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Performance analysis for power-splitting energy harvesting based two-way full-duplex relaying network over nakagami-m fading channel

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Abstract

Energy harvesting relay network is considered as the promising solution for a wireless communication network in our time. In this research, we present and demonstrate the system performance of the energy harvesting based two-way full-duplex relaying network over Nakagami-m fading environment. Firstly, we propose the analytical expressions of the achievable throughput and outage probability of the proposed system. In the second step, the effect of various system parameters on the system performance is presented and investigated. In the final step, the analytical results are also demonstrated by Monte-Carlo simulation. The numerical results demonstrated and convinced the analytical and the simulation results are agreed with each other.

Keywords*: full-duplex, outage probability, throughput, wireless energy harvesting (EH)*

1. Introduction

Radio frequency (RF) energy transfer and harvesting has recently emerged as a promising way to extend the lifetime of energy-constrained wireless networks, especially when conventional energy harvesting techniques from renewable energy sources are not applicable. This technique enables wireless terminals to scavenge energy from RF signals broadcast by ambient/dedicated wireless transmitters to support their operation and information transmission. This new communication format has been termed wireless-powered communication (WPC) in the literature, which advocates the dual function of RF signals for both information delivery and energy transfer. In WPC, wireless terminals can avoid being interrupted by their batteries' depletion, which can thus be deployed more flexibly and maintained at lower cost. In this sense, WPC has greater potential to sustain the network operation than its conventional battery-powered counterpart in a long run. Thanks to these inherent merits, WPC has been regarded as an indispensable and irreplaceable building block in a wide range of applications, e.g., RFID, wireless sensor networks, machine-to-machine communications, low-power wide-area networks, and Internet of Things, and so on [1-7].

In this paper, the system performance of the energy harvesting based two-way full-duplex re-laying network over Nakagami-m fading environment is proposed and investigated. Firstly, we analyze and demonstrate the analytical expressions of the achievable throughput, and outage probability of the proposed system. In the second step, the effect of various system parameters on the system performance is presented and investigated. In the final step, the analytical results are also demonstrated by Monte-Carlo simulation.

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The numerical results demonstrated and convinced the analytical and the simulation results are agreed with each other. The main contributions of the paper are summarized as follows:

i). The system model of energy harvesting based two-way full-duplex re-laying network over Nakagami-m fading environment with the power switching protocol is proposed and investigated.

ii). The closed-form of the outage probability and throughput of the proposed system is derived.

iii). The influence of the main parameters on the system performance is demonstrated entirely.

The remaining of this paper is presented as follows. Sections 2 presents the system model of the model system. Sections 3 proposes and demonstrates the analytical mathematical expressions of the system performance. Section 4 provides the numerical results and some discussions. Finally, section 5 concludes the paper.

2. System Model

In this section, energy harvesting based two-way full-duplex relaying network over Nakagami-m fading environment is proposed in Figure 1. The information transmission and energy transfer between the nodes C, D via the helping relay R are presented in Figure 1. In this system model, each node C, D has two antennas which are responsible for signal transmission and reception, respectively. The line topology is adopted, where the relay node is located on the straight line connecting the two source nodes. Assume that the two source nodes cannot receive signals from each other directly due to high path loss caused by obstacles [8-17]. In this model, the following set of assumptions are considered:

– There is no connection between the source and the destination in the results of elimination transmission information.

– The required power of the data decoding process at the relay is negligible in comparison to the signal transmission energy from the relay to the destination.

Moreover, the energy harvesting and information processing at the relay by the power switching protocol are proposed in Figure 2. In Figure 2, T is the block time, in which nodes C and D connected with each other via the helping relay R.

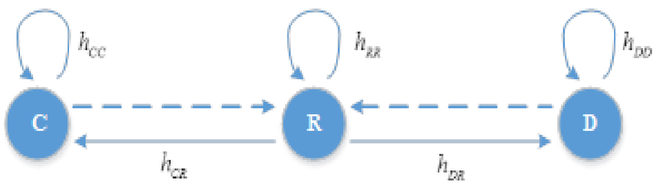

Figure 1. The proposed system model

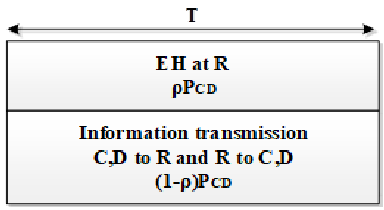

Figure 2. The energy harvesting and information processing in the proposed system

3. System Performance Analysis

The total harvested energy of R during energy harvesting time T is given by:

$$E_R = \eta P_{CD}\left(|h_{CR}|^2 + |h_{DR}|^2\right)\rho T \quad (1)$$

where $0 < \eta < 1$ is the energy conversion efficiency which depends on the rectification process and the energy harvesting circuitry in [10] and $P_C = P_D = P_{CD}$ denotes the transmission power of node C and D. Furthermore, $0 < \rho < 1$: is the power fraction, which can affect the system throughput. Moreover, the average transmission power of R is computed by:

$$P_R = \frac{E_R}{T} = \frac{\eta\rho T P_{CD}}{T}\left(|h_{CR}|^2 + |h_{DR}|^2\right) = \eta\rho P_{CD}\left(|h_{CR}|^2 + |h_{DR}|^2\right) \quad (2)$$

Due to the full-duplex system, the multiple-access phase (MAP) and the broadcast phase (BCP) can work at the same time. Therefore, the received signal at the relay can be expressed as:

$$y_R = \sqrt{1-\rho}\, h_{CR} x_C + \sqrt{1-\rho}\, h_{DR} x_D + h_{RR} x_R + n_R \quad (3)$$

where x_C, x_D are the transmission signal from node C and D , respectively, h_{RR} denotes the residual self-interference channel at R and n_R the zero-mean additive white Gaussian noise (AWGN) with variance N_0, and $\mathrm{E}\left\{|x_C|^2\right\} = \mathrm{E}\left\{|x_D|^2\right\} = P_{CD}; E\left\{|x_R|^2\right\} = P_R$. Here E{.} denotes the expectation operation, h_{CR}, h_{DR} are the Nakagami-m distribution factors. In this research model, the amplify-and-forward protocol is used. Hence, the received signal at the relay is amplified by a factor β which is given by:

$$\beta = \frac{x_R}{y_R} = \sqrt{\frac{P_R}{(1-\rho)P_{CD}\left[|h_{CR}|^2 + |h_{DR}|^2\right] + P_R|h_{RR}|^2 + N_0}} \quad (4)$$

The receive signal at the C can be express as:

$$y_C = h_{CR} x_R + h_{CC} x_C + n_C \quad (5)$$

where x_R are the transmission signal from R, h_{CC} denotes the residual self-interference channel at node A and n_C the zero-mean additive white Gaussian noise (AWGN) with variance N_0 combine (3) and (4), (5) can be rewritten as:

$$\begin{aligned} y_C &= h_{CR}\beta y_R + h_{CC} x_C + n_C \\ &= h_{CR}\beta\left[\sqrt{1-\rho}\, h_{CR} x_C + \sqrt{1-\rho}\, h_{DR} x_D + h_{RR} x_R + n_R\right] + h_{CC} x_C + n_C \\ &= \sqrt{1-\rho}\,\beta h_{CR}^2 x_C + \sqrt{1-\rho}\,\beta h_{CR} h_{DR} x_D + \beta h_{CR} h_{RR} x_R + \beta h_{CR} n_R + h_{CC} x_C + n_C \end{aligned} \quad (6)$$

The first term of $\sqrt{1-\rho}\,\beta h_{CR}^2 x_C$ can be totally canceled due to network coding in [11]. Substituting (2), (4) into (6), with some mathematic manipulation, the received signal to interference noise ratio (SINR) at the node C can be obtained as:

$$\gamma_C = \frac{(1-\rho)\eta\kappa^2 |h_{CR}|^2 |h_{DR}|^2 \left(|h_{CR}|^2 + |h_{DR}|^2\right)}{\kappa\eta\rho|h_{CR}|^2\left(|h_{CR}|^2 + |h_{DR}|^2\right)N_0 + \kappa(1-\rho)\left(|h_{CR}|^2 + |h_{DR}|^2\right)N_0 + N_0^2} \quad (7)$$

where we denote $\kappa = \frac{P_{CD}}{\Omega_{RR}+1} = \frac{P_{CD}}{\Omega_{CC}+1} = \frac{P_{CD}}{\Omega_{DD}+1}$. At the high SNR region, (7) can be approximated as:

$$\gamma_C \approx \frac{(1-\rho)\eta\kappa^2\omega_1\omega_2}{\kappa\eta\rho\omega_1 N_0 + \kappa(1-\rho)N_0} = \frac{(1-\rho)\eta\theta\omega_1\omega_2}{\eta\rho\omega_1 + 1 - \rho} \quad (8)$$

where we denote $\theta = \frac{\kappa}{N_0}, \omega_1 = |h_{CR}|^2, \omega_2 = |h_{DR}|^2$. In this analysis section, please note that for convenience, the residual self-interference at the three nodes is modeled as AWGN with zero mean and variance of $\Omega_{RR}, \Omega_{CC}, \Omega_{DD}$ [12] are totally identical. Similarity, we can obtain SINR at the node B as:

$$\gamma_D = \frac{(1-\rho)\eta\theta\omega_1\omega_2}{\eta\rho\omega_2 + 1 - \rho} \tag{9}$$

In this work, we consider the delay limited (DL) transmission mode, where the outage probability can compute the average throughput. At first, we will determine the probability density function (PDF) and the cumulative density function (CDF) of a random variable (RV) ω_i which $i \in \{1,2\}$. As in [13] the PDF of RV can be calculated by the following:

$$f_{\omega_i}(x) = \frac{x^{m_{\omega_i}-1}}{(m_{\omega_i}-1)!(\Omega_{\omega_i})^{m_{\omega_i}}} \exp(-\frac{x}{\Omega_{\omega_i}}) \tag{10}$$

from (10) The CDF of RV ω_i can be obtained with the help of [Eq 8.353.4] in [18].

$$F_{\omega_i}(x) = 1 - \exp(-\frac{x}{\Omega_{\omega_i}}) \sum_{t=0}^{m_{\omega_i}-1} \frac{x^t}{t!(\Omega_{\omega_i})^t} \tag{11}$$

where $\Omega_{\omega_i} = \frac{\lambda_{\omega_i}}{m_{\omega_i}}$; m_{ω_i} is the Nakagami-m parameter and note that the case of $m_{\omega_i} = 1$ corresponds to Rayleigh fading; λ_{ω_i} is the mean of RV ω_i which $i \in \{1,2\}$.

$$P_{out\_C} = F_{\gamma_C}(\gamma_{th}) = \Pr(\gamma_C < \gamma_{th}) = \Pr\left(\frac{(1-\rho)\eta\theta\omega_1\omega_2}{\eta\rho\omega_1 + 1 - \rho} < \gamma_{th}\right) \tag{12}$$

where $\gamma_{th} = 2^{2R} - 1$ is the threshold.

$$P_{out\_C} = \int_0^\infty \Pr\left\{\omega_2 < \frac{\gamma_{th}\eta\rho\omega_1 + \gamma_{th}[1-\rho]}{(1-\rho)\eta\theta\omega_1} | \omega_1\right\} f_{\omega_1}(\omega_1) d\omega_1 = \int_0^\infty F_{\omega_2}\left\{\omega_2 < \frac{\gamma_{th}\eta\rho\omega_1 + \gamma_{th}[1-\rho]}{(1-\rho)\eta\theta\omega_1} | \omega_1\right\} f_{\omega_1}(\omega_1) d\omega_1 \tag{13}$$

Combine (13) with (11), (12) we have:

$$\begin{aligned} P_{out\_C} &= 1 - \int_0^\infty \exp\left(-\frac{\gamma_{th}}{\theta\Omega_{\omega_2}}\left[\frac{\rho}{(1-\rho)} + \frac{1}{\eta\omega_1}\right]\right) \times \sum_{t=0}^{m_{\omega_2}-1} \frac{1}{t!}\left\{\frac{\gamma_{th}}{\theta\Omega_{\omega_2}}\left[\frac{\rho}{(1-\rho)} + \frac{1}{\eta\omega_1}\right]\right\}^t \\ &\times \frac{(\omega_1)^{m_{\omega_1}-1}}{(m_{\omega_1}-1)!(\Omega_{\omega_1})^{m_{\omega_1}}} \times \exp\left(-\frac{\omega_1}{\Omega_{\omega_1}}\right) d\omega_1 \end{aligned} \tag{14}$$

Now by applying the $(x+y)^m = \sum_{n=0}^{m} \binom{m}{n} x^{m-n} y^n$ to (14), the outage probability can demonstrate as follow:

$$P_{out\_C} = 1 - \int_0^{\infty} \exp\left(-\frac{\gamma_{th}}{\theta\Omega_{\omega_2}}\left[\frac{\rho}{(1-\rho)} + \frac{1}{\eta\omega_1}\right]\right) \times \sum_{t=0}^{m_{\omega_2}-1} \sum_{n=0}^{t} \frac{1}{t!}\left\{\frac{\gamma_{th}}{\theta\Omega_{\omega_2}}\right\}^t \binom{t}{n} \left[\frac{\rho}{(1-\rho)}\right]^{t-n} \frac{1}{(\eta\omega_1)^n} \times \frac{(\omega_1)^{m_{\omega_1}-1}}{(m_{\omega_1}-1)!(\Omega_{\omega_1})^{m_{\omega_1}}} \times \exp\left(-\frac{\omega_1}{\Omega_{\omega_1}}\right) d\omega_1 \tag{15}$$

$$P_{out\_C} = 1 - \exp\left(-\frac{\gamma_{th}}{\theta\Omega_{\omega_2}}\left[\frac{\rho}{(1-\rho)}\right]\right) \times \sum_{t=0}^{m_{\omega_2}-1} \sum_{n=0}^{t} \frac{1}{(t-n)!n!(m_{\omega_1}-1)!(\eta)^n(\Omega_{\omega_1})^{m_{\omega_1}}} \left\{\frac{\gamma_{th}}{\theta\Omega_{\omega_2}}\right\}^t \left[\frac{\rho}{(1-\rho)}\right]^{t-n} \times \int_0^{\infty} (\omega_1)^{m_{\omega_1}-1-n} \times \exp\left(-\frac{\omega_1}{\Omega_{\omega_1}}\right) \times \exp\left(-\frac{\gamma_{th}}{\theta\eta\omega_1\Omega_{\omega_2}}\right) d\omega_1 \tag{16}$$

using Table of Integral [3.471,9] in [18], the (16) can reformulate as:

$$P_{out\_C} = 1 - 2\exp\left(-\frac{\gamma_{th}}{\theta\Omega_{\omega_2}}\left[\frac{\rho}{(1-\rho)}\right]\right) \times \sum_{t=0}^{m_{\omega_2}-1} \sum_{n=0}^{t} \frac{1}{(t-n)!n!(m_{\omega_1}-1)!(\eta)^n(\Omega_{\omega_1})^{m_{\omega_1}}} \left\{\frac{\gamma_{th}}{\theta\Omega_{\omega_2}}\right\}^t \left[\frac{\rho}{(1-\rho)}\right]^{t-n} \times \left(\frac{\gamma_{th}\Omega_{\omega_1}}{\theta\eta\Omega_{\omega_2}}\right)^{\frac{m_{\omega_1}-n}{2}} \times K_{m_{\omega_1}-n}\left(2\sqrt{\frac{\gamma_{th}}{\theta\eta\Omega_{\omega_2}\Omega_{\omega_1}}}\right) \tag{17}$$

$$P_{out\_C} = 1 - 2\exp\left(-\frac{\gamma_{th}}{\theta\Omega_{\omega_2}}\left[\frac{\rho}{(1-\rho)}\right]\right) \times \sum_{t=0}^{m_{\omega_2}-1} \sum_{n=0}^{t} \frac{1}{(t-n)!n!(m_{\omega_1}-1)!(\eta\Omega_{\omega_1})^{\frac{m_{\omega_1}+n}{2}}} \times \left(\frac{\gamma_{th}}{\theta\Omega_{\omega_2}}\right)^{\frac{2t+m_{\omega_1}-n}{2}} \times \left[\frac{\rho}{(1-\rho)}\right]^{t-n} \times K_{m_{\omega_1}-n}\left(2\sqrt{\frac{\gamma_{th}}{\theta\eta\Omega_{\omega_2}\Omega_{\omega_1}}}\right) \tag{18}$$

similiarity:

$$P_{out\_D} = 1 - 2\exp\left(-\frac{\gamma_{th}}{\theta\Omega_{\omega_1}}\left[\frac{\rho}{(1-\rho)}\right]\right) \times \sum_{t=0}^{m_{\omega_1}-1} \sum_{n=0}^{t} \frac{1}{(t-n)!n!(m_{\omega_2}-1)!(\eta\Omega_{\omega_2})^{\frac{m_{\omega_1}+n}{2}}} \times \left(\frac{\gamma_{th}}{\theta\Omega_{\omega_1}}\right)^{\frac{2t+m_{\omega_2}-n}{2}} \times \left[\frac{\rho}{(1-\rho)}\right]^{t-n} \times K_{m_{\omega_2}-n}\left(2\sqrt{\frac{\gamma_{th}}{\theta\eta\Omega_{\omega_2}\Omega_{\omega_1}}}\right) \tag{19}$$

where $K_v(\bullet)$ is the modifed Bessel function of the second kind and v[th] order. Finally, the achievable throughput at the source nodes C and D can compute by:

$$\tau_j = (1 - P_{out\_j}) \times R \text{ which } j \in (C, D) \tag{20}$$

4. Numerical Results and Discussion

In this section, Monte Carlo simulation results are presented to verify our theoretical derivations section 3. In this section, we investigate the system performance (in term of the throughput, the outage probability) of the energy harvesting based two-way full-duplex relaying network over Nakagami-m fading environment is validated in details [14-25]. The simulation parameters are listed in Table 1.

Table 1. Simulation Parameters

Symbol	Name	Values
η	Energy harvesting efficiency	0.7
λ_{ω_1}	Mean of $\lvert h_{CR}\rvert^2$	1
λ_{ω_2}	Mean of $\lvert h_{DR}\rvert^2$	1
m	Nakagami m-factor	3
γ_{th}	SNR threshold	7
Ps/N0	Source power to noise ratio	0-40dB
$\Omega_{AA}=\Omega_{BB}=\Omega_{RR}=\Omega$	Residual self-interference	0-5dB
R	Source rate	1.5 bit/s/Hz

Figures 3 and 4 investigates the impact of P_{CD}/N_0 on the outage probability and throughput of the proposed model system. The parameters of this figure are set by ρ=0.5 and Ω=0, 0.5, 5. As we can see, as P_{CD}/N_0 from 0 to 40, the outage probability of the model system decreases but the throughput increases remarkably. Moreover, the Monter Carlo simulation agrees well with the analytical expression. In another hand, the system performance is presented as a function of ρ when P_{CD}/N_0=20 and Ω=0, 0.5, 5 as shown in Figures 5 and 6. As the research results, we can see that outage probability significantly increases, and the throughput rapidly decreases when the value of ρ increases from 0 to 1. We can observe that the simulation results match very well with the theoretical results.

Furthermore, In Figures 7 and 8, we investigate the impact of Ω on outage probability and the throughput of the model system, respectively. In this simulation, we set the main system parameters as P_{CD}/N_0=20 and ρ=0.3, 0.6, 0.9. In these figures, we can see that that outage probability significantly increases and the throughput rapidly decreases when the value of Ω increases from 0 to 5. Once again, the theoretical and simulation results are in a good agreement. On the other way, Figure 9 and 10 illustrates system performance as a function of $m=m_1=m_2$ from 0 to 8 when P_{CD}/N_0=20 and Ω=0, 0.5, 5. It can be seen from the research results that as increasing the value of $m=m_1=m_2$, the outage probability of the model system decreases but the throughput increases remarkably. Again, the theoretical and simulation results agree with each other very well.

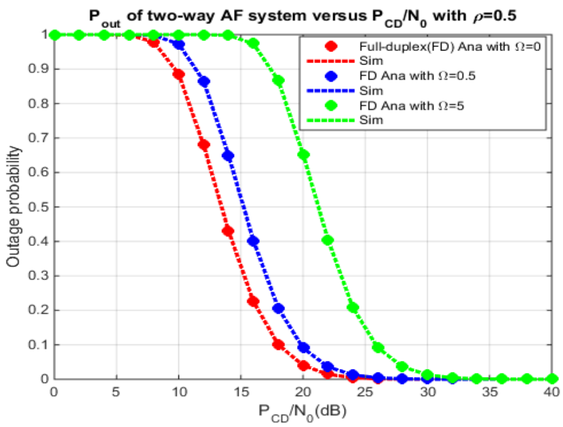

Figure 3. Outage probability versus PCD/N0

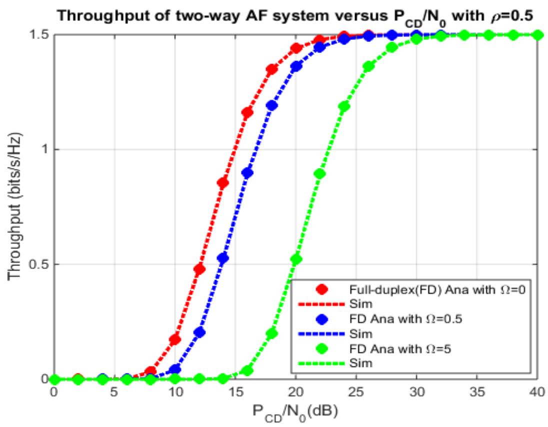

Figure 4. Throughput versus PCD/N0

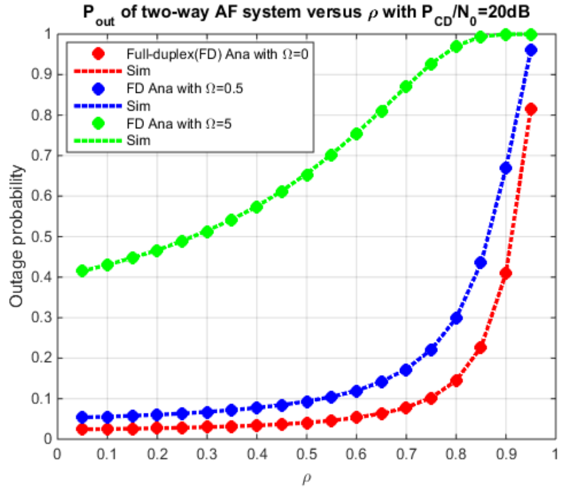

Figure 5. Outage probability versus ρ

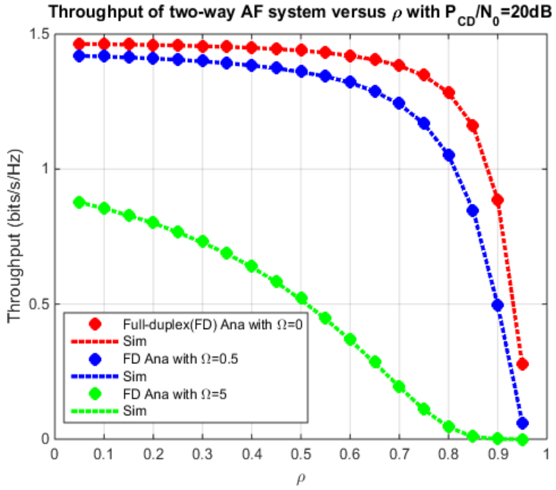

Figure 6. Throughput versus ρ

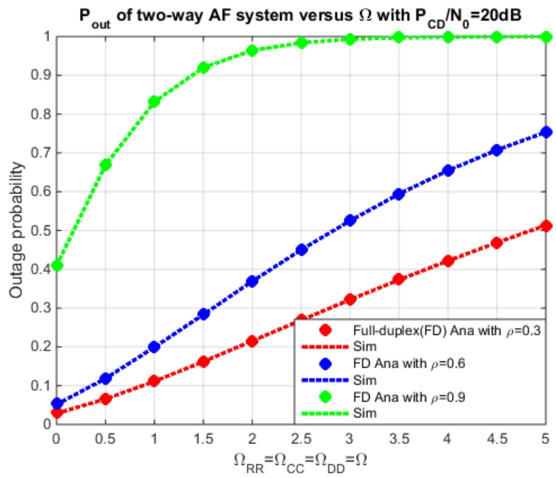

Figure 7. Outage probability versus Ω

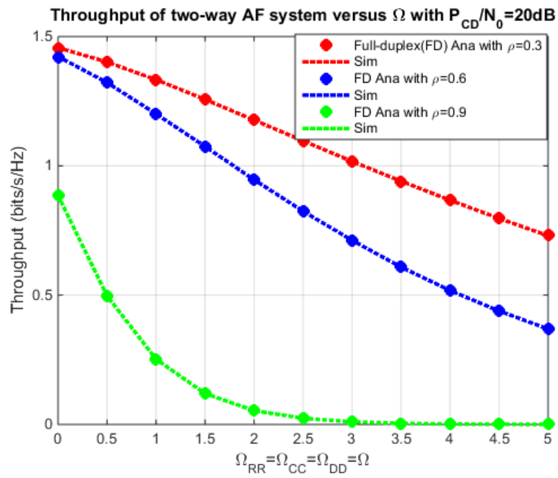

Figure 8. Throughput versus Ω

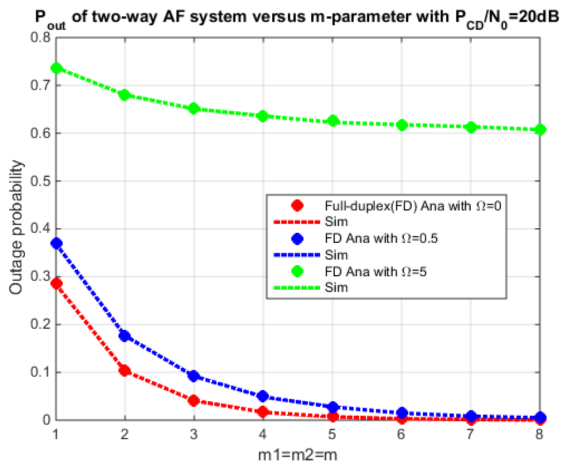

Figure 9. Outage probability versus $m=m_1=m_2$

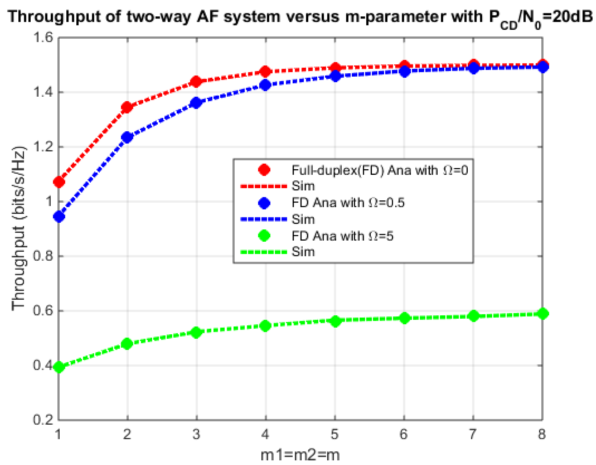

Figure 10. Throughput versus $m=m_1=m_2$

4. Conclusion

In this paper, the system performance of the energy harvesting based two-way full-duplex relaying network over Nakagami-m is demonstrated. Analytical expressions for the outage probability, and the throughput are proposed and investigated for investigating the system performance. The research results show that the analytical mathematical expression and the simulation results using Monte Carlo method are totally matched each other. Moreover, this paper has provided practical insights into the effect of various system parameters on the system performance. The results could be providing the prospective solution for the communication network via helping relay.

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