying network is considered in the condition that the channel state information at the relay is not perfect. The effect of hardware impairment on the performance of TSR protocol for half-duplex relaying networks was introduced in [8] for decode-and-forward strategy as well as in [9] for amplify-and-forward strategy. Other reports on the applications of SWIPT in wireless networks such as physical layer security, cognitive networks can be found in [10] and [11].

As mentioned before, all these works above consider each energy harvesting protocol separately. From the analysis, it is explained that PSR requires a complicated hardware structure to make sure that a proper portion of energy from source signal is extracted for energy harvesting. In contrast, TSR can simplify the hardware at the expense of the throughput or achievable rate of the system. Because both TSR and PSR protocols have their own drawbacks, a natural idea is to combine these two protocols to get the best out of them. This idea has been introduced in [12], in which the authors derived the outage probability for decode-and-forward relay networks in the presence of interference. However, the authors only limited their analysis at the delay-sensitive transmission mode only. In addition, the analysis for amplify-and-forward relaying strategy has not been mentioned in [12]. In fact, the analysis for amplify-and-forward is more complicated because the parameters for the first transmission hop is fully integrated to the received signal at the destination. That makes the derivation of the closed-form formula for outage probability a more difficult task.

Our motivation for this paper is to extend significantly the work in [12], due to the potential that the combination of two protocols mentioned above could provide better performance for energy-harvesting-based relay networks. In this paper, we represent the latest analysis on the performance of hybrid TSR-PSR protocol for amplify-and-forward half-duplex relaying networks. The paper also extends the analysis to both transmission modes: delay-limited (or delay-sensitive) transmission mode and delay-tolerant transmission mode. These transmission modes were introduced in [13] for the purpose of performance analysis of energy-harvesting-based relay networks. Our contributions in this paper can be summarized below:

- Provide the rigorous analysis on the performance of hybrid TSR-PSR energy harvesting protocol for amplify-and-forward relay networks, in terms of the closed-form expressions for outage probability and the throughput of the system in delay-limited transmission mode;
- Provide the analysis of the same model for delay-tolerant transmission mode to find the formula of the ergodic capacity of the system of interest;
- Conduct Monte Carlo simulation to verify the analysis results, to compare the performance of TSR, PSR, and the hybrid TSR-PSR methods, and to figure out the optimal time-switching and power-splitting factors.

The remaining of this paper is organized as follows. In Section 2, the system model of wireless relay networks of interest is described in details. Then in Section 3, we provide the rigorous performance analysis of the system for both delay-limited and delay-tolerant transmission modes. The outcomes of our analysis are closed-form formulas of outage probability and average throughput of the system for delay-limited mode and the ergodic capacity for the delay-tolerant mode. Numerical results to support our analysis are presented in Section 4. Finally, Section 5 concludes the paper.

2. System Model

The half-duplex relaying network of interest is illustrated in Fig. 1, where the source S sends information to the destination D with the help of a relay R. For relaying strategy, this network employs the amplify-and-forward protocol at the relay node. The direct connection between source and destination is presumably weak, so the only available link is via the relay node. The relay is assumed to have no own transmission data and no other energy supply, so that it needs to harvest energy from the source.

Here, the hybrid TSR-PSR energy harvesting protocol [12] for separating between information transmission and energy harvesting processes is employed at relay node, as illustrated in Fig. 2. The entire symbol slot is denoted by T, which is divided into three intervals. The first portion of time βT is used for energy harvesting from the source power P_S. In the second interval, whose length is αT, the source signal is divided into two streams. During this interval, a fraction of the power ρP_S is used for energy harvesting from the source signal by the relay node, and the other fraction $(1-\rho)P_S$ is used for decoding the information signal sent from the source. The remaining interval of the length $T - \alpha T - \beta T$ is used for information forwarding from the relay to the destination node. Obviously, $0 \leq \alpha \leq 1$ and $0 \leq \beta \leq 1$. If $\alpha = 0$, this scheme becomes PSR. If $\beta = \frac{1-\alpha}{2}$ and $\rho = 0$ then it becomes the TSR protocol.

We assume that the channel state information can be obtained perfectly. The channels from the source to the relay and from the relay to the destination are denoted as h and g, respectively. All channels are assumed as Rayleigh fading channels, which keep constant during each transmission block (slow fading). As a result, $|h|^2$ is an exponential random variable with parameter λ_h, and $|g|^2$ is also exponentially distributed with parameter λ_g.

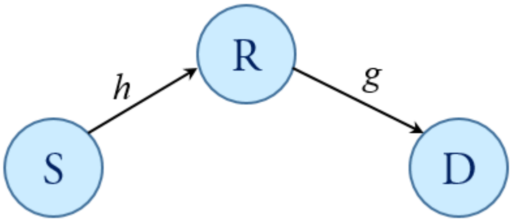

Fig. 1: System Model.

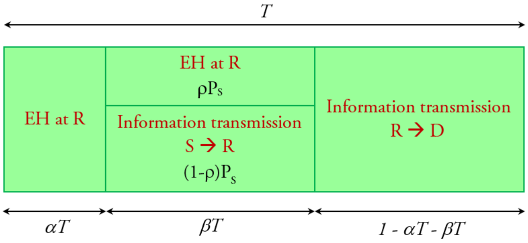

Fig. 2: General hybrid TSR-PSR relaying protocol.

2.1. Energy Harvesting Phase

During the energy harvesting phase, the received signal at the relay node can be expressed as

$$y_e = h x_e + n_r \tag{1}$$

where x_e is the energy-transmitted signal with $E[|x_e|^2] = P_s$ (where $E[\cdot]$ denotes the expectation operation) and n_r is the zero-mean additive white Gaussian noise (AWGN) with variance N_0. The energy harvested at the relay node is the combination of two components: the first one is the received energy during the first interval as in Fig. 2, i.e. from TSR protocol, while the second one comes from the PSR interval:

$$E_h = \eta P_s |h|^2 \alpha T + \eta \rho P_s |h|^2 \beta T \tag{2}$$

where η is a constant and denotes the energy conversion efficiency.

The relay will use this energy to transmit information signal to the destination during the next phase, so the relay transmitted power in that phase can be calculated as

$$\begin{aligned} P_R &= \tfrac{E_h}{T-\alpha T-\beta T} = \tfrac{\eta P_s |h|^2(\alpha+\rho\beta)}{1-\alpha-\beta} \\ &= \kappa P_s |h|^2 \end{aligned} \tag{3}$$

where $\kappa \triangleq \frac{\eta(\alpha+\beta\rho)}{1-\alpha-\beta}$. Note that $0<\alpha+\beta<1$, to make sure that the communication is valid.

2.2. Information Transmission Phase

The information transmission phase lasts $(1-\beta)T$ and is divided into two equal-length subintervals. In the first interval, the relay receives the message signal from the source, which is given by

$$y_r = hx_s + n_r \tag{4}$$

where x_s is the transmitted signal, which satisfies $E[|x_s|^2 = (1-\rho)P_S$ and n_r is the AWGN noise at relay node as in (1). In our model, amplify-and-forward protocol is used, hence, the received signal at relay is amplified by a factor ξ, and then forwarded to the destination during the second interval. The amplification factor ξ is given by

$$\xi = \frac{x_r}{y_r} = \frac{\sqrt{P_R}}{\sqrt{(1-\rho)P_s|h|^2 + N_0}} \tag{5}$$

The received signal at the destination during the second interval of information transmission phase is expressed as

$$\begin{aligned} y_d &= gx_r + n_d = g\xi y_r + n_d \\ &= g\xi[hx_s + n_r] + n_d \\ &= \underbrace{g\xi h x_s}_{signal} + \underbrace{g\xi n_r + n_d}_{noise} \end{aligned} \tag{6}$$

It is assumed that the link between source and destination is very weak, so the communication in this interval relies mostly on the forwarded signal from the relay. In (6), n_d is the noise at the destination, which is assumed to have the same power as n_r. Then the end-to-end signal-to-noise-ratio at the destination node can be written as

$$SNR = \frac{E\{|signal|^2\}}{E\{|noise|^2\}} = \frac{(1-\rho)|g|^2\xi^2|h|^2 P_s}{|g|^2\xi^2 N_0 + N_0} \tag{7}$$

By substituting (3) and (5) into (7), we obtain

$$SNR = \frac{(1-\rho)|h|^2|g|^2 P_s}{|g|^2 N_0 + \frac{N_0^2}{\kappa P_S |h|^2} + \frac{N_0}{\kappa(1-\rho)}} \tag{8}$$

Due to the fact that $P_S >> N_0$, the SNR now can be approximated closely to

$$\begin{aligned} SNR &\approx \tfrac{(1-\rho)|h|^2|g|^2 P_s}{|g|^2 N_0 + \frac{N_0}{\kappa(1-\rho)}} \\ &= \tfrac{(1-\rho)\kappa|h|^2|g|^2 P_s}{\kappa|g|^2 N_0 + N_0(1-\rho)} \end{aligned} \tag{9}$$

3. Performance Analysis

For the purpose of performance analysis, the communication among the source node, the relay node, and the destination node in half-duplex relaying networks can be divided into three communication modes [13]: instantaneous transmission, delay-limited transmission, and delay tolerant transmission. These three communication modes can be distiguished from the others based on the availability of the channel state information (CSI) at the relay (in fact, CSI is always assumed to be known at the destination). For the instantaneous transmission mode, the optimal time split is updated for each channel realization, which should be computed by a centralized entity having access to the global instantaneous CSI. On the other hand, for the delay limited transmission and delay tolerant transmission modes, only the channel statistics are required to compute the optimal time split [13]. For delay-limited transmission, the source transmits at a constant rate, which may subject to outage due to the random fading of the wireless channel. In the delay tolerant (DT) context, the resource transfers at any unchanged rate upper bounded by the ergodic capacity.

In this section, we derive the outage probability and throughput performance of the proposed system for delay-limited transmission mode and the ergodic capacity of the system for delay-tolerant mode. The dependence of average throughput and outage probability as well as the ergodic capacity of the proposed system on the time-switching and power splitting factors is also analyzed and the optimal time and power allocation is found by numerical algorithm.

3.1. Delay-limited Transmissions

For the delay limited transmission and delay tolerant transmission modes, only the channel statistics are required to compute the optimal time split [13]. As mentioned in Section 2. , both channels h and g are assumed as Rayleigh fading channels. Let $X = |h|^2, Y = |g|^2$, then X and Y are two independent exponential random variables with parameters λ_h and λ_g, respectively.

Assume that the source transmits at a constant rate R. Let $\gamma = 2^{2R} - 1$ be the lower threshold for SNR at both relay and destination nodes. That means the outage occurs if SNR falls below this threshold. Then we can claim the following theorem on the outage probability and the average throughput of the system of interest.

Theorem 1. *For the AF half-duplex relaying system with hybrid TSR-PSR energy harvesting protocol, the outage probability and the average throughput of the system can be expressed respectively as*

$$P_{out} = 1 - e^{-\frac{\lambda_h \gamma}{Q(1-\rho)}} \sqrt{\frac{\lambda\gamma}{\kappa Q}} K_1 \left(\sqrt{\frac{\lambda\gamma}{\kappa Q}} \right) \qquad (10)$$

and

$$\tau = \frac{R}{2}(1-\alpha-\beta).e^{-\frac{\lambda_h \gamma}{Q(1-\rho)}} \sqrt{\frac{\lambda\gamma}{\kappa Q}} K_1 \left(\sqrt{\frac{\lambda\gamma}{\kappa Q}} \right) \qquad (11)$$

where $Q = \frac{P_S}{N_0}$, $\lambda = 4\lambda_h\lambda_g$, and $K_n(\cdot)$ is the n^{th} order modified Bessel function of the second kind.

Proof. The equation (9) can be rewritten as

$$SNR = \frac{(1-\rho)\kappa XYP_s}{\kappa YN_0 + N_0(1-\rho)} \qquad (12)$$

The outage occurs when the SNR at the destination node falls below the threshold value. Hence, the outage probability is determined by

$$\begin{aligned} P_{out} &= \Pr(SNR < \gamma) \\ &= \Pr\left\{ \tfrac{(1-\rho)\kappa XYP_s}{\kappa YN_0 + N_0(1-\rho)} < \gamma \right\} \\ &= \Pr\left\{ \kappa Y \left[(1-\rho)XP_s - \gamma N_0 \right] < \gamma N_0(1-\rho) \right\} \\ &= \Pr\left\{ (1-\rho)XP_s - \gamma N_0 > 0, Y < \tfrac{\gamma N_0/\kappa}{XP_s - \frac{\gamma N_0}{1-\rho}} \right\} \\ &+ \Pr\left\{ (1-\rho)XP_s - \gamma N_0 < 0 \right\} \end{aligned} \qquad (13)$$

Denote $f_X(x) \triangleq \lambda_h e^{-\lambda_h x}$ and $f_Y(y) \triangleq \lambda_g e^{-\lambda_g y}$ as the probability density functions of X and Y, respectively. In addition, let $g(x) \triangleq \frac{\gamma N_0}{\kappa(xP_s - \frac{\gamma N_0}{1-\rho})} = \frac{\gamma}{\kappa(xQ - \frac{\gamma}{1-\rho})}$. Then (13) becomes

$$\begin{aligned} P_{out} &= \Pr\left\{ X > \tfrac{\gamma}{Q(1-\rho)}, Y < g(X) \right\} \\ &+ \Pr\left\{ X < \tfrac{\gamma}{Q(1-\rho)} \right\} \\ &= \int_0^{\frac{\gamma}{Q(1-\rho)}} f_X(x)dx + \int_{\frac{\gamma}{Q(1-\rho)}}^{\infty} f_X(x)dx \int_0^{g(X)} f_Y(y)dy \\ &= \int_0^{\frac{\gamma}{Q(1-\rho)}} f_X(x)dx \\ &+ \int_{\frac{\gamma}{Q(1-\rho)}}^{\infty} f_X(x) \left\{ 1 - e^{-\lambda_g g(X)} \right\} dx \\ &= 1 - \int_{\frac{\gamma}{Q(1-\rho)}}^{\infty} \lambda_h e^{-\lambda_h x} e^{-\lambda_g g(X)} dx \end{aligned} \qquad (14)$$

By changing variable $t = (1-\rho)xQ - \gamma$, (14) can be rewritten to

$$P_{out} = 1 - \frac{\lambda_h}{Q} \int_0^{\infty} e^{-\lambda_h \frac{t + \frac{\gamma}{1-\rho}}{Q} - \frac{\lambda_g \gamma}{\kappa t}} dt \qquad (15)$$

Now, we can apply the integral formula (3.324.1) in [14] to get the formula (10). Finally, the average throughput of the system can be found by substituting (9) into the throughput definition formula $\tau \triangleq (1-P_{out})\frac{R}{2}(1-\alpha-\beta)$. ■

3.2. Delay-tolerant Transmission

In this model, the source transfers at any target rate upper bounded by the ergodic capacity. As the codeword length is sufficiently large in comparison with the block length, the codeword could experience all potential knowledge of the channel [13]. Hence, the ergodic capacity is given by the following formula:

$$\begin{aligned} C &= E_{h,g}\left\{\log_2(1+SNR)\right\} \\ &= \int_0^\infty f_{SNR}(\gamma)\log_2(1+\gamma)d\gamma \end{aligned} \tag{16}$$

where $f_{SNR}(\gamma)$ is the probability density function of SNR, which is defined as

$$f_{SNR}(\gamma) \triangleq \frac{\partial F_{SNR}(\gamma)}{\partial\gamma} \tag{17}$$

Here, $F_{SNR}(\gamma)$ is the cumulative distribution function of SNR, which can be found by

$$\begin{aligned} F_{SNR}(\gamma) &= \Pr(SNR<\gamma) \\ &= 1-e^{-\frac{\lambda_h\gamma}{Q(1-\rho)}}\sqrt{\frac{\lambda\gamma}{\kappa Q}}K_1\left(\sqrt{\frac{\lambda\gamma}{\kappa Q}}\right) \end{aligned} \tag{18}$$

Now, we can state the second theorem as follows.

Theorem 2. *The ergodic capacity of AF half-duplex relaying system with hybrid TSR-PSR energy harvesting protocol can be expressed as*

$$\begin{aligned} C = \int_0^\infty \frac{\lambda e^{-\frac{\lambda_h\gamma}{Q(1-\rho)}}}{2\kappa Q}K_0\left(\sqrt{\frac{\lambda\gamma}{\kappa Q}}\right)\log_2(1+\gamma)d\gamma + \\ \int_0^\infty \frac{\lambda_h e^{-\frac{\lambda_h\gamma}{Q(1-\rho)}}}{Q(1-\rho)}\sqrt{\frac{\lambda\gamma}{\kappa Q}}K_1\left(\sqrt{\frac{\lambda\gamma}{\kappa Q}}\right)\log_2(1+\gamma)d\gamma \end{aligned} \tag{19}$$

where $Q=\frac{P_S}{N_0}$, $\lambda=4\lambda_h\lambda_g$, and $K_n(\cdot)$ is the n^{th} order modified Bessel function of the second kind.

Proof. By taking derivative of (18) and using the formula $\frac{\partial K_n(z)}{\partial z}=-K_{n-1}(z)-\frac{n}{z}K_n(z)$, we obtain

$$\begin{aligned} f_{SNR}(\gamma) = \frac{\lambda_h}{Q(1-\rho)}e^{-\frac{\lambda_h\gamma}{Q(1-\rho)}}\sqrt{\frac{\lambda\gamma}{\kappa Q}}K_1\left(\sqrt{\frac{\lambda\gamma}{\kappa Q}}\right) \\ + e^{-\frac{\lambda_h\gamma}{Q(1-\rho)}}\frac{\lambda}{2\kappa Q}K_0\left(\sqrt{\frac{\lambda\gamma}{\kappa Q}}\right) \end{aligned} \tag{20}$$

By substituting (20) into (16), we complete the proof. ■

4. Numerical Analysis

In this section, we conduct Monte Carlo simulation to verify the analysis developed in the previous section. For simplicity, in our simulation model, we assume that the source-relay and relay-destination distances are both normalized to unit value. Other simulation parameters are listed in Table 1.

Table 1. Simulation parameters

Symbol	Name	Values
R	Source rate	1.5 bps/Hz
γ	SNR threshold	7
η	Energy harvesting efficiency	0.6
λ_h	Parameter of $\|h\|^2$	0.5
λ_g	Parameter of $\|g\|^2$	0.5
P_s/N_0	Signal to Noise Ratio	0-30 dB

4.1. Delay-limited transmission

Figure 3 and Figure 4 respectively illustrate the achievable throughput and outage probability of the system versus the ratio P_S/N_0 for three protocols TSR, PSR, and hybrid TSR-PSR. For the hybrid one, α is set to 0.1, β is set to 0.45, and ρ is set to 0.3. From this setting, we set up the parameters for TSR and PSR accordingly to make sure that the information transmission time is equal between 3 methods. The simulation curve and the analytical curve overlap together, which confirms that our analysis is reasonable. As to be expected, the throughput increases and the outage probability decreases when the value of P_S/N_0 increases. It is also observed that the hybrid TSR- PSR can give better performance than both TSR and PSR.

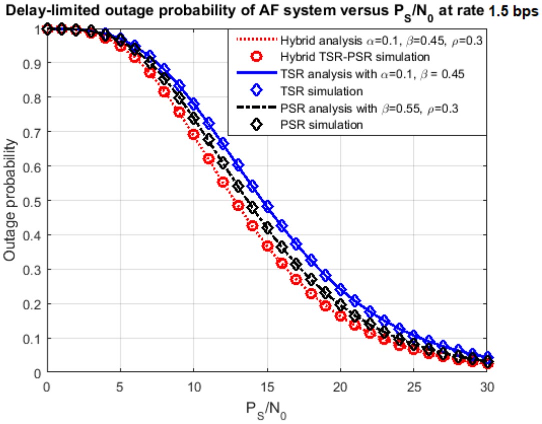

Fig. 3: Outage probability versus P_S/N_0 for 3 protocols.

Figure 5 plots the throughput of PSR and hybrid protocols versus the value of ρ. Note that when $\rho = 0$, the hybrid protocol becomes the TSR protocol. Again, we can see that the hybrid protocol outperforms the PSR one, especially when the P_S/N_0 is small. Each protocol has an optimal ρ to maximize the throughput of the system. This value is in the interval 0.5 to 0.6 for PSR and around 0.4 - 0.5 for the hybrid one.

Similarly, the effect of the factor α on the throughput is illustrated in Fig. 6. The hybrid protocol provides more throughput than TSR protocol at low P_S/N_0 regime. At high P_S/N_0 regime, both methods seem to have similar throughput values.

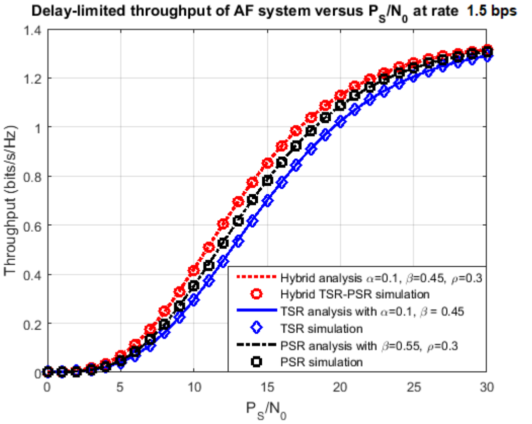

Fig. 4: Throughput versus P_S/N_0 for 3 protocols.

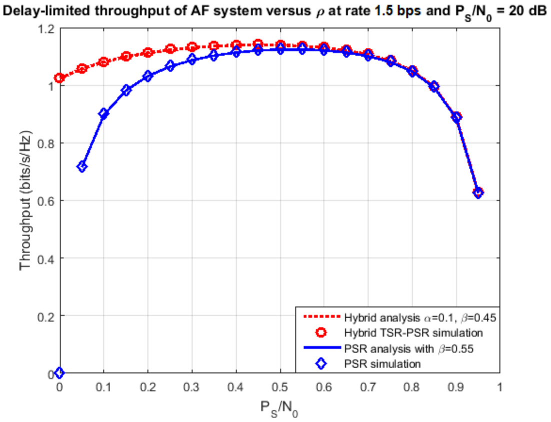

Fig. 5: Throughput versus ρ for hybrid and PSR protocols.

4.2. Delay-tolerant transmission

In this section, we provide the numerical results for delay-tolerant transmission. Figure 7 displays the plot of ergodic capacity curves of three protocols with the same settings as in the previous section. The hybrid TSR-PSR protocol still dominates the other two protocols. The simulation results agree with the mathematical analysis. It is observed that the ergodic capacity is an increasing function with respect to the ratio P_S/N_0.

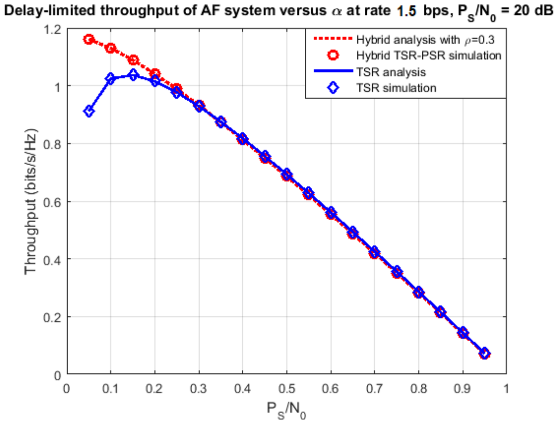

Fig. 6: Throughput versus α for hybrid and TSR protocols.

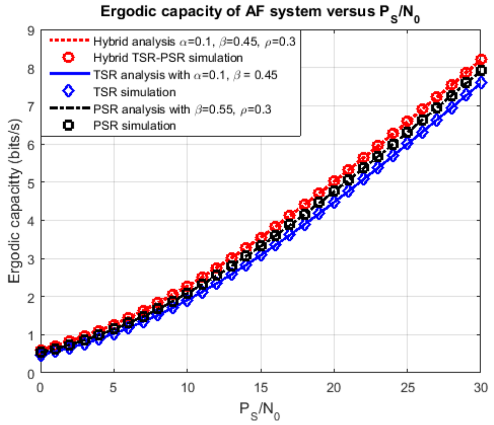

Fig. 7: Ergodic capacity versus P_S/N_0 for 3 protocols.

As introduced previously, the ergodic capacity is an upper bound of the achievable rate of the system, because in this mode, the codeword could experience all potential knowledge of the channel. This concept is confirmed by numerical results in Fig. 8. In this figure, the ergodic capacity for delay-tolerant mode and the throughput for delay-limited mode are compared to each other with various settings of parameters.

Finally, Fig. 9 and Fig. 10 show the effect of parameters ρ and α on the ergodic capacity of the system, respectively. It can be seen in Fig. 9 that there is an optimal value of ρ that maximizes the capacity. Also, the capacity curve tends to shift upward when the value of α increases. In Fig. 10, the capacity is an increasing function with respect to α and the curve is shifting downward when ρ increases.

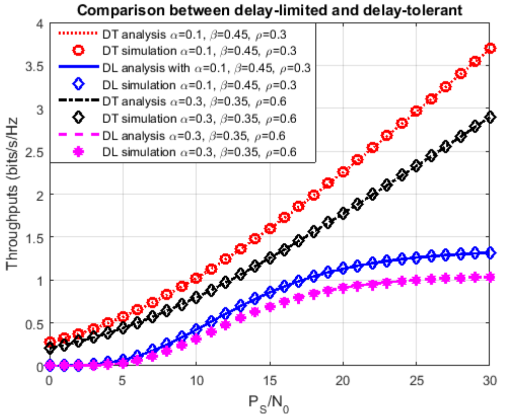

Fig. 8: Comparison of delay-limited and delay-tolerant modes.

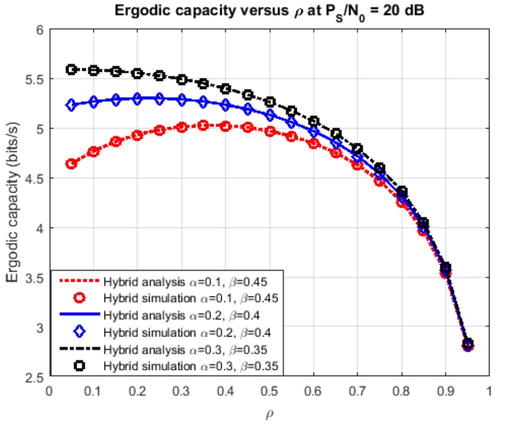

Fig. 9: Ergodic capacity of hybrid TSR-PSR versus ρ.

5. Conclusion

In this paper, we provide a rigorous analysis on the performance of AF half-duplex relaying networks, which employ the general hybrid TSR-PSR energy harvesting protocol at the relay nodes. Different from previous papers that only focused on these harvesting protocols separately, this work combines the advantages of both methods in a so-called hybrid TSR-PSR energy protocol. It is found that with a proper choice of the

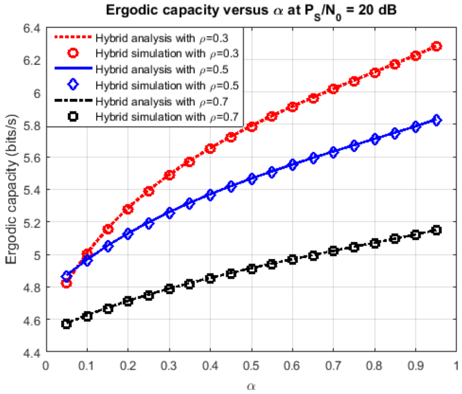

Fig. 10: Ergodic capacity of hybrid TSR-PSR versus α.

power-splitting as well as the time-switching factors, this hybrid protocol can outperform each of the original ones. In particular, the throughput can be improved 1.5 times at low P_s/N_0. The analysis is conducted for both transmission modes: delay-limited and delay-tolerant, which can give an insightful understanding of the improvement that the proposed protocol can provide. All of the analytical results are confirmed by Monte Carlo simulation. The results from this work can open the door to further research on this hybrid protocol in more complicated scenarios, such as different channel distributions or with the presence of hardware impairment.

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