TELKOMNIKA, Vol.16, No.5, October 2018, pp. 1947~1956
ISSN: 1693-6930, accredited First Grade by Kemenristekdikti, Decree No: 21/E/KPT/2018
DOI: 10.12928/TELKOMNIKA.v16i5.9118

Hybrid Time-power Switching Protocol of Energy Harvesting Bidirectional Relaying Network: Throughput and Ergodic Capacity Analysis

Tran Hoang Quang Minh
Faculty of Electrical and Electronics Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam
*Corresponding author, e-mail: tranhoangquangminh@tdtu.edu.vn

Abstract

In this paper, we investigate system performance in term of throughput and ergodic capacity of the hybrid time-power switching protocol of energy harvesting bidirectional relaying network. In the first stage, the analytical expression of the system throughput and ergodic capacity of the model system is proposed and derived. In this analysis, both delay-limited and delay-tolerant transmission modes are presented and considered. After that, the effect of various system parameters on the proposed system is investigated and demonstrated by Monte-Carlo simulation. Finally, the results show that the analytical mathematical and simulated results match for all possible parameter values for both schemes.

Keywords*: decode-and-forward (DF), relay network, throughput, outage probability, wireless energy harvesting (EH).*

1. Introduction

Energy harvesting (EH) wireless communication has been attracting intensive research interests from both academia and industry, as it can substantially prolong the network lifetime, especially for wireless sensor networks with low power nodes. Energy can be harvested from environment resources, but EH from conventional sources, such as solar and wind, may be sporadic or intermittent, which makes it difficult to satisfy the data transmission requirements. One particular energy source is the radio frequency (RF) signal, which can recharge nodes more controllable. Wireless energy transfer (WET) in the network with a helping relay is the most popular technique.

The helping relay with energy harvesting has been proposing and studied in many last papers. In more details, [3] presented energy harvesting in amplify-and-forward (AF) relaying. In [4], the total energy harvested from multiple sources was optimally allocated among different destinations. In [5], the effect of large-scale network interference on energy harvesting decode-and-forward (DF) was considered. Moreover, the effect of the random location of the relay on DF relaying is investigated in [6] and [7] maximized the achievable throughput of an AF energy harvesting system. Furthermore, a similar problem was studied in [8] for DF and [9] proposed the achievable throughput of an AF energy harvesting system was optimized. From this point of view, energy harvesting relaying network is the hot direction in the communication network and is necessary to develop more and more.

In this work, the hybrid time-power switching protocols for the energy harvesting bidirectional relaying network is presented. In this relaying network, the outage probability and the ergodic capacity are proposed and demonstrated for both delay-limited (DL) and delay-tolerant (DT) transmission modes. The main contributions of the paper are summarized as follows:

a. The system model of the hybrid time-power switching protocols for the energy harvesting bidirectional relaying network is proposed for both delay-limited (DL) and delay-tolerant (DT) transmission modes.
b. The closed-form of the outage probability and ergodic capacity for the system is derived.
c. The influence of the main parameters on the system performance is demonstrated entirely.

The structure of this paper is proposed as follows. The system model of the hybrid time-power switching protocols for the energy harvesting bidirectional relaying network is proposed and presented in section 2. Sections 3 proposed outage probability and ergodic

Received February 28, 2018; Revised August 25, 2018; Accepted September 10, 2018

capacity for both delay-limited (DL) and delay-tolerant (DT) transmission modes are investigated and derived, respectively. Section 4 provides the numerical results and some discussions. Finally, some conclusions are proposed in section 5.

2. System Model

In this section, the system model is presented in Figure 1. In this model, the user is intended to send information to the access point (AP) with the assistance of a relay R and the AP transfer the energy to the user by the helping relay. Moreover, the direct connection between the AP and the user is so weak, hence, the only available communication path as well as power transfer path is via the relay R. The relay R plays both roles of energy relaying from the AP to the user and information forwarding from the user to the AP [10,11]. All nodes are assumed to operate in half-duplex mode, and decode-and-forward (DF) can be used at the relay for information transfer. Regarding the channel model, the perfect channel state information (CSI) is available at the relay and the AP. All channels here experience Rayleigh fading and keep constant during each transmission block so that they can be considered as slow fading.

The Figure 2 displayed the time-power switching based protocol model. In the first interval time αT, the AP transfer energy by RF to the relay R, $0\leq\alpha\leq1$. After that, the energy transfer from the AP to the R and the information transmission from the U to the R are performed instantaneously in the second interval βT, $0\leq\beta\leq1$. Moreover, finally, the information transmission process from R to AP and the energy transfer process from the R to U are made in the remaining interval time (1-α-β)T. In this model, we assume that the circuit power consumption is negligible as compared to the radiation power, which is reasonable for low-power devices such as sensor nodes. In this system model, $0\leq\alpha\leq1$ and $0\leq\beta\leq1$. If $\alpha=0$, this scheme becomes a power splitting protocol. If $\beta=(1-\alpha)/2$ and $\rho=0$ then it becomes the time switching protocol.

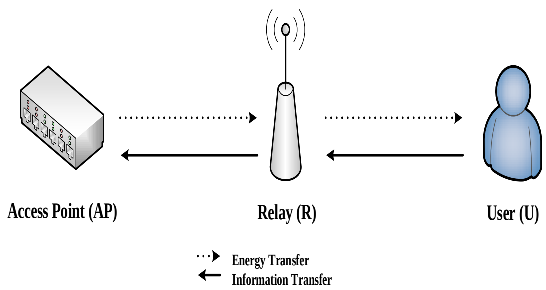

Figure 1. System model

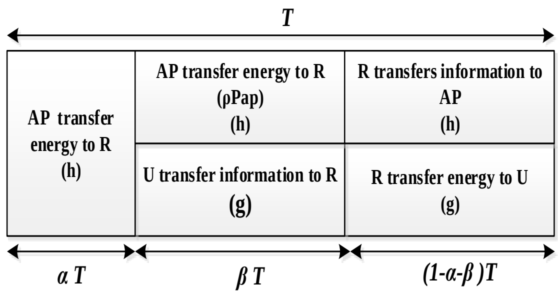

Figure 2. The hybrid time-power switching based protocol model

3. The outage probability and ergodic capacity

In this part, the system performance of the hybrid time-power switching protocols for the energy harvesting bidirectional relaying network is presented, analyzed and demonstrated for both delay-limited (DL) and delay-tolerant (DT) transmission modes in details in this section. Let x_u denote the transmitted signal from the user during the second phase, and P_u denotes the power of this signal. Then, the received signal at the relay R can be calculated by:

$$y_r = \sqrt{P_{ap}}hx_{ap} + \sqrt{P_u}gx_u + n_r \quad (1)$$

After pre-canceling the signal x_{ap} the remaining part of the received signal at the relay is written as

$$y_r = \sqrt{1-\rho}\sqrt{P_u}gx_u + n_r \quad (2)$$

Where n_r~$N(0,N_0)$ denotes the Gaussian distributed noise at the relay R and then the received signal at the user in the third interval is expressed as:

$$y_u = \sqrt{P_r} h x_r + n_u \quad (3)$$

Where P_u: the power at the user, P_r: the power at the relay, n_r,n_d: the additive white Gaussian noise (AWGN) at *R, U* with zero mean and variance N_0, h and g he channels from the AP to the relay and from the user to the relay, respectively. The harvesting energy E_r at R in the first and second interval time can be formulated as:

$$E_r = \eta P_{ap} |h|^2 \alpha T + \eta \rho P_{ap} |h|^2 \beta T \quad (4)$$

From that harvesting energy, the transmission power of the R in the thirst interval can be calculated as the following:

$$P_r = \frac{E_r}{(1-\alpha-\beta)T} = \frac{\eta P_{ap} |h|^2 \alpha T + \eta \rho P_{ap} |h|^2 \beta T}{(1-\alpha-\beta)T} = kP_{ap}|h|^2 \quad (5)$$

Where we denote $k = \frac{\eta(\alpha+\beta\rho)}{1-\alpha-\beta}$. Similarly, while the AP receives the information signal, the mobile user also receives the RF energy sent from the relay. By ignoring the noise energy, which is negligible as compared to the signal energy. The received signal at the mobile user is $y_u=gx_r$. Hence, the energy harvested during this phase can be determined by:

$$E_u = \eta |g|^2 E_r = \eta |g|^2 \left\{ \eta P_{ap} |h|^2 \alpha T + \eta \rho P_{ap} |h|^2 \beta T \right\} \quad (6)$$

So the transmit power of the user during the thirst phase is expressed in the below equation:

$$P_u = \frac{E_u}{(1-\alpha-\beta)T} = \frac{\eta |g|^2 \left\{ \eta P_{ap} |h|^2 \alpha T + \eta \rho P_{ap} |h|^2 \beta T \right\}}{1-\alpha-\beta} = k\eta P_{ap} |h|^2 |g|^2 \quad (7)$$

In this case, we select $(\alpha+\beta)<1$, because P_r, P_u must be positive.

3.1. The delay-limited transmission mode (DL)

From (5), the signal to noise ratio (SNR) at the relay R can be computed by the following equation:

$$SNR_1 = \frac{P_r |h|^2}{N_0} = \frac{kP_{ap}|h|^4}{N_0} = \frac{kP_{ap}X^2}{N_0} = \gamma_0 X^2 \quad (8)$$

Where we denote $X = |h|^2$, and $\gamma_0 = k\frac{P_{ap}}{N_0}$. Similarity, the signal to noise ratio (SRN) at the user based on (8) can be formulated by:

$$SNR_2 = \frac{(1-\rho)P_u |g|^2}{N_0} = \frac{(1-\rho)k\eta P_{ap} |h|^2 |g|^4}{N_0} = \frac{(1-\rho)k\eta P_{ap} XY^2}{N_0} = (1-\rho)\gamma_0 \eta XY^2 \quad (9)$$

Where we denote $Y = |g|^2$. Theorem 1. The exact integral form for the outage probability of the proposed system can be expressed as:

$$P_{out}=1-\Gamma\left(1,\lambda_h x_0,\lambda_g y_0\sqrt{x_0\lambda_h},\frac{1}{2}\right) \tag{10}$$

Proof 1 See Appendix A.

3.2. The Delay-Tolerant transmission mode (DT)

In this section, the ergodic capacity from the source to relay C_r, and for relay to the user C_u are formulated. By using the received signal SNR in (8), (9), the ergodic capacity C_r and C_u are given by the following equations:

$$C_r=\mathrm{E}_{|h|^2}\left\{\log_2(1+SNR_1)\right\} \tag{11}$$

$$C_u=\mathrm{E}_{|h|^2,|g|^2}\left\{\log_2(1+SNR_2)\right\} \tag{12}$$

From the equations (11) and (12), the ergodic capacity of the proposed system can be chosen as:

$$C=\min(C_r,C_u) \tag{13}$$

Then the throughput of the proposed system can be calculated by the below equation:

$$\tau^{DT}=C\frac{(1-\alpha-\beta)T}{T}=C(1-\alpha-\beta) \tag{14}$$

Theorem 2. The exact integral forms for the ergodic capacity C_r and C_u of the proposed system can be expressed as the followings:

$$C_r=\frac{1}{\ln 2}\int_0^\infty \frac{e^{-\frac{\lambda_h}{\sqrt{\gamma_0}}\sqrt{\gamma_{th}}}}{1+\gamma_{th}}d\gamma_{th} \tag{15}$$

$$C_u=\frac{1}{\ln 2}\int_0^\infty \frac{H_{0,2}^{2,0}\left(\lambda_g\sqrt{\frac{\gamma_{th}\lambda_h}{(1-\rho)\gamma_0\eta}}\left|\begin{matrix} - & - \\ (0,1) & \left(1,\frac{1}{2}\right)\end{matrix}\right.\right)}{1+\gamma_{th}}d\gamma_{th} \tag{16}$$

Proof 2 See Appendix B.

4. Numerical Results and Discussion

In this paper, the Monte Carlo simulation was conducted 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. For the delay-limited transmission mode, the outage probability, and achievable throughput are analyzed in details. On the other hand, the outage probability, and the ergodic capacity for the delay-tolerant transmission mode are proposed and demonstrated.

Figures 3 and 4 plot the effect of ρ on the outage probability and system throughput in the DL transmission mode, respectively. In this simulation, we set P_{ap}/N_0=10 dB and α, β in Figures 3 and 4. Moreover, Figures 5 and 6 present the dependent of the outage probability and system throughput in the DL transmission mode on the η of the proposed system.

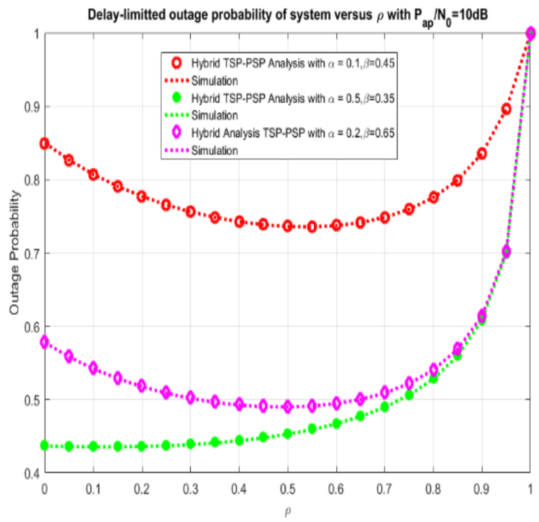

Figure 3. The outage probability versus ρ for DL transmission mode

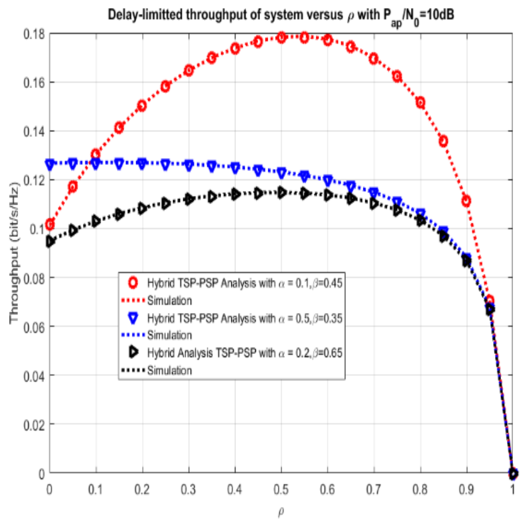

Figure 4. The throughput versus ρ for DL transmission mode

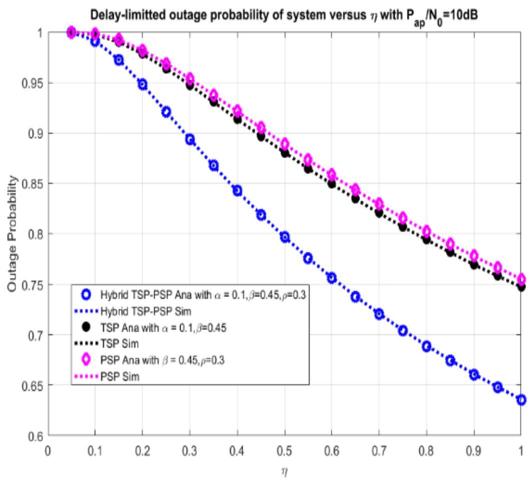

Figure 5. The outage probability versus η for DL transmission mode

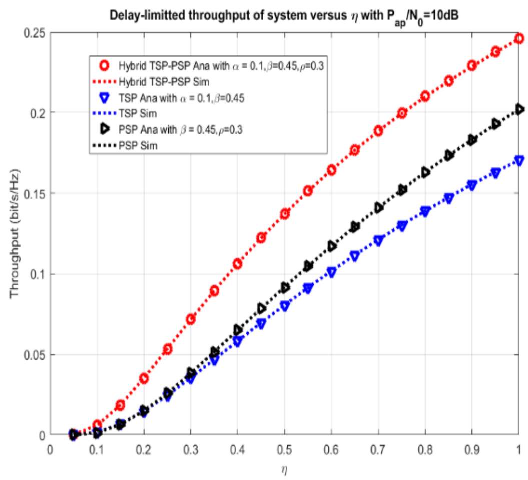

Figure 6. The throughput versus η for DL transmission mode

Furthermore, Figures 7 and 8 show the influence of the outage probability and system throughput in the DL transmission mode on the ratio P_{ap}/N_0. From the results, we can see that the analytical and simulation results well agree with each other. On another way, Figure 9 and Figure 10 plot the effect of ρ on the outage probability and system throughput in the DT transmission mode, respectively. In this simulation, we set P_{ap}/N_0=10 dB and α, β in Figures 9 and 10. Moreover, Figures 11 and 12 present the dependent of the outage probability and system throughput in the DT transmission mode on the η of the proposed system. Furthermore, Figures 13 and 14 show the influence of the outage probability and system throughput in the DT transmission mode on the ratio P_{ap}/N_0. From the results, we can see that the analytical and simulation results well agree with each other. Also, the Figure 15 presents Comparison of the throughput versus P_{ap}/N_0 for DT and DL transmission modes for the both analytical and simulation cases.

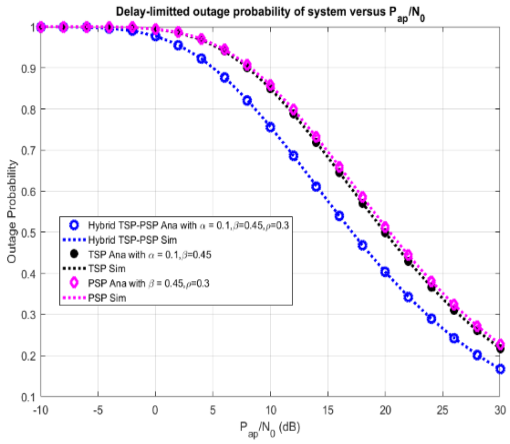

Figure 7. The outage probability versus P_a/N_0 for DL transmission mode

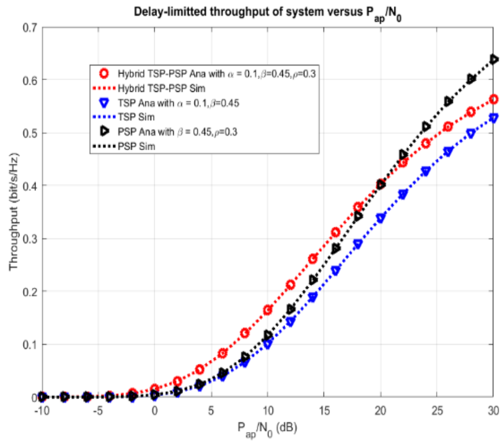

Figure 8. The throughput versus P_a/N_0 for DL transmission mode

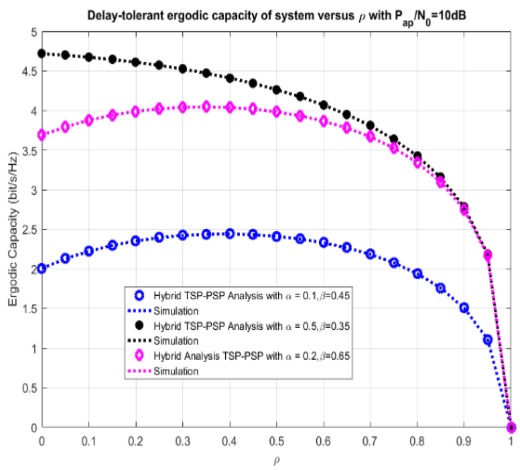

Figure 9. The outage probability versus ρ for DT transmission mode

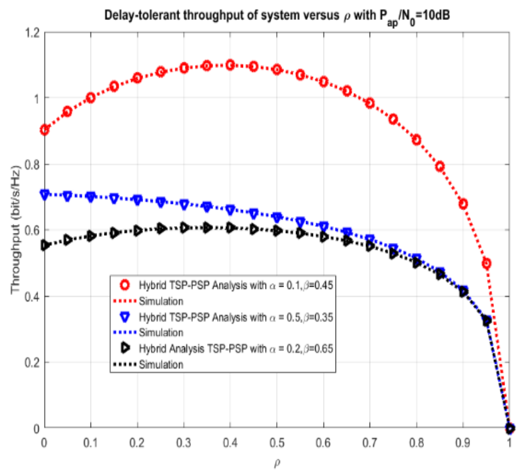

Figure 10. The throughput versus ρ for DT transmission mode

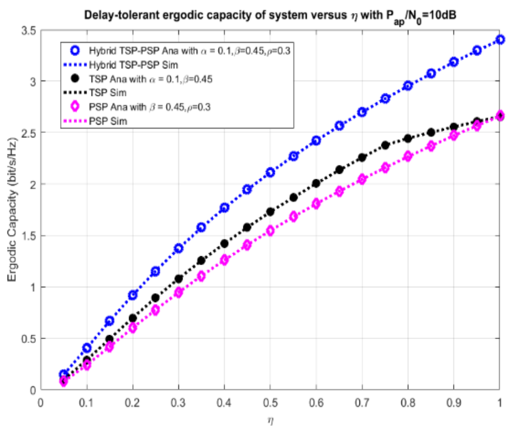

Figure 11. The ergodic capacity versus η for DT transmission mode

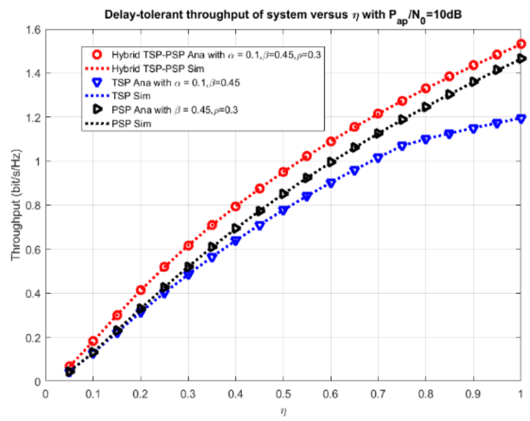

Figure 12. The throughput versus η for DT transmission mode

4. Conclusion

In this paper, the hybrid time-power switching protocol of energy harvesting bidirectional relaying network is proposed and investigated. In order to analyze the system performance, analytical expressions for the outage probability, ergodic capacity and the throughput of the delay-limited and delay-tolerant transmission mode are investigated ad derived. The results show that the analytical mathematical and simulated results by Monte-Carlo simulation match for all possible parameter values for both schemes. The results could be provide the prospective solution for the communication network in the near future.

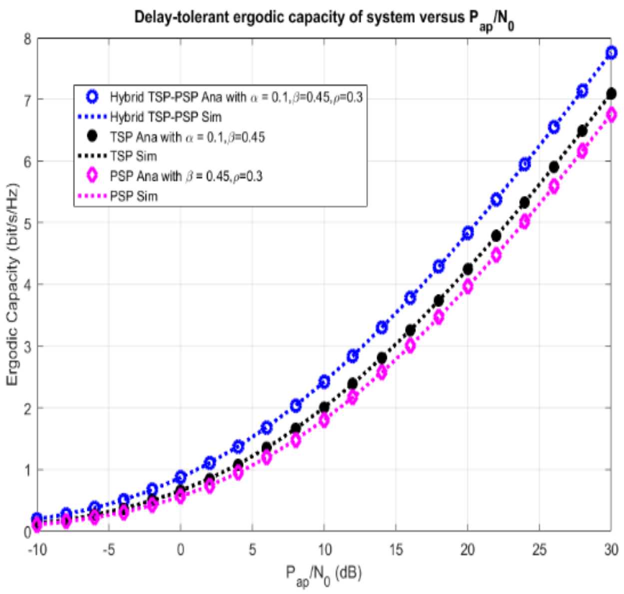

Figure 13. The ergodic capacity versus P_{ap}/N_0 for DT transmission mode

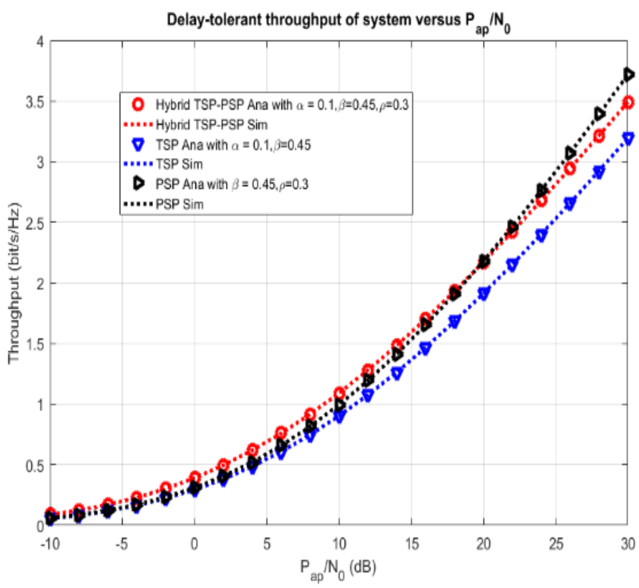

Figure 14. The throughput versus P_{ap}/N_0 for DT transmission mode

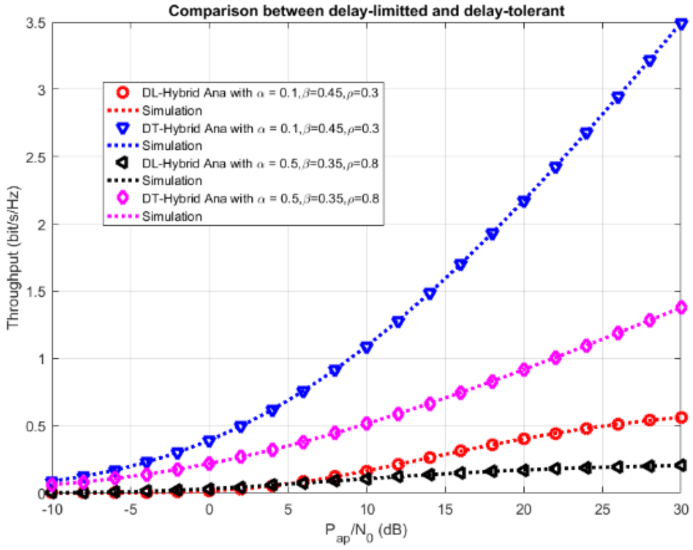

Figure 15. Comparison of the throughput versus P_{ap}/N_0 for DT and DL transmission modes

APPENDIX A

In this case, to compute the system throughput, we will evaluate the outage probability and the throughput of the proposed system by the followings:

$$P_{out} = 1 - \Gamma\left(1, \lambda_h x_0, \lambda_g y_0 \sqrt{x_0 \lambda_h}, \frac{1}{2}\right) \quad \text{(A1)}$$

$$\tau^{DL} = (1 - P_{out}) R \frac{(1-\alpha-\beta)T}{T} = R(1-\alpha-\beta)\Gamma\left(1, \lambda_h x_0, \lambda_g y_0 \sqrt{x_0 \lambda_h}, \frac{1}{2}\right) \quad \text{(A2)}$$

Where $\Gamma(\alpha, x, b, \beta) \approx \int_x^\infty t^{\alpha-1} e^{-t-bt^{-\beta}} dt$ is the extended incomplete gamma function, which is defined in [12], we denote $x_0 = \sqrt{\frac{\gamma_{th}}{\gamma_0}}$, $y_0 = \sqrt{\frac{\gamma_{th}}{(1-\rho)\gamma_0 \eta x_0}}$, $\gamma_{th} = 2^{2R} - 1$. Where R: target rate. Then the outage probability can be formulated as:

$$P_{out} = \Pr\left[\min(SNR_1, SNR_2) < \gamma_{th}\right] \quad \text{(A3)}$$

$$P_{out} = \Pr\left[\min\left(\frac{kP_{ap}X^2}{N_0}, \frac{(1-\rho)k\eta P_{ap} XY^2}{N_0}\right) < \gamma_{th}\right] = 1 - \Pr\left(\gamma_0 X^2 \ge \gamma_{th}, (1-\rho)\gamma_0 \eta XY^2 \ge \gamma_{th}\right) \quad \text{(A4)}$$

$$P_{out} = 1 - \Pr\left(Y \ge \sqrt{\frac{\gamma_{th}}{(1-\rho)\gamma_0 \eta X}}, X \ge x_0\right) = 1 - \Pr\left(Y \ge y_0\sqrt{\frac{x_0}{X}}, X \ge x_0\right) = 1 - \Pr\begin{pmatrix} X \ge x_0, \\ y_0\sqrt{\frac{x_0}{X}} \le Y < y_0 \end{pmatrix}$$
$$- \Pr(X \ge x_0, Y \ge y_0) = 1 - e^{-\lambda_h x_0 - \lambda_g y_0} - \int_{x_0}^{\infty} f_X(x)\left(\int_{y_0\sqrt{\frac{x_0}{X}}}^{y_0} f_Y(y)dy\right)dx \quad \text{(A5)}$$

Here we consider:

$$I_1 = -\int_{x_0}^{\infty} f_X(x)\left(\int_{y_0\sqrt{\frac{x_0}{X}}}^{y_0} f_Y(y)dy\right)dx = -\int_{x_0}^{\infty}\lambda_h e^{-\lambda_h x}\left(e^{-\lambda_g y_0\sqrt{\frac{x_0}{x}}} - e^{-\lambda_g y_0}\right)dx = -\int_{x_0}^{\infty}\lambda_h e^{-\lambda_h x} e^{-\lambda_g y_0\sqrt{\frac{x_0}{x}}}dx + e^{-\lambda_g y_0 - \lambda_h x_0} \quad \text{(A6)}$$

By changing the variable $u = \lambda_h x$ to (A6) we have:

$$I_1 = -\int_{\lambda_h x_0}^{\infty} e^{-u} e^{-\lambda_g y_0\sqrt{\frac{\lambda_h x_0}{u}}}du + e^{-\lambda_g y_0 - \lambda_h x_0} \quad \text{(A7)}$$

The equation (14) can be obtained by substituting (A7) to (A5).

APPENDIX B

Proof C_r

$$F_{SNR_1}(\gamma_{th}) = \Pr(SNR_1 < \gamma_{th}) = \Pr\left(\gamma_0 X^2 < \gamma_{th}\right) = \Pr\left(X < \sqrt{\frac{\gamma_{th}}{\gamma_0}}\right) = 1 - e^{-\lambda_h\sqrt{\frac{\gamma_{th}}{\gamma_0}}} \quad \text{(B1)}$$

$$C_r = \frac{1}{\ln 2}\int_0^{\infty}\frac{1 - F_{SNR_1}(\gamma_{th})}{1+\gamma_{th}}d\gamma_{th} = \frac{1}{\ln 2}\int_0^{\infty}\frac{e^{-\frac{\lambda_h}{\sqrt{\gamma_0}}\sqrt{\gamma_{th}}}}{1+\gamma_{th}}d\gamma_{th} \quad \text{(B2)}$$

Proof C_u

$$\begin{aligned} F_{SNR_2}(\gamma_{th}) &= \Pr(SNR_2 < \gamma_{th}) = \Pr\left[(1-\rho)\gamma_0\eta XY^2 < \gamma_{th}\right] \\ &= \Pr\left(Y < \sqrt{\frac{\gamma_{th}}{(1-\rho)\gamma_0\eta X}}\right) = \int_0^{\infty} f_X(X)\left(\int_0^{\sqrt{\frac{\gamma_{th}}{(1-\rho)\gamma_0\eta X}}} f_Y(Y)dY\right)dX \\ &= \int_0^{\infty}\lambda_h e^{-\lambda_h X}\left(1 - e^{-\lambda_g\sqrt{\frac{\gamma_{th}}{(1-\rho)\gamma_0\eta X}}}\right)dX = 1 - \int_0^{\infty}\lambda_h e^{-\lambda_h X} e^{-\lambda_g\sqrt{\frac{\gamma_{th}}{(1-\rho)\gamma_0\eta X}}}dX \\ &= 1 - \int_0^{\infty} e^{-u} e^{-\lambda_g\sqrt{\frac{\gamma_{th}\lambda_h}{(1-\rho)\gamma_0\eta u}}}du = 1 - \Gamma\left(1, 0, \lambda_g\sqrt{\frac{\gamma_{th}\lambda_h}{(1-\rho)\gamma_0\eta}}, \frac{1}{2}\right) \end{aligned} \quad \text{(B3)}$$

Where $\Gamma(\alpha,0,b,\beta) \approx \int_0^{\infty} t^{\alpha-1}e^{-t-bt^{-\beta}}dt$ is the complete gamma function which is defined in [12]. Then we can rewrite as:

$$\Gamma(\alpha,0,b,\beta) = H_{0,2}^{2,0}\left(\lambda_g\sqrt{\frac{\gamma_{th}\lambda_h}{(1-\rho)\gamma_0\eta}}\left|\begin{matrix} - & - \\ (0,1) & \left(1,\frac{1}{2}\right)\end{matrix}\right.\right)$$

In which $H_{0,2}^{2,0}$ is Fox's H-functions [13].

$$C_u = \frac{1}{\ln 2}\int_0^{\infty}\frac{1-F_{SNR_2}(\gamma_{th})}{1+\gamma_{th}}d\gamma_{th} = \frac{1}{\ln 2}\int_0^{\infty}\frac{H_{0,2}^{2,0}\left(\lambda_g\sqrt{\frac{\gamma_{th}\lambda_h}{(1-\rho)\gamma_0\eta}}\middle|\begin{matrix} - & - \\ (0,1) & \left(1,\frac{1}{2}\right)\end{matrix}\right)}{1+\gamma_{th}}d\gamma_{th} \quad \text{(B4)}$$

References

[1] Bi, S, Ho, C K, Zhang, R. Wireless powered communication: Opportunities and challenges. *IEEE Communications Magazine*. 2015; 53(4): 117-125

[2] Niyato D, Kim D I, Maso M, Han Z. Wireless Powered Communication Networks: Research Directions and Technological Approaches. *IEEE Wireless Communications*. 2017: 2-11.

[3] Nasir, A A, Zhou, X, Durrani, S, Kennedy, R A. Relaying Protocols for Wireless Energy Harvesting and Information Processing. *IEEE Transactions on Wireless Communications.* 2013; 12(7): 3622-3636.

[4] Baidas, M W, Alsusa, E A. Power allocation, relay selection and energy cooperation strategies in energy harvesting cooperative wireless networks. *Wireless Communications and Mobile Computing,* 2016; 16(14): 2065-2082.

[5] Krikidis, I. Simultaneous Information and Energy Transfer in Large-Scale Networks with/without Relaying. *IEEE Transactions on Communications,* 2014; 62(3), 900-912.

[6] Ding, Z, Krikidis, I, Sharif, B, Poor, H V. Wireless Information and Power Transfer in Cooperative Networks with Spatially Random Relays. *IEEE Transactions on Wireless Communications,* 2014; 13(8): 4440-4453.

[7] Tin, Phu Tran, Tran Hoang Quang Minh, Tan N. Nguyen, and Miroslav Voznak. System Performance Analysis of Half-Duplex Relay Network over Rician Fading Channel. *TELKOMNIKA,* 2018; 16(1): 189.

[8] Rashid, Tarique, Sunil Kumar, Akshay Verma, Prateek Raj Gautam, Arvind Kumar. Pm-EEMRP: Postural Movement Based Energy Efficient Multi-hop Routing Protocol for Intra Wireless Body Sensor Network (Intra-WBSN). *TELKOMNIKA,* 2018; 16(1): 166.

[9] Ahmed, I, Ikhlef, A, Schober, R, Mallik, R K. Joint Power Allocation and Relay Selection in Energy Harvesting AF Relay Systems. *IEEE Wireless Communications Letters,* 2013; 2(2), 239-242.

[10] Zeng, Y, Chen, H, Zhang, R. Bidirectional Wireless Information and Power Transfer with a Helping Relay. *IEEE Communications Letters,* 2016; 20(5), 862-865.

[11] Gurakan, B, Ozel, O, Yang, J, Ulukus, S. *Energy cooperation in energy harvesting two-way communications*. 2013 IEEE International Conference on Communications (ICC).

[12] Chaudhry, M, Zubair, S. Extended incomplete gamma functions with applications. *Journal of Mathematical Analysis and Applications,* 2002; 274(2), 725-745.

[13] J, J E. The H-Function with Applications in Statistics and Other Disciplines. *Technometrics,* 1979, 21(3), 392-393.

[14] Table of Integrals, Series, and Products. (2015).