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Static and dynamic power splitting protocol enabled in DF energy harvesting Half-Duplex relaying network: Ergodic capacity analysis

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ABSTRACT

In this research, we propose and examine the DF Energy Harvesting Half-Duplex Relaying Network. For this system model, the DF Energy Harvesting Half-Duplex Relaying Network is analyzed in two cases: Static and Dynamic Power Splitting Protocol. The Ergodic Capacity (EC) is introduced and derived in relation to all the primary system parameters in order to evaluate system performance. The Monte Carlo simulation results demonstrate that the mathematical and simulation are in agreement, thereby confirming the accuracy of the analytical description.

1. INTRODUCTION

In the past decade, Wireless Powered Communication Networks (WPCNs) have become a significant area of interest in the field of radio frequency (RF) energy harvesting (EH). In these networks, components initially gather energy from RF signals transmitted by dedicated energy sources. This harvested energy is then utilized to power communication in the subsequent stage, making WPCNs a promising solution for energy-efficient wireless communication systems (Nasir et al., 2013; Niyato et al., 2017). WPCNs enable perpetual communication, providing a higher throughput network, a longer lifetime, and flexibility than a battery-powered network (Bi et al., 2015). However, wireless power transfer could potentially increase the risk of eavesdropping, as a power receiver is usually closer to the source than an information receiver, making it easier to intercept. Chen et al. (2016) considered a variety of effective physical security techniques, which can substantially boost the effectiveness of simultaneous wireless information and power transfer (SWIPT), and massive Multiple Input Multiple Output (MIMO) methods have been proposed to enhance SWIPT. Atallah et al. (2016) examined the feasibility of EH in vehicular networks and the challenges that must be addressed to make it viable in a vehicular environment. Wang et al. (2014) examined a protocol for wireless EH and information forwarding within cognitive radio (CR) relay networks, employing a secondary network to scavenge energy from surrounding signals of the primary network while simultaneously helping the secondary transmission by sharing the spectrum. Energy harvesting applies to new devices in wireless sensor networks (WSNs) to collect data from the environment and infrastructure where devices have limited energy (Lakshmi et al., 2018). Nguyen et al. (2016) demonstrated that an amplify-and-forward (AF) relay network utilizing SWIPT with time-switching relaying was evaluated under imperfect channel state information (CSI) conditions. Gu and Aissa (2015) studied the system performance of the multi-hop cooperative relaying transmission and wireless MIMO systems to optimize the efficiency of simultaneous information and energy transmission (Zhou et al., 2014). The EH K-hop relay network (That et al., 2023) relays collect energy from a power beacon and utilize the NOMA scheme to increase system throughput. Furthermore, the performance of the CR network is considered in Liu et al. (2013), Biglieri et al. (1998), Abd El-Malek et al. (2016), and the system performance of the two-way relay network is proposed in Duy et al. (2016). In Agrawal et al. (2022), time-switching (TS) and power-splitting (PS) within a two-hop cooperative network that included a battery-assisted EH relay were investigated with selective DF significantly enhancing the throughput. Omidkar et al. (2022) introduced the energy efficiency (EE) optimization algorithm for D2D and IoT equipment, through frequency allocation and the use of harvested energy, which improved system performance with the proposed algorithm. The BER performance of a DF relay-assisted cooperative non-orthogonal multiple access (CNOMA) scheme was considered in the presence of imperfect CSI and successive interference cancelation (SIC), with inter-cell interference (ICI) (Khennoufa et al., 2022). Sun et al. (2022) evaluated the sum rate of AF and DF in the two-way system model, and the algorithm for gradient descent was introduced to optimize the PS factor efficiently and also improve the system performance. Nguyen et al. (2021) examined a SWIPT decode-and-forward (DF) relay system by analyze the outage probability and throughput performance in two relaying methods, which are static power splitting-based relaying (SPSR) and optimal dynamic power splitting-based relaying (ODPSR). Additionally, Nguyen et al. (2022) explored physical layer security (PLS) within a SWIPT cooperative network, focusing on both SPSR and ODPSR scenarios.

Different from the above-mentioned works, in this article, we analyze the system performance of the proposed DF EH Half-Duplex Relaying Network in two cases: Static and Dynamic Power Splitting (PS) Protocol Enabled. The EC mathematical expression is proposed and derived. The key contributions and innovations are described below:

– We consider multiple advanced strategies, including one-way HD relaying, as well as static and dynamic PS. As a result, the systems under consideration are complex and encompass numerous random variables (RVs) that may not be mutually independent.

– We obtain integral-form expressions for the EC in both static and dynamic PS scenarios.

– We present simulation results obtained via the Monte Carlo method to validate the precision of the developed mathematical framework.

– This study demonstrates how various key parameters impact system performance.

2. SYSTEM MODEL

Figure 1 shows the DF energy harvesting half-duplex relay network. The PS protocol is illustrated in Figure 2. All channels from the source (S) to the relay (R) and from R to the destination (D) are considered to be Rayleigh channels (Biglieri et al., 1998; Liu et al., 2013; Abd El-Malek et al., 2016; Duy et al., 2016).

The signal collected by the relay can be represented as

$$y_R = \sqrt{1-\rho} h_{SR} x_s + n_R, \quad (1)$$

Here, x_s represents the energy symbol with $\mathrm{E}\left\{|x_s|^2\right\} = P_s$, $\mathrm{E}\{\bullet\}$ signifies the expectation operation, and n_R stands for the zero-mean additive white Gaussian noise (AWGN) with variance N_0.

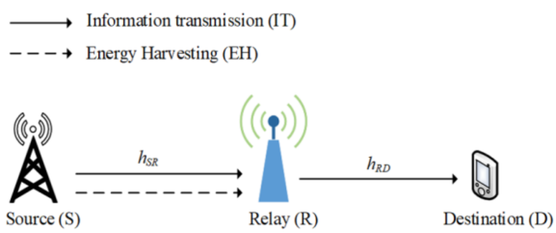

Figure 1. Considered Model

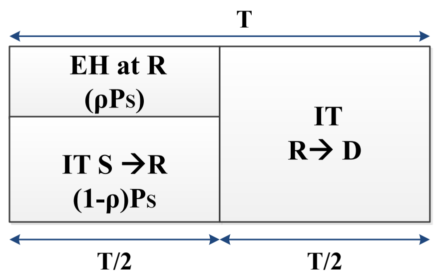

Figure 2. The protocol of power splitting

The amount of energy collected at the relay is defined as:

$$E_R = \eta\rho(T/2)P_s\left|h_{SR}\right|^2, \quad (2)$$

According to equation (2), the relay node's average transmit power can be represented as:

$$P_R = \frac{E_R}{T/2} = \eta \rho P_s \left| h_{SR} \right|^2, \tag{3}$$

where $0 < \eta \le 1$: the efficiency of energy conversion, considering the energy losses in both the harvesting circuits and the circuits used for decoding and processing.

In this model, we utilize the DF protocol. Consequently, the relay node has the signal-to-interference plus noise ratio (SINR) as indicated in (1), is expressed as:

$$\gamma_R = (1-\rho)\Psi \left| h_{SR} \right|^2, \tag{4}$$

Where $\Psi = \frac{P_S}{N_0}$.

The signal received and the SNR at the destination are, respectively, represented by

$$y_D = h_{RD} x_R + n_D \tag{5}$$

$$\gamma_D = \frac{P_R \left| h_{RD} \right|^2}{N_0} = \eta \rho \Psi \left| h_{SR} \right|^2 \left| h_{RD} \right|^2 \tag{6}$$

where n_D stand for zero-mean AWGN with variance N_0. The end-to-end SNR and the total capacity of D are as follows, respectively.

$$\gamma_{DF} = \min\left(\gamma_R, \gamma_D\right), \tag{7}$$

$$C_{DF} = \frac{1}{2}\log_2\left(1+\gamma_{DF}\right). \tag{8}$$

3. SYSTEM PERFORMANCE

3.1. Case 1: Static power splitting protocol (SPSP)

The system's ergodic capacity (EC) can be found by

$$C_{DF} = \frac{1}{2\ln 2}\int_0^\infty \frac{1-F_{\gamma_{DF}}(x)}{1+x}dx, \tag{9}$$

From (9), the cumulative distribution probability (CDF) of γ_{DF} is:

$$F_{\gamma_{DF}}(x) = \Pr\left(\gamma_{DF} < x\right) = \Pr\left(\min\left(\gamma_R, \gamma_D\right) < x\right) \tag{10}$$

By substituting (4) and (6) into (10), $F_{\gamma_{DF}}$ can be reformulated as

$$\begin{aligned} F_{\gamma_{DF}}(x) &= \Pr\left(\min\left((1-\rho)\Psi\left|h_{SR}\right|^2, \eta\rho\Psi\left|h_{SR}\right|^2\left|h_{RD}\right|^2\right) < x\right) \\ &= 1-\Pr\left((1-\rho)\gamma_{SR}\Psi \ge x, \eta\rho\Psi\gamma_{SR}\gamma_{RD} \ge x\right) \\ &= 1-\Pr\left(\gamma_{SR} \ge \frac{x}{(1-\rho)\Psi}, \gamma_{SR}\gamma_{RD} \ge \frac{x}{\eta\rho\Psi}\right) \\ &= 1-\int_0^{\xi} f_{\gamma_{RD}}(y)dy \int_{\frac{\gamma_{th}}{\eta\rho\Psi x}}^{\infty} f_{\gamma_{SR}}(x)dx - \int_{\xi}^{\infty} f_{\gamma_{RD}}(y)dy \int_{\vartheta}^{\infty} f_{\gamma_{SR}}(x)dx \\ &= 1-\exp\left(-\lambda_{SR}\vartheta - \lambda_{RD}\xi\right) - \lambda_{RD}\int_0^{\xi}\exp\left(-\frac{\gamma_{th}\lambda_{SR}}{\eta\rho\Psi x} - \lambda_{RD}x\right)dx, \end{aligned} \tag{11}$$

where

$$\vartheta = \frac{x}{(1-\rho)\Psi}, \xi = \frac{(1-\rho)}{\eta\rho}, \gamma_{SR} = \left|h_{SR}\right|^2, \gamma_{RD} = \left|h_{RD}\right|^2.$$

Given the challenge in determining the closed-form solution for (11) because of the integral $\int_{m_1}^{m_2}\exp\left(\frac{v_1}{x}\right)\exp\left(v_2 x\right)dx$, the Gaussian-Chebyshev quadrature will instead be utilized.

Firstly, we substitute the variable in (11) by setting $x = \frac{\xi}{2}y + \frac{\xi}{2}$. Consequently, Equation (11) can be reformulated as:

$$F_{\gamma_{DF}}(x) = 1-\exp\left(-\lambda_{SR}\vartheta - \lambda_{RD}\xi\right) - \frac{\lambda_{RD}\zeta}{2}\exp\left(-\frac{\lambda_{RD}\xi}{2}\right)\int_{-1}^{1}\exp\left(-\frac{\gamma_{th}\lambda_{SR}}{\eta\rho\Psi\Delta(y)} - \frac{\lambda_{RD}y\zeta}{2}\right)dy, \tag{12}$$

Utilizing the Gaussian-Chebyshev quadrature, equation (12) can be derived as

$$F_{\gamma_{DF}}(x) = 1-\exp\left(-\lambda_{SR}\vartheta - \lambda_{RD}\xi\right) - \sum_{m=1}^{N}\frac{\pi\lambda_{RD}\xi}{2N}\sqrt{1-\mu_m^2}\exp\left(-\frac{\lambda_{RD}\xi}{2} - \frac{k\lambda_{SR}\gamma_{th}}{\eta\rho\Psi\Lambda(\theta_m)} - \frac{\lambda_{RD}\xi\theta_m}{2}\right), \tag{13}$$

Here, N is a parameter that establishes the balance between intricacy and precision in the approximation based on Gaussian-Chebyshev quadrature and $\mu_m = \cos\left(\frac{\pi(2m-1)}{2M}\right)$ and $\theta_m = \frac{\xi}{2}\mu_m + \frac{\xi}{2}$.

Finally, by substituting (13) into (9), the EC of the system can be obtained by

$$C_{DF} = \frac{1}{2\ln 2}\int_0^\infty \frac{\left\{ \begin{matrix} \exp\left(-\lambda_{SR}\vartheta - \lambda_{RD}\xi\right) + \sum_{m=1}^{N} \frac{\pi\lambda_{RD}\xi}{2N}\sqrt{1-\mu_m^2} \\ \exp\left(-\frac{\lambda_{RD}\xi}{2} - \frac{k\lambda_{SR}\gamma_{th}}{\eta\rho\Psi\Lambda(\theta_m)} - \frac{\lambda_{RD}\xi\theta_m}{2}\right) \end{matrix} \right\}}{1+x} dx, \quad (14)$$

3.2. Case 2: Dynamic power splitting protocol (DPSP)

We design the ρ^* to maximize the capacity of our proposed system in this case. Because in our proposed model, we examined the DF protocol; hence, the ρ^* can be calculated by solving formulas as follows.

$$\begin{aligned} \gamma_R = \gamma_D &\leftrightarrow (1-\rho)\Psi|h_{SR}|^2 \\ &= \eta\rho\Psi|h_{SR}|^2|h_{RD}|^2 \rightarrow \rho^* = \frac{1}{\eta\gamma_{RD}+1} \end{aligned} \quad (15)$$

Substituting (15) into (11), the $F^*_{\gamma_{DF}}$ can be computed by

$$\begin{aligned} F^*_{\gamma_{DF}}(x) &= \Pr\left(\frac{\eta\Psi\gamma_{SR}\gamma_{RD}}{\eta\gamma_{RD}+1} < x\right) = \Pr\left(\gamma_{SR} < \frac{x(\eta\gamma_{RD}+1)}{\eta\Psi\gamma_{RD}}\right) \\ &= \int_0^\infty F_{\gamma_{SR}}\left(\frac{x(\eta y+1)}{\eta\Psi y}\right) \times f_{\gamma_{RD}}(y)dy \\ &= 1 - \lambda_{RD}\exp\left(-\frac{x\lambda_{SR}}{\Psi}\right)\int_0^\infty \exp\left(-\frac{x\lambda_{SR}}{\eta\Phi y} - \lambda_{RD}y\right)dy, \end{aligned} \quad (16)$$

By adopting Eq[3.324,1] in Gradshteyn and Ryzhik (2014), equation (16) become:

$$F^*_{\gamma_{DF}}(x) = 1 - 2\exp\left(-\frac{x\lambda_{SR}}{\Psi}\right)\sqrt{\frac{x\lambda_{SR}\lambda_{RD}}{\eta\Phi}} \times K_1\left(2\sqrt{\frac{x\lambda_{SR}\lambda_{RD}}{\eta\Phi}}\right), \quad (17)$$

Here, $K_v(\bullet)$ is the modified Bessel function of the second kind and v-th order.

By inserting (17) into (9), the EC, in this case, can be claimed by

$$C^*_{DF} = \frac{1}{\ln 2}\int_0^\infty \frac{\exp\left(-\frac{x\lambda_{SR}}{\Psi}\right)\sqrt{\frac{x\lambda_{SR}\lambda_{RD}}{\eta\Phi}} \times K_1\left(2\sqrt{\frac{x\lambda_{SR}\lambda_{RD}}{\eta\Phi}}\right)}{1+x} dx. \quad (18)$$

4. NUMERICAL RESULTS AND DISCUSSION

In this section, EC as a function of Ψ is illustrated in Figures 3 and 4. When Ψ or η increases, the EC of the proposed system also increases. The main parameters of the system are set as η=0.8, C_{th}=0.35 bps/Hz, for Figure 3 and C_{th}=0.35 bps/Hz, Ψ = 3dB for Figure 4, respectively. This simulation shows that the system performance has a huge increase when Ψ varies from -5 dB to 10 dB. From the research results, the system performance with dynamic ρ is the best compared to the system performance with ρ=0.25 and 0.75 while Ψ varies from -5 dB to 10 dB. The simulation and analytical results show concordance in both Figures 3 and 4.

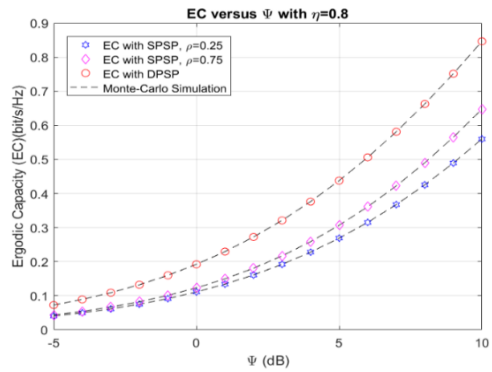

Figure 3. EC versus Ψ with *η*=0.8

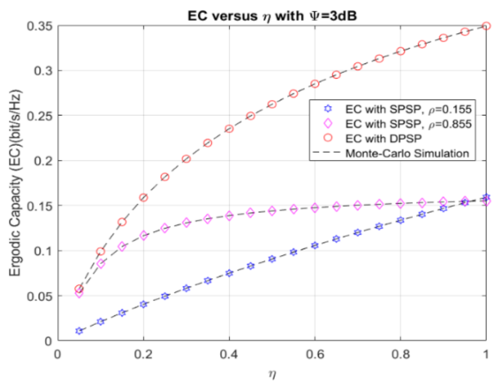

Figure 4. EC versus η with Ψ=3dB

Figures 5 and 6 explore the effect of varying the power splitting factor ρ and varying λ on the EC of the proposed system. In Figure 5, we considered three cases with ρ = 0.15, 0.85, and dynamic value, and set the primary system parameters as C_{th} = 0.35 bps/Hz, and Ψ = 1dB. From the simulation results, the EC of the system has a significant improvement with DPSP compared to SPSP at the same η value. Furthermore, there exists an optimal value in the case of SPSP is that ρ around 0.5. The EC as the energy coefficient function is shown in Figure 6 with C_{th} = 0.35 bps/Hz, η = 0.8, ρ = 0.5, and Ψ = 1dB and 4dB. We can discover that the system performance with the dynamic ρ is superior than in other cases, and the EC of the system in all cases has a considerable reduction with the rising of λ. Again, the theoretical and simulation results agree well, as in Figures 5 and 6.

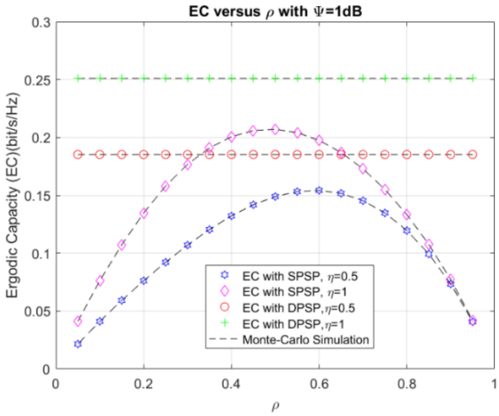

Figure 5. EC versus ρ with Ψ=1Db

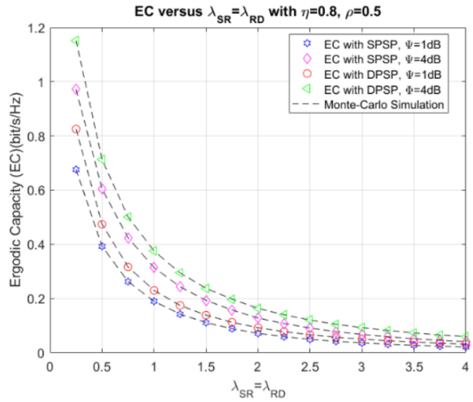

Figure 6. EC versus $\lambda_{SR} = \lambda_{RD}$ with η=0.8, ρ=0.5.

5. CONCLUSION

This paper considers the ergodic capacity analysis of the DF energy harvesting half-duplex relaying network in two cases of power splitting control that are enabled by the static and dynamic power splitting protocol. The mathematical expression of the EC is derived and validated for the correctness of the analytical description by Monte Carlo simulation. The results show that the dynamic power splitting protocol has significantly improved the system performance compared to the static power splitting protocol. The ergodic capacity of the proposed system has been improved by choosing a reasonable dynamic power splitting factor. Future work should consider the system model with multiple relaying.

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