International Journal of Electrical and Computer Engineering (IJECE)
Vol. 9, No. 5, October 2019, pp. 3399~3406
ISSN: 2088-8708, DOI: 10.11591/ijece.v9i5.pp3399-3406

Half-duplex power beacon-assisted energy harvesting relaying networks: system performance analysis

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Article Info

Article history:

Received Nov 11, 2018
Revised Apr 6, 209
Accepted Apr 18, 2019

Keywords:

Half-duplex (HD)
Outage probability (OP)
System throughput (ST)
Wireless energy harvesting (EH)

ABSTRACT

In this work, the half-duplex (HF) power beacon-assisted (PB) energy harvesting (EH) relaying network, which consists of a source (S), Relay (R), destination (D) and a power beacon (PB) are introduced and investigated. Firstly, the analytical expressions of the system performance in term of outage probability (OP) and the system throughput (ST) are analyzed and derived in both amplify-and-forward (AF) and decode-and-forward (DF) modes. After that, we verify the correctness of the analytical analysis by using Monte-Carlo simulation in connection with the primary system parameters. From the numerical results, we can see that all the analytical and the simulation results are matched well with each other.

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1. INTRODUCTION

Energy harvesting (EH) relay network, which uses a radio frequency (RF) signal for wirelessly transferring power, has attracted much attention because of prolonging the lifetime of a wireless network. This solution can be obtained because RF signal can simultaneously transfer energy and information [1-10]. Nowadays, the system performance of EH relaying network has been studied in many studies. [11] investigated the full-duplex EH, the development of cooperative protocols for EH relaying network is fully studied in [12-13]. Furthermore, [14-15] introduce and investigate a "harvest-then-transmit" protocol for a multi-user relaying network. In all papers above, the relay (R) and the destination (D) nodes only receive energy from the source (S) or the access point nodes. In the trends to improving EH and information transmission (IT) processes in the wireless relay network, some researchers proposed the idea of deploying dedicated power beacon node (PB). In the wireless relay network with using the PB node, D and R can receive energy both from S and PB nodes [16-17]. The problem of energy harvesting is also encountered in directional MANET contexts involving high directive beamforming devices [18].

In this work, we introduce and investigate the system performance analysis of HD power beacon-assisted EH relay network in both the amplifier-and-forward (AF) and decode-and-forward (DF) modes via the Raleigh fading channels. Firstly, the integral closed-form expression of the outage probability (OP) and system throughput (ST). After that, the analytical expressions are convinced by using Monte-Carlo simulation with helping Mat Lab software in both amplifier-and-forward (AF) and decode-and-forward (DF) modes. Finally, the numerical analysis can be demonstrated in connection with the primary system parameter.

2. SYSTEM MODEL AND PERFORMANCE ANALYSIS

Figure 1 illustrates the system model of the proposed system. In Figure 1, the information is transferred from S to D with helping of an intermediate R. Here S, and R are harvest energy from the PB node directly. In this model, all the block-fading channels are the Raleigh fading channels. Figure 2 illustrates the energy harvesting and information transmission processes. In this proposed system model, the node PB transfers the energy to S and R in αT (≤ α ≤ 1). After that, S transfers the information to R in the next interval time (1-α)T/2. Finally, the relay node R transfers the information to the destination node D in (1-α)T/2.

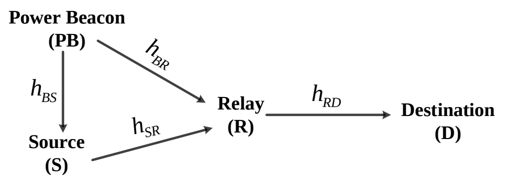

Figure 1. System model

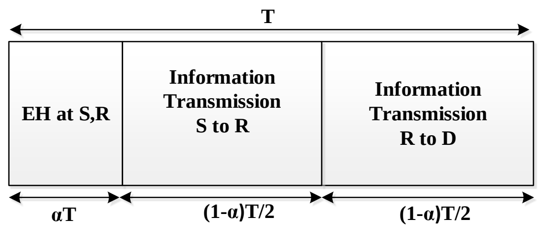

Figure 2. EH and IT processes

2.1. The amplifier and forward (AF) mode

In αT, the PB node transfers energy to both source node S and relay node R. Then the harvested energy at the source node S can be calculated by

$$E_s = \eta\alpha T P_B \left|h_{BS}\right|^2 \tag{1}$$

where 0<η <1 is the energy conversion efficiency. From this energy, the average transmits power at S can be formulated as

$$P_s = \frac{E_s}{(1-\alpha)T/2} = kP_B \left|h_{BS}\right|^2 \tag{2}$$

Similarity, the harvested energy at R is

$$E_r = \eta\alpha T P_B \left|h_{BR}\right|^2 \tag{3}$$

Then the average transmits power at R is

$$P_r = \frac{E_r}{(1-\alpha)T/2} = kP_B \left|h_{BR}\right|^2 \tag{4}$$

where we denote that $k = \dfrac{2\eta\alpha}{1-\alpha}$.

After that, S transfers the information to R. The received signal is

$$y_r = h_{SR} x_s + n_r \tag{5}$$

where x_s is the transmission signal from S.

In the next stage, R transfers the information, which is received from the source to D in the remaining interval time. The received signal at D is formulated as

$$y_d = h_{RD} x_r + n_d \tag{6}$$

where n_r,n_d are the additive white Gaussian noise (AWGN) at *R*, *D* with zero mean and variance N_0, $\mathrm{E}\left[|x_s|^2\right] = P_r$, $\mathrm{E}\left[|x_r|^2\right] = P_r$, and $\mathrm{E}[\bullet]$ is expectation operator, x_r is the transmission signal from R.

In the AF mode, we can calculate the amplifier factor as

$$\beta = \frac{x_r}{y_r} = \sqrt{\frac{P_r}{P_s |h_{SR}|^2 + N_0}} \tag{7}$$

From (6) and (7), the received signal at D is

$$y_d = h_{RD}\beta y_r + n_d = h_{RD}\beta\left[h_{SR}x_s + n_r\right] + n_d = \underbrace{h_{SR}h_{RD}\beta x_s}_{signal} + \underbrace{h_{RD}\beta n_r + n_d}_{noise} \tag{8}$$

Using (8), we can calculate the signal to noise ratio (SRN) at D by

$$\gamma_{e2e} = \frac{\beta^2 |h_{SR}|^2 |h_{RD}|^2 P_s}{|h_{RD}|^2 \beta^2 N_0 + N_0} = \frac{|h_{SR}|^2 |h_{RD}|^2 P_s}{|h_{RD}|^2 N_0 + \dfrac{N_0 (P_s |h_{SR}|^2 + N_0)}{P_r}} \tag{10}$$

The equation (10) is reformulated by using $N_0 << P_r$

$$\gamma_{e2e} = \frac{|h_{SR}|^2 |h_{RD}|^2 P_s P_r}{|h_{RD}|^2 P_r N_0 + N_0 P_s |h_{SR}|^2} \tag{11}$$

Combining with (2),(4) and substituting into (11), SNR is

$$\gamma_{e2e} = \frac{k P_B |h_{SR}|^2 |h_{RD}|^2 |h_{BR}|^2 |h_{BS}|^2}{|h_{RD}|^2 |h_{BR}|^2 N_0 + N_0 |h_{BS}|^2 |h_{SR}|^2} = \frac{k\gamma_0 XY}{X+Y} \tag{12}$$

where we denote $\gamma_0 = \dfrac{P_B}{N_0}$, $X = |h_{RD}|^2 |h_{BR}|^2$, $Y = |h_{SR}|^2 |h_{BS}|^2$.

For more analysis, utilizing the result in [19], the c.d.f. of X and Y is

$$F_X(x) = 1 - 2\sqrt{\lambda_{RD}\lambda_{BR} x} K_1\left(2\sqrt{\lambda_{RD}\lambda_{BR} x}\right) \tag{13}$$

$$F_Y(y) = 1 - 2\sqrt{\lambda_{SR}\lambda_{BS} y} K_1\left(2\sqrt{\lambda_{SR}\lambda_{BS} y}\right) \tag{14}$$

OP of the proposed system is

$$P_{out}^{AF} = \Pr(\gamma_{e2e} < \gamma_{th}) = \Pr\left(\frac{k\gamma_0 XY}{X+Y} < \gamma_{th}\right) = \Pr\left(X\left[k\gamma_0 Y - \gamma_{th}\right] < \gamma_{th} Y\right)$$

$$= \Pr\begin{cases} X < \dfrac{\gamma_{th} Y}{k\gamma_0 Y - \gamma_{th}}, & Y \geq \dfrac{\gamma_{th}}{k\gamma_0} \\ 1 & , Y < \dfrac{\gamma_{th}}{k\gamma_0} \end{cases} \tag{15}$$

where $\gamma_{th} = 2^R - 1$ is a threshold, and R is source rate.

Proposition 1**:** OP of the proposed system is given by

$$P_{out}^{AF} = 1 - 4\lambda_{SR}\lambda_{BS}\int_{\frac{\gamma_{th}}{k\gamma_0}}^{\infty}\sqrt{\frac{\lambda_{RD}\lambda_{BR}\gamma_{th} y}{k\gamma_0 y - \gamma_{th}}}K_0(2\sqrt{\lambda_{SR}\lambda_{BS} y})K_1\left(2\sqrt{\frac{\lambda_{RD}\lambda_{BR}\gamma_{th} y}{k\gamma_0 y - \gamma_{th}}}\right)dy \tag{16}$$

Proof: See Appendix A.
Finally, The system throughput at D is formulated as

$$\tau^{AF} = (1 - P_{out}^{AF})\frac{R(1-\alpha)T}{2T} = (1 - P_{out}^{AF})\frac{R(1-\alpha)}{2} = 2R(1-\alpha)\lambda_{SR}\lambda_{BS}\int_{\frac{\gamma_{th}}{k\gamma_0}}^{\infty}\sqrt{\frac{\lambda_{RD}\lambda_{BR}\gamma_{th} y}{k\gamma_0 y - \gamma_{th}}}K_0(2\sqrt{\lambda_{SR}\lambda_{BS} y}) K_1\left(2\sqrt{\frac{\lambda_{RD}\lambda_{BR}\gamma_{th} y}{k\gamma_0 y - \gamma_{th}}}\right)dy \tag{17}$$

2.2. The decode and forward (DF) mode

From (1) and (2) we have the SNR for the DF mode:

$$SNR_1 = \frac{P_s |h_{SR}|^2}{N_0} = \frac{kP_B |h_{BS}|^2 |h_{SR}|^2}{N_0} = k\gamma_0 Y \tag{18}$$

$$SNR_2 = \frac{P_r |h_{RD}|^2}{N_0} = \frac{kP_B |h_{BR}|^2 |h_{RD}|^2}{N_0} = k\gamma_0 X \tag{19}$$

Furthermore, OP of the proposed system is

$$P_{out}^{DF} = \Pr\left(\min\left[SNR_1, SNR_2\right] < \gamma_{th}\right) = \Pr\left\{\min\left[k\gamma_0 Y, k\gamma_0 X\right] < \gamma_{th}\right\} \tag{20}$$

Proposition 2**:** The outage probability at the destination node of the proposed system is given by:

$$P_{out}^{DF} = 1 - 4\frac{\gamma_{th}}{k\gamma_0}\sqrt{\lambda_{RD}\lambda_{BR}\lambda_{SR}\lambda_{BS}}K_1\left(2\sqrt{\frac{\lambda_{RD}\lambda_{BR}\gamma_{th}}{k\gamma_0}}\right)K_1\left(2\sqrt{\frac{\lambda_{SR}\lambda_{BS}\gamma_{th}}{k\gamma_0}}\right) \tag{21}$$

Proof: See Appendix B.
Finally, the throughput τ at D is given by:

$$\tau^{DF} = (1 - P_{out}^{DF})\frac{R(1-\alpha)}{2} = 2R(1-\alpha)\frac{\gamma_{th}}{k\gamma_0}\sqrt{\lambda_{RD}\lambda_{BR}\lambda_{SR}\lambda_{BS}}K_1\left(2\sqrt{\frac{\lambda_{RD}\lambda_{BR}\gamma_{th}}{k\gamma_0}}\right)K_1\left(2\sqrt{\frac{\lambda_{SR}\lambda_{BS}\gamma_{th}}{k\gamma_0}}\right) \tag{22}$$

3. RESULTS AND DISCUSSION

We use the Monte Carlo simulation to verify the correctness of the analytical expression of the OP and ST in the above section in the connection of the primary parameters of the proposed system. Other simulation parameters are listed in Table 1.

Table 1. Simulation parameters

Symbol	Name	Values
η	Energy harvesting efficiency	0.7
λ_{BS}	Mean of $\|h_{BS}\|^2$	0.5
λ_{BR}	Mean of $\|h_{BR}\|^2$	0.5
λ_{SR}	Mean of $\|h_{SR}\|^2$	0.5
λ_{RD}	Mean of $\|h_{RD}\|^2$	0.5
γ_{th}	SNR threshold	7
P_B/N_0	Source power to noise ratio	0-20dB
R	Source rate	1.5 bit/s/Hz

Figure 3 and Figure 4 plot the curves of OP and ST versus α for both AF and DF modes. It is shown in Figure 3 and Figure 4 that P_B/N_0 at 10 and 20 dB, and α varies from 0 to 1. We can see from the results that OP has a decrease when α increase from 0 to 1 as shown Figure 3. Moreover, Figure 4 shows that the throughput increases in the first stage when α increases from 0 to the optimal value. After that, the system throughput has a significant decrease while α varies from optimal value to 1. In both Figure 3 and Figure 4, the analytical and simulation results agree very well with each other.

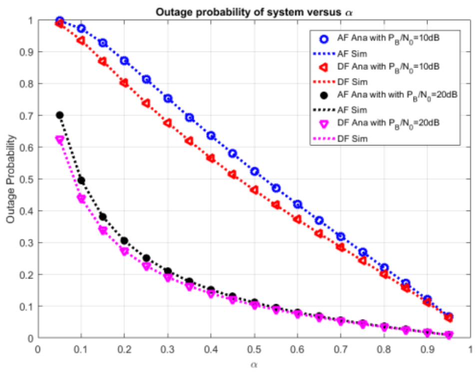

Figure 3. Outage probability versus α

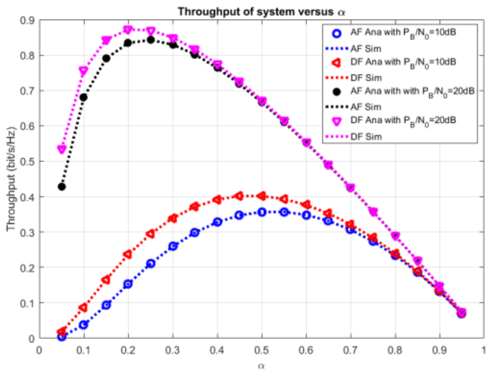

Figure 4. Throughput versus α

Figure 5 and Figure 6 illustrate the effect of η on OP and ST of the model system. Here we set α=0.5 and P_B/N_0 at 10 and 20 dB, respectively. From the results, OP decreases while η increases from 0 to 1 as shown in Figure 5. In contrast, ST has a considerable improvement when η increases from 0 to 1 as shown in Figure 6. For both cases, the analytical simulation results are the same values. Moreover, OP and ST versus R are shown in Figure 7 and Figure 8, respectively. Similarity, we set P_B/N_0 at 10 and α at 0.2, 0.8. From Figure 7 we see that OP increases while R varies from 1 to 8. In contrast, ST increase in the first interval R to optimal value then has a huge decrease as shown in Figure 8. Furthermore, Figure 10 shows the optimal time switching factor of the proposed system at R=1 and 3 bps. In all figures, the simulation and analytical results agree with each other.

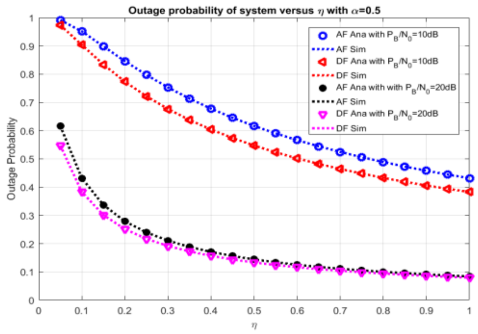

Figure 5. Outage probability versus η

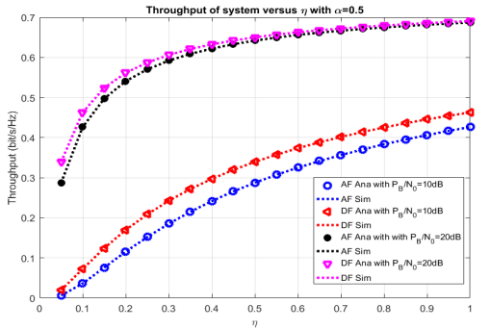

Figure 6. Throughput versus η

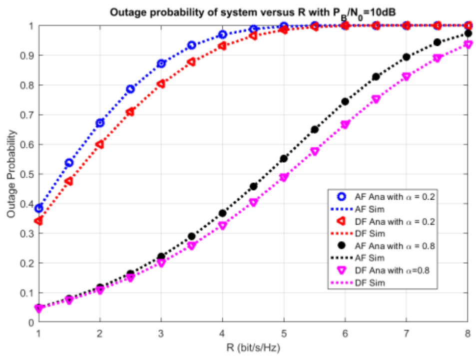

Figure 7. Outage probability versus R

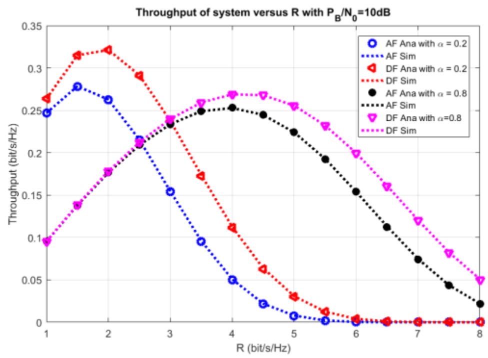

Figure 8. Throughput versus R

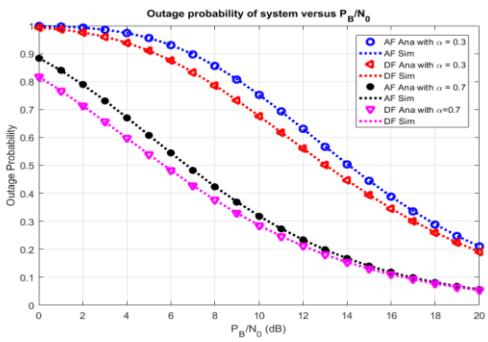

Figure 9. Outage probability versus PB/N0

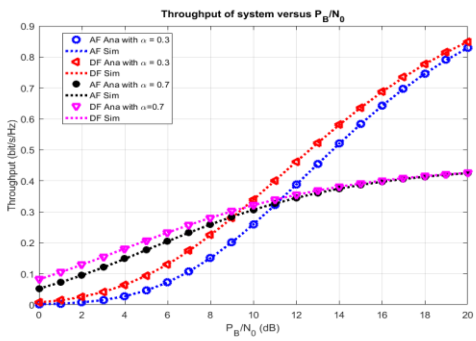

Figure 10. Throughput versus PB/N0

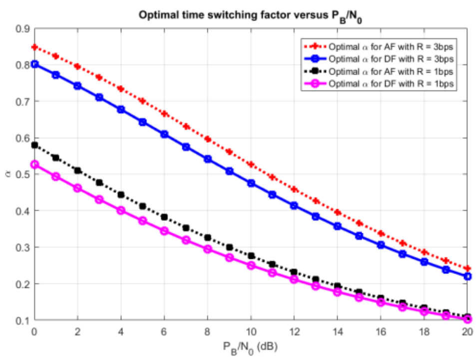

Figure 11. Optimal time switching factor versus PB/N0

4. CONCLUSION

In this paper, we investigate the HD PB EH relay network in both AF and DF modes. We derive the closed-form expressions of OP and ST of the model system. Moreover, the analytical analysis is convinced totally by the Monte Carlo simulation. Also, the optimal time switching factor is investigated. All the analytical and simulation are the same with the primary system parameters. The results can be considered as the recommendation for EH relaying network research.

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APPENDIX A

From (15), we have:

$$P_{out}^{AF} = \int_0^{\frac{\gamma_{th}}{k\gamma_0}} f_Y(y)dy + \int_{\frac{\gamma_{th}}{k\gamma_0}}^{\infty} f_Y(y)dy \int_0^{\frac{\gamma_{th}Y}{k\gamma_0 Y-\gamma_{th}}} f_X(x)dx$$
$$= \int_0^{\frac{\gamma_{th}}{k\gamma_0}} f_Y(y)dy + \int_{\frac{\gamma_{th}}{k\gamma_0}}^{\infty} f_Y(y)dy \left\{1-2\sqrt{\frac{\lambda_{RD}\lambda_{BR}\gamma_{th}Y}{k\gamma_0 Y-\gamma_{th}}}K_1\left(2\sqrt{\frac{\lambda_{RD}\lambda_{BR}\gamma_{th}Y}{k\gamma_0 Y-\gamma_{th}}}\right)\right\} \tag{A1}$$

$$P_{out}^{AF} = 1-2\int_{\frac{\gamma_{th}}{k\gamma_0}}^{\infty} \sqrt{\frac{\lambda_{RD}\lambda_{BR}\gamma_{th}Y}{k\gamma_0 Y-\gamma_{th}}}K_1\left(2\sqrt{\frac{\lambda_{RD}\lambda_{BR}\gamma_{th}Y}{k\gamma_0 Y-\gamma_{th}}}\right)f_Y(y)dy \tag{A2}$$

So, we can compute $f_Y(y)$ by using equation [8.486,18] in [22]

$$\frac{d}{dz}(z^v K_v(z)) = -z^v K_{v-1}(z) \tag{A3}$$

$$f_Y(y) = \frac{d\{F_Y(y)\}}{dy} = 2\lambda_{SR}\lambda_{BS} K_0(2\sqrt{\lambda_{SR}\lambda_{BS} y}) \tag{A4}$$

Combine (A3), (A4), OP is obtained as in (16).

APPENDIX B

$$P_{out}^{DF} = 1 - \Pr\left(X \ge \frac{\gamma_{th}}{k\gamma_0}, Y \ge \frac{\gamma_{th}}{k\gamma_0} \right) = 1 - \Pr\left(X \ge \frac{\gamma_{th}}{k\gamma_0} \right) \Pr\left(Y \ge \frac{\gamma_{th}}{k\gamma_0} \right) \tag{B1}$$

$$\Pr\left(X \ge \frac{\gamma_{th}}{k\gamma_0} \right) = 1 - \Pr\left(X < \frac{\gamma_{th}}{k\gamma_0} \right) = 1 - F_X\left(\frac{\gamma_{th}}{k\gamma_0} \right) \tag{B2}$$

From (9) we obtain:

$$\Pr\left(X \ge \frac{\gamma_{th}}{k\gamma_0} \right) = 2\sqrt{\frac{\lambda_{RD}\lambda_{BR}\gamma_{th}}{k\gamma_0}} K_1\left(2\sqrt{\frac{\lambda_{RD}\lambda_{BR}\gamma_{th}}{k\gamma_0}} \right) \tag{B3}$$

Similar as above, we can compute:

$$\Pr\left(Y \ge \frac{\gamma_{th}}{k\gamma_0} \right) = 2\sqrt{\frac{\lambda_{SR}\lambda_{BS}\gamma_{th}}{k\gamma_0}} K_1\left(2\sqrt{\frac{\lambda_{SR}\lambda_{BS}\gamma_{th}}{k\gamma_0}} \right) \tag{B4}$$

From (B4), (20) is demonstrated.