Throughput Analysis of the Two-way Relay System with Network Coding and Energy Harvesting

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***Abstract*—This paper studies the throughput performance of a two-way energy harvesting relaying system. Network Coding and Energy Harvesting are promising techniques that can improve the transmission efficiency and the energy efficiency of wireless systems, respectively. In particular, we focus on the energy harvesting system with the power splitting-based relaying (PSR) protocol, and consider both the amplify-and-forward (AF) relaying and decode-and-forward (DF) relaying methods for the network coding. We successfully derive the expressions for both the outage probability and the system throughput for each case. It can be shown that DF relaying system outperforms AF relaying system in terms of both the outage probability and the throughput. Furthermore, simulations show that the throughput gain brought by network coding highly depends on the signal-to-noise ratio (SNR) at the receiver. The throughput gain can be up to 33% in the high SNR region.**

***Index Terms*—Two-way relay system, throughput, network coding, energy harvest, outage probability.**

I. Introduction

Energy harvesting (EH) technology is a promising technique that can prolong the lifetime of wireless devices [1–6]. In particular, radio-frequency (RF) signal energy harvesting technology is widely used in the wireless communication system [1, 2]. Compared with the conventional energy harvesting methods (i.e. solar, wind, thermal, vibration, etc.) [3], RF energy harvesting technology has an abundant of energy supplied by ambient signal sources regarding of the system's location or time of day [4, 5].

In this paper, we are interested in the throughput performance of the two-way relay system where the relay node has the energy harvesting capability. Simultaneous energy and information transmission in wireless system was first proposed in [7]. The authors in [7] showed that the system can achieve more throughput in the ideal receiver which can extract energy and decode information simultaneously. However, [8] showed that information decoding and energy extracting can't be implemented simultaneously, because of the limit of the circuit. Since then, several receiver models have been proposed, such as Time Switching, Power Splitting, Antenna Switching, and Spatial Switching [9–12]. The authors in [10] have studied both TSR protocol and PSR protocol of one-way energy harvesting relaying system, and derived its throughput expression. The authors in [13] considered the PSR protocol in the two-way relay system *without* network coding, and analyzed the outage probability of the system using GA algorithm.

Network coding can further improve the transmission efficiency of the two-way relay system [14, 15]. It was showed that the three-slot network coding system can achieve a throughput improvement of 33% over the traditional transmission scheduling scheme [15]. The authors in [16] further proposed the Denoise-and-forward (DNF) Bi-directional Amplification of Throughput (BAT) relaying method, and made a comparison among AF BAT-relaying, DF BAT-relaying and DNF BAT-relaying, without energy harvesting. The throughput performance of different network coding relaying schemes has been studied extensively [17, 18]. However, all these works are based on conventional power supply. Therefore, how much can the network coding technique improve the throughput performance of the two-way relay system with *energy harvesting relay* is still an open problem.

In this paper, we give a comprehensive study on both the outage probability and the system throughput for the two-way energy harvesting relaying system with network coding scheme. In particular, we focus on the PSR protocol when the relay node performances energy harvesting and communication. Furthermore, we consider both the amplify-and-forward (AF) and decode-and-forward (DF) when the relay performs network coding. The main contributions of this paper are listed as follows:

1) We successfully derive the expressions of the outage probability and the system throughput for both the PSR AF relaying system and the PSR DF relaying system. The accuracy of the analytical expressions is verified.
2) We show that, given the same receiver architecture, DF relaying system achieves more throughput than the AF relaying system does.
3) We further compare the throughput performance with the energy harvesting relaying system without network coding scheme. It turns out that the throughput gain brought by network coding in the AF scheme highly depends on the SNR at the receiver. The throughput gain can be up to 33% in the high SNR region.

The remainder of this paper is organized as follows: Section II presents the system model and the PSR protocol. In Section III, we derive the analytical expressions of outage probability

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and throughput for the AF scheme and DF scheme in the PSR protocol, respectively. Section IV presents the simulation results. Finally, Section V concludes the paper and summarizes the key results.

II. System Model

We consider a two-way energy harvesting relaying system, as showed in Fig. 1. The network contains three nodes: two users S_1 and S_2, and one relay node R. Nodes S_1 and S_2 aim to exchange their information with the help of the relay node which is energy constrained. With energy harvesting technology, the relay node can extract energy from RF signals transmitted from S_1 and S_2. Such energy can be used for the information process and transmission at the relay node.

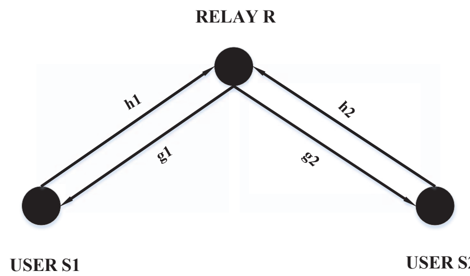

Fig. 1. Network model, where h_1, h_2, g_1, g_2 are channel gains.

In the following discussion, we make several assumptions:

- There is no direct link between S_1 and S_2.
- The processing power required by the transmit/receive circuitry at R is negligible.
- The channel is constant over the block time T and independent and identically distributed between adjacent time blocks, following a Rayleigh distribution [8, 9].

Since R can't receive information and extract energy from the received signal simultaneously, we adopt the power splitting-based relaying (PSR) protocol [7]. In the network coding scheme, the end-to-end transmission is completed with three time slots: R receives the signal from S_1 and S_2, and extracts energy from both signals in the first two time slots, then R broadcasts the processed signal to both S_1 and S_2 in the third slot. In PSR protocol, S_1 and S_2 transmit signal to R in the first two time slots; R receives these signals, a part of power is used for energy harvesting, the other is for information transmission. We assume that the duration of the first phase and the second phase are both θT, then the time and power allocation is

$$T\begin{cases}\theta T & \begin{cases}\rho P_1 & EHatS1\\(1-\rho)P_1 & S1\rightarrow R\end{cases}\\ \theta T & \begin{cases}\rho P_2 & EHatS2\\(1-\rho)P_2 & S2\rightarrow R\end{cases}\\ (1-2\theta)T & \quad BC\end{cases}$$

where θ is the time fraction, and ρ is the power fraction. The transmission power of S_1 and S_2 are denoted by P_1 and P_2.

A. Phase 1 and 2 (relay receives signal from users)

In the first two time slots, user 1 (or 2) transmits normalized signal $x_i(t)$ to R with power P_i, i.e. $E\left\{|x_i(t)|^2\right\} = 1$, $i = 1, 2$. The received signal at R is

$$y_{ri}(t) = \sqrt{P_i}h_i x_i(t) + \widetilde{n}_{ai}^{[r]}(t), \tag{1}$$

where $\widetilde{n}_{ai}^{[r]}(t)$ is the noise introduced at R, $i = 1, 2$. This signal is divided into two parts. The first part ρP_i is used for energy harvesting, with the duration θT. The extracted energy at R is given by

$$E_{hi} = \theta\rho\eta P_i\left|h_i\right|^2 T, \tag{2}$$

where $0 < \eta < 1$ is the energy conversion efficiency which depends on the technology of energy harvesting. The rest power $(1-\rho)P_i$ is used for information transmission. After RF band to baseband signal conversion, the received sampled signal at R is

$$y_{ri}(k) = \sqrt{(1-\rho)P_i}h_i x_i(k) + \sqrt{(1-\rho)}n_{ai}^{[r]}(k) + n_{ci}^{[r]}(k), \tag{3}$$

where $n_{ci}^{[r]}(k)$ is the Gaussian noise introduced due to RF band signal to baseband signal conversion. When it comes to how to deal with the two information signals from S_1 and S_2, we consider both the amplify-and-forward (AF) relaying and decode-and-forward (DF) relaying methods.

B. Amplify-and-forward relaying protocol

In the first two phases, R receives two packets from S_1 and S_2. In the AF relaying protocol: R combines these two packets, adding up the signal received at R. Thus the received signal at R is given by

$$y_r(k) = \sqrt{(1-\rho)P_1}h_1x_1(k) + \sqrt{(1-\rho)P_2}h_2x_2(k) + n^{[r]}(k), \tag{4}$$

where $n^{[r]}(k) \triangleq n_1^{[r]}(k) + n_2^{[r]}(k)$ and $n_i^{[r]}(k) \triangleq \sqrt{(1-\rho)}n_{ai}^{[r]}(k) + n_{ci}^{[r]}(k)$ are the noise introduced in the first two time slots.

In the AF relaying protocol, the combined signal is amplified. R then broadcasts the processed signal in the third time slot using its stored energy. Thus the broadcast power P_r at R is given by

$$P_r = \frac{E_{h1} + E_{h2}}{(1-2\theta)T} = \frac{\theta\rho\eta\left(P_1\left|h_1\right|^2 + P_2\left|h_2\right|^2\right)}{1-2\theta}. \tag{5}$$

Then the signal is amplified. The achieved signal $x_r(k)$ is

$$\begin{aligned}x_r(k) &= \frac{\sqrt{P_r}y_r(k)}{\sqrt{(1-\rho)P_1\left|h_1\right|^2 + (1-\rho)P_2\left|h_2\right|^2 + \sigma^2_{n_1^{[r]}} + \sigma^2_{n_2^{[r]}}}}\\ &\approx \frac{\sqrt{P_r}y_r(k)}{\sqrt{(1-\rho)P_1\left|h_1\right|^2 + (1-\rho)P_2\left|h_2\right|^2}}\\ &= \frac{\sqrt{\theta\rho\eta}}{\sqrt{(1-\rho)(1-2\theta)}}\Big[\sqrt{(1-\rho)P_1}h_1x_1(k)\\ &\quad + \sqrt{(1-\rho)P_2}h_2x_2(k) + n_1^{[r]}(k) + n_2^{[r]}(k)\Big],\end{aligned} \tag{6}$$

where $\sqrt{(1-\rho)P_1|h_1|^2+(1-\rho)P_2|h_2|^2+\sigma^2_{n_1^{[r]}}+\sigma^2_{n_2^{[r]}}}$ is the power constraint factor at R, $\sigma^2_{n_1^{[r]}}$ and $\sigma^2_{n_2^{[r]}}$ are the variances of the noise. When the SNR at R is large enough, the impact of noise can be ignored. In this case, the noise variance terms can be removed, and the power constraint factor can be simplified.

After information processing, R broadcasts the combined signal to S_1 and S_2. User S_i receives the signal Since it knows its own transmitted signal, that part of signal will be considered as noise and be subtracted. Thus the final signal at user S_i is

$$\begin{aligned} y_i(k) =& g_i x_r(k) + n_i^{[d]}(k) \\ =& \frac{\sqrt{\theta\rho\eta}}{\sqrt{(1-\rho)(1-2\theta)}}\left[\sqrt{(1-\rho)P_j}g_i h_j x_j(k) + \right. \\ & \left. g_i\left(n_1^{[r]}(k)+n_2^{[r]}(k)\right)\right] + n_i^{[d]}(k), i,j=1,2; i\neq j, \end{aligned} \tag{7}$$

where $\sigma^2=\sigma^2_{n_1^{[r]}}=\sigma^2_{n_2^{[r]}}=\sigma^2_{n_1^{[d]}}=\sigma^2_{n_2^{[d]}}$, and $n_i^{[d]}(k)$ is the noise introduced in the third time slot.

C. Decode-and-forward relaying protocol

In the decode-and-forward (DF) relaying protocol, R receives signals from S_1 and S_2 in two separate slots. It then decodes the packets: $y_{r1}(k) \xrightarrow{Decode} x_1(k)$; $y_{r2}(k) \xrightarrow{Decode} x_2(k)$.

R encodes these two decoded packets with XOR operation, and obtains the normalized packet $x(k)$: $x_1(k)\oplus x_2(k)\rightarrow x(k)$, where $E\left\{|x(k)|^2\right\}=1$.

R then broadcasts $x(k)$ to S_1 and S_2. User S_i receives the packet, and decodes it using XOR operation with its own transmitted packet. So the received signal at user S_i is given by

$$y_i(k)=\sqrt{P_r}g_i x(k)+n_i^{[d]}(k), \quad i,j=1,2; i\neq j, \tag{8}$$

where $n_i^{[d]}(k)$ is the noise introduced in the third time slot. The broadcast power P_r is the same as given in (5).

III. Outage Probability and Throughput Analysis

In this section, we aim to derive expressions of achievable throughput for both the AF scheme and DF scheme under the PSR protocol. In each case, we need to first derive the outage probability and then compute the achievable throughput.

A. PSR AF protocol

In the AF relaying scheme, the finally received signal at each end user is given by (7). Therefore, according to equation $\gamma=\frac{E\left\{|signal-part|^2\right\}}{E\left\{|noise-part|^2\right\}}$, we can compute the SNR at each end user, which is given by

$$\gamma_i=\frac{(1-\rho)\theta\rho\eta P_j|g_i|^2|h_j|^2}{2\theta\rho\eta\sigma^2|g_i|^2+(1-\rho)(1-2\theta)\sigma^2}, i,j=1,2; i\neq j, \tag{9}$$

where $\sigma^2=\sigma^2_{n_1^{[r]}}=\sigma^2_{n_2^{[r]}}=\sigma^2_{n_1^{[d]}}=\sigma^2_{n_2^{[d]}}$.

Next we will derive the expression of outage probability, which is very important to compute the achievable throughput. When the user node transmits signal at a fixed rate U, p_{out} is given by

$$p_{out}=1-p(\gamma_1\geq\gamma_0)p(\gamma_2\geq\gamma_0), \tag{10}$$

where γ_0 is the SNR threshold value at the receiver for correct reception at rate U, i.e., $\gamma_0=2^U-1$. The following proposition shows the outage probability at user S_1.

Proposition 1: The outage probability at user S_1 is given by

$$\begin{aligned} p(\gamma_1\geq\gamma_0) =& \frac{1}{\lambda_{g_1}}\exp\left(-\frac{2\gamma_0\sigma^2}{(1-\rho)P_2\lambda_{h_2}}\right) \\ & * \int_{z=0}^{\infty}\exp\left(-\frac{(1-2\theta)\sigma^2\gamma_0}{\theta\rho\eta P_2\lambda_{h_2}z}-\frac{z}{\lambda_{g_1}}\right)dz, \end{aligned} \tag{11}$$

where $|h_2|^2$ and $|g_1|^2$ are exponential random variables, and λ_{h_2} and λ_{g_1} are their mean values, respectively.

Proof: See Appendix A.

Similarly, the expression of $p(\gamma_2\geq\gamma_0)$ is given by

$$\begin{aligned} p(\gamma_2\geq\gamma_0) =& \frac{1}{\lambda_{g_2}}\exp\left(-\frac{2\gamma_0\sigma^2}{(1-\rho)P_1\lambda_{h_1}}\right) \\ & * \int_{z=0}^{\infty}\exp\left(-\frac{(1-2\theta)\sigma^2\gamma_0}{\theta\rho\eta P_1\lambda_{h_1}z}-\frac{z}{\lambda_{g_2}}\right)dz, \end{aligned} \tag{12}$$

where $|h_1|^2$ and $|g_2|^2$ are exponential random variables, and λ_{h_2} and λ_{g_2} are their mean values, respectively.

Substituting (11) and (12) into (10), we can derive the analytical expression of the outage probability of this system. Users transmit signal at rate U, and the effective transmission duration is the minimum of θT and $(1-2\theta)T$. Therefore, the achievable throughput is given by

$$\tau=(1-p_{out})U\times 2\min(\theta,1-2\theta). \tag{13}$$

B. PSR DF protocol

In the DF relaying scheme, we first compute the SNR of uplink and down link, respectively. In the uplink ($S_i\rightarrow R$), the SNR of the signal S_i at R is given by

$$\gamma_{r,i}=\frac{(1-\rho)P_i|h_i|^2}{\sigma^2}. \tag{14}$$

In the down-link phase, the SNR of the signal from R at user S_i is given by

$$\gamma_{s,i}=\frac{P_r|g_i|^2}{\sigma^2}=\frac{\theta\rho\eta\left(P_1|h_1|^2|g_i|^2+P_2|g_i|^2|h_2|^2\right)}{(1-2\theta)\sigma^2}. \tag{15}$$

In the DF relaying scheme,the outage probability is given by

$$p_{out}=1-p(\gamma_{r,1}\geq\gamma_0)p(\gamma_{r,2}\geq\gamma_0)p(\gamma_{s,1}\geq\gamma_0)p(\gamma_{s,2}\geq\gamma_0). \tag{16}$$

Equation (16) shows that the outage probability of the system in the DF relaying scheme depends on both uplink and down link. In the following, we will show how to compute each component in (16).

In the uplink phase, the outage probability $p(\gamma_{r,i} \geq \gamma_0)$ is given by

$$p(\gamma_{r,i} \geq \gamma_0) = p(\frac{(1-\rho)P_i |h_i|^2}{\sigma^2} \geq \gamma_0) = \exp(-\frac{\gamma_0 \sigma^2}{(1-\rho)\lambda_{h_i} P_i}). \tag{17}$$

The following proposition shows the outage probability at user S_1 in the down-link phase.

Proposition 2: In the down-link phase, the outage probability at user S_1 is given by:

$$\begin{aligned} &p(\gamma_{s,1} \geq \gamma_0) \\ =&\frac{2}{\lambda_{h_2}\lambda_{g_1}\sqrt{\lambda_{g_1}\lambda_{h_1}}} \int_{z=0}^{A_P}\int_{x=0}^{\infty} \frac{1}{x} B_P \\ &* K_1\left(\sqrt{\frac{4}{\lambda_{g_1}\lambda_{h_1}} B_P}\right) \exp\left(-\frac{x}{\lambda_{g_1}} - \frac{z}{x\lambda_{h_2}}\right) dxdz \\ &+ 2\sqrt{\frac{A_P}{\lambda_{h_2}\lambda_{g_1}}} K_1\left(2\sqrt{\frac{A_P}{\lambda_{h_2}\lambda_{g_1}}}\right), \end{aligned} \tag{18}$$

where $A_P = \frac{(1-2\theta)\sigma^2\gamma_0}{\theta\rho\eta P_2}$, and $B_P = \sqrt{\frac{(1-2\theta)\sigma^2\gamma_0}{\theta\rho\eta P_1} - \frac{P_2}{P_1} z}$. The notate $K_1(\cdot)$ denotes the first-order modified Bessel function of the second kind.

Proof: See Appendix B.

Similarly, the expression of the outage probability at user S_2 is given by

$$\begin{aligned} &p(\gamma_{s,2} \geq \gamma_0) \\ =&p\left(\frac{\theta\rho\eta\left(P_1 |h_1|^2 |g_2|^2 + P_2 |h_2|^2 |g_2|^2\right)}{(1-2\theta)\sigma^2} \geq \gamma_0\right) \\ =&\frac{2}{\lambda_{g_2}\lambda_{h_2}\sqrt{\lambda_{g_2}\lambda_{h_1}}} \int_{z=0}^{A_P}\int_{x=0}^{\infty} \frac{1}{x} B_P \\ &* K_1\left(\sqrt{\frac{4}{\lambda_{g_2}\lambda_{h_1}} B_P}\right) \exp\left(-\frac{x}{\lambda_{g_2}} - \frac{z}{x\lambda_{h_2}}\right) dxdz \\ &+ 2\sqrt{\frac{A_P}{\lambda_{g_2}\lambda_{h_2}}} K_1\left(2\sqrt{\frac{A_P}{\lambda_{g_2}\lambda_{h_2}}}\right). \end{aligned} \tag{19}$$

Finally, the achievable system throughput in the DF scheme is given by

$$\tau = (1 - p_{out})U \times 2\min(\theta, 1-2\theta). \tag{20}$$

IV. Numerical Results and Simulations

In this section, we conduct extensive simulations to evaluate the throughput performance of both the AF relaying system and DF relaying system under the PSR protocol. In particular, we first verify the the analytical throughput results. Furthermore, we compare the throughput performance of the energy harvesting relay system with and without network coding schemes. Finally, we show how the conversion efficiency affects the throughput performance.

A. Model validation

To validate our analytical throughput result, we calculate the achievable throughput result under different system parameters with Monte Carlo simulations. The system parameters are set as follows: $P_1 = P_2 = 1W, U = 3bits/sec/Hz, \eta = 1, \lambda_{g_1} = \lambda_{g_1} = \lambda_{h_1} = \lambda_{h_2} = 1$. Figure 2 shows the analytical throughput and the simulation results for both AF scheme and DF scheme of the PSR protocol as ρ varies from 0 to 1.

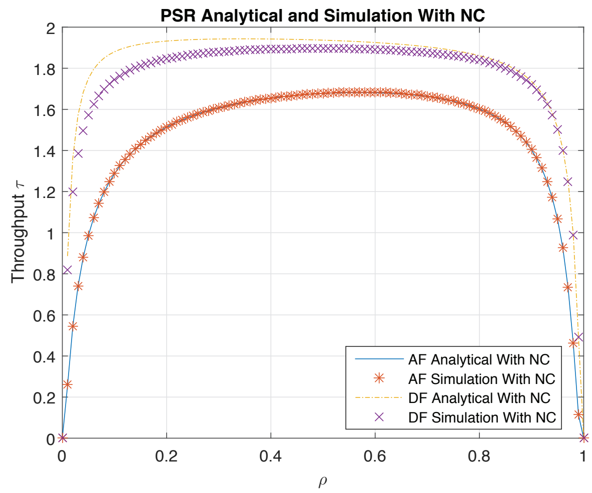

Fig. 2. PSR Protocol. Other parameter: $\sigma^2 = 10^{-3}$

From Fig. 2 we can see that the analytical throughput for both AF and DF schemes are quite accurate, since the two curves in each case are very close. Another observation from Fig. 2 is that the throughput first increases and then decreases as ρ increases from 0 to 1. This is because when ρ is small, the energy harvested at R is small, then R does not have enough power for the BC phase. On the other hand, when the harvested energy is large enough, a larger ρ means less signal power accepted at R for the information communication, so the throughput will decrease too. We can further observe that the throughput achieved in the DF scheme outperforms that in the AF scheme.

B. Throughput gain with network coding

Next, we investigate the throughput performance gain brought by the network coding scheme. We take the AF relaying scheme as an example. Figure 3 shows the throughput performance of the AF scheme with and without network coding operation R. The noise variance is set to 10^{-3}. Similarly, we can observe that the throughput first increases and then decreases as ρ increases. When $\sigma^2 = 10^{-3}$, the maximum throughputs with and without network coding scheme are $1.682bits/sec$ and $1.308bits/sec$, respectively. In the AF scheme, the network coding operation can improve the system throughput by more than 28%.

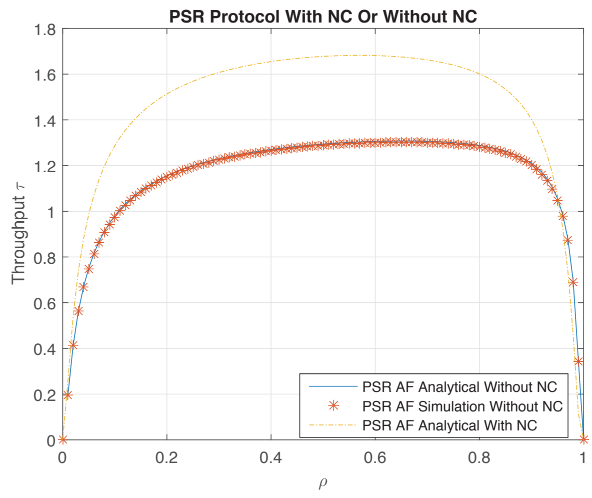

Fig. 3. PSR Protocol. The noise variance: $\sigma^2 = 10^{-3}$

Figure 4 shows the maximum system throughput as the noise variance σ^2 changes from 10^{-4} to 10^{-1}. We can observe that the throughput gain brought by network coding scheme highly depends on the noise variance. When the noise variance σ^2 is below 10^{-2}, the throughput of the network coding scheme outperforms the one without network coding scheme. The improvement of the system throughput can reach up to 33%. However, when the noise variance σ^2 is larger than 10^{-2}, the throughput of the system without network coding is higher than the one with network coding.

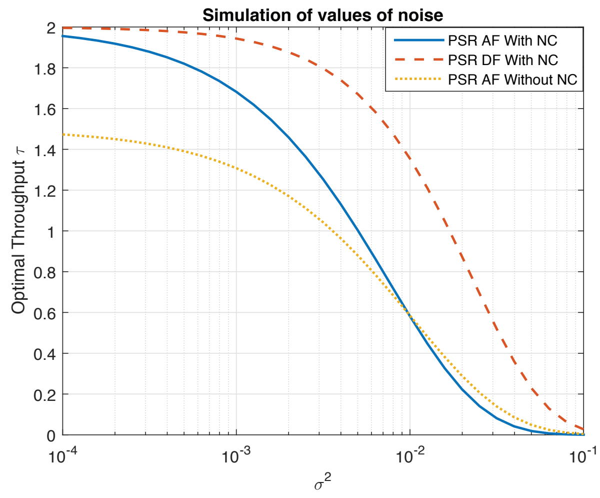

Fig. 4. The throughput v.s. noise variance. Where $P_1 = P_2 = 1W, U = 3bits/sec/Hz, \eta = 1$.

C. Effect of the conversion efficiency

Finally, we investigate how the system throughput changes as the conversion efficiency (η) varies. Figure 5 shows the maximum throughput for different systems as the energy conversion efficiency η changes from 0 to 1. It is obvious that the three time slots system outperforms the four time slots system; in the three time slots system, the DF relaying protocol outperforms the AF protocol, its optimal throughput increases faster and has a larger maximum.

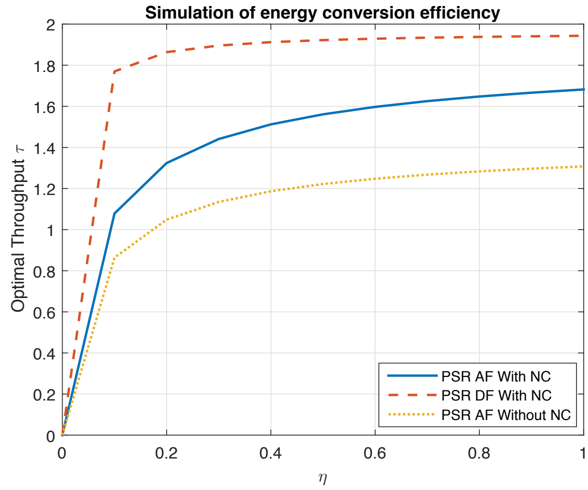

Fig. 5. Energy conversion efficiency. Other parameter: $\sigma^2 = 10^{-3}$

V. Conclusion

In this paper, we investigated the throughput performance of a two-way energy harvesting relaying system with network coding scheme. We have derived the analytical expressions for both the outage probability and achievable throughput for both the PSR AF relaying system and the PSR DF relaying system. Simulations results show that the analytical throughput result is quite accurate. We further find that the DF relaying scheme outperforms the AF relaying scheme in terms of the system throughput. In the two-way energy harvesting relaying system, the throughput gain brought by network coding operation highly depends on the noise variance.

Appendix A
Proof of Equation (11)

To derive the expression of $p(\gamma_1 \geq \gamma_0)$, we substitute (9) into $p(\gamma_1 \geq \gamma_0)$. The $p(\gamma_1 \geq \gamma_0)$ can be calculated as follows:

$$\begin{aligned}
&p(\gamma_1 \geq \gamma_0)\\
&=p\left(\frac{(1-\rho)\theta\rho\eta P_2 |g_1|^2 |h_2|^2}{2\theta\rho\eta\sigma^2 |g_1|^2 + (1-\rho)(1-2\theta)\sigma^2} \geq \gamma_0\right)\\
&=p\left(|h_2|^2 \geq \frac{2\gamma_0\sigma^2}{(1-\rho)P_2} + \frac{(1-2\theta)\sigma^2\gamma_0}{\theta\rho\eta P_2 |g_1|^2}\right)\\
&=\int_{z=0}^{\infty} f_{|g_1|^2}(z) p\left(|h_2|^2 \geq \frac{2\gamma_0\sigma^2}{(1-\rho)P_2} + \frac{(1-2\theta)\sigma^2\gamma_0}{\theta\rho\eta P_2 z}\right) dz\\
&=\frac{1}{\lambda_{g_1}} \exp(-\frac{2\gamma_0\sigma^2}{(1-\rho)P_2\lambda_{h_2}})\\
&\qquad * \int_{z=0}^{\infty} \exp(-\frac{(1-2\theta)\sigma^2\gamma_0}{\theta\rho\eta P_2\lambda_{h_2} z} - \frac{z}{\lambda_{g_1}})dz,
\end{aligned} \tag{21}$$

where $|h_2|^2$ and $|g_1|^2$ are exponential random variables, and $\lambda_{h_2}$and λ_{g_1} are their mean values, respectively. We used these equations: $f_{|h|^2}(z) \triangleq \frac{1}{\lambda_h} e^{-z/\lambda_h}$; $F_{|g|^2}(z) \triangleq p(|g|^2 < z) = 1 - e^{-z/\lambda_g}$.

APPENDIX B
PROOF OF EQUATION (18)

We first substitute the expression of SNR into $p(\gamma_{s,1} \geq \gamma_0)$. The $p(\gamma_{s,1} \geq \gamma_0)$ can be calculated as follows:

$$\begin{aligned}
&p(\gamma_{s,1} \geq \gamma_0) \\
=&p\left(\frac{\theta\rho\eta\left(P_1 |h_1|^2 |g_1|^2 + P_2 |g_1|^2 |h_2|^2\right)}{(1-2\theta)\sigma^2} \geq \gamma_0\right) \\
=&p\left(|h_1|^2 |g_1|^2 \geq \frac{(1-2\theta)\sigma^2\gamma_0}{\theta\rho\eta P_1} - \frac{P_2}{P_1} |g_1|^2 |h_2|^2\right) \\
=&\int_{z=0}^{\infty} f_{|g_1|^2|h_2|^2}(z) p\left(|h_1|^2 |g_1|^2\right. \\
&\quad \left.\geq \frac{(1-2\theta)\sigma^2\gamma_0}{\theta\rho\eta P_1} - \frac{P_2}{P_1} z\right) dz \\
=&\frac{2}{\lambda_{h_2}\lambda_{g_1}\sqrt{\lambda_{g_1}\lambda_{h_1}}} \int_{z=0}^{A_P} \int_{x=0}^{\infty} \frac{1}{x} B_P \\
&* K_1\left(\sqrt{\frac{4}{\lambda_{g_1}\lambda_{h_1}}} B_P\right) \exp\left(-\frac{x}{\lambda_{h_2}} - \frac{z}{x\lambda_{g_1}}\right) dx dz \\
&\quad + 2\sqrt{\frac{A_P}{\lambda_{h_1}\lambda_{g_1}}} K_1\left(2\sqrt{\frac{A_P}{\lambda_{h_1}\lambda_{g_1}}}\right),
\end{aligned} \tag{22}$$

where $A_P = \frac{(1-2\theta)\sigma^2\gamma_0}{\theta\rho\eta P_2}$, and $B_P = \sqrt{\frac{(1-2\theta)\sigma^2\gamma_0}{\theta\rho\eta P_1} - \frac{P_2}{P_1} z}$. The notation $K_1(\cdot)$ denotes the first-order modified Bessel function of the second kind.

In the proof of Proposition 2, we used two equations listed below

$$\begin{aligned}
F_{|h_1|^2|h_2|^2}(z) &= p(|h_1|^2 \leq \frac{z}{|h_2|^2}) \\
&= \int_{x=0}^{\infty} f_{|h_2|^2}(x) p\left(|h_1|^2 \leq \frac{z}{x}\right) dx \\
&= \frac{1}{\lambda_{h_2}} \int_{x=0}^{\infty} e^{-\frac{x}{\lambda_{h_2}}} \left(1 - e^{-\frac{z}{x\lambda_{h_1}}}\right) dx,
\end{aligned} \tag{23}$$

and

$$\begin{aligned}
f_{|g_1|^2|h_2|^2}(z) &= \left(F_{|g_1|^2|h_2|^2}(z)\right)' \\
&= \left(\int_{x=0}^{\infty} \frac{1}{\lambda_{h_2}} e^{-\frac{x}{\lambda_{h_2}}} \left(1 - e^{-\frac{z}{x\lambda_{g_1}}}\right) dx\right)' \\
&= \frac{1}{\lambda_{g_1}\lambda_{h_2}} \int_{x=0}^{\infty} \frac{1}{x} \exp\left(-\frac{x}{\lambda_{h_2}} - \frac{z}{x\lambda_{g_1}}\right) dx.
\end{aligned} \tag{24}$$

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