Performance Analysis of Energy Harvesting-based Multiple Antenna and Multiple Relays Networks

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Abstract. Harvesting regenerable energy from the surrounding environment is an effective way to solve the energy limitation of wireless communication, and energy harvesting communication has become one of the key technologies of 5G. In this paper, based on energy harvesting technology, we study the multiple antenna multiple relaying networks under different relay selection schemes. We design the Maximal ratio combining (MRC) techniques to enhance the system performance under the situation of partial and opportunistic relay selection scheme being used. On this foundation, we investigate the effects of relay selection scheme, multi-antenna technology and number of relays on the multiple relay network. At the same time, we obtain the closed-form expressions for the outage probability of the multiple relaying networks. In addition, Monte Carlo simulation results and intuitive discussions are provided to show the correctness of the analytical results.

1. Introduce

Energy harvesting technology is changing the lifetime of nodes, and it has become one of the research hotspots, that the combination with wireless communication. [1]-[3].

In [4] and [5], the authors investigated power allocation of the entire system and antenna selection schemes based on energy harvesting relay schemes. In [6] and [7], The author investigated the multi-antenna relay technology based on energy harvesting non-orthogonal multiple access technology. In [8] and [9], the authors analyze cognitive large-scale antenna technology based on energy harvesting technology. In [10], the authors investigated the role of antenna selection schemes and relays in multi-antenna relay networks based on energy harvesting. In [11] and [12], the authors optimized the power allocation problem based on energy harvesting multi-antenna systems to optimize system performance.

Energy harvesting technology is becoming the basic application technology of wireless communication networks [13]. Therefore, it is very important to investigate the influence of time ratio of energy transmission in multi-antenna technology and multi-relay technology on node energy collection.

Based on these observations, the main logical structure of this paper is as shown below:
1. First of all, we investigate the effect of the period ratio of energy transfer on the entire information transmission process during energy transfer.

2. Secondly, we derive the closed-form expression of the outage probability of the system under partial relay and selective relay schemes, and analyse the system performance under the different schemes [14].

3. Finally, we derive the relationship between energy harvesting factors and system throughput.

2. System model
We design a double-hop energy harvesting multi-relay model with multi-antenna, as shown in Figure 1. It is consisted by a source station $S$, a relay station $R$, and a destination station $D$. The station $S$ and $D$ with multiple antennas, the number is $M$. The station $R$ with a single antenna. And we can get the specific meaning of each parameter through Table 1.

Due to the distance and the fading, there isn’t straight transmission link between the $S$ and the $D$ [15]. Besides, all nodes of Figure 1 are assumed to work in half-duplex mode. In the energy harvesting phase, the signal derived at the $i$th relay can be derived as

$$y_{ri}^e = \omega_i^H h_i x_r + n_{ri}^e \quad (1)$$

$y_{ri}^e$ is the energy signal received at the $i$th relay, and its energy can be expressed as $E_{ri}$, which is derived by the formula (1), and $E_{ri}$ can be derived by the following formula

$$E_{ri} = \mu \alpha TP_i |\omega_i^H h_i|^2 \quad (2)$$

In the first half period $T/2$ of the information transmission period, the $S$ broadcasts the signal to the $R$, The received signal in the $i$th relay station $R_i$ is

| Parameter | Name | Description |
|-----------|------|-------------|
| $T$ | Time | Total transmission time from source $S$ to destination $D$ |
| $\alpha$ | Energy harvesting factor | The energy that the relay can collect from the source and $0 \leq \alpha \leq 1$ |
| $(1-\alpha)T/2$ | Time | The time that transmit the signal of the source $S$ to the relay terminal $R$ |
| $(1-\alpha)T/2$ | Time | The time that transmit the relay $R$ signal to the destination $D$ |
| $\omega_i$ | Beamforming factor | Beamforming factor at source $S$ |
| $\omega_{iD}$ | Beamforming vector | Beamforming vector at destination $D$ |
| $(\cdot)^H$ | Matrix | Representing matrix transposition |
| $h_i$ | Channel fading vector | The channel fading vector from the source $S$ to the $i$th relay $R$ can be modeled as a Rayleigh channel |
| $h_{iD}$ | Channel fading component | The channel fading component of the $i$th relay to the destination $D$ is Rayleigh fading |
| $x_r$ | Energy signal | (Energy harvesting phase) represents the transmitted energy signal, the power of which is $P$ |
| $x_d$ | Signal | (Signal transmission phase) represents the transmitted signal, which has energy $P$ |
Noise power \( n_{r_i} \) (Energy harvesting phase) represents the White Gaussian Noise at the \( i^{th} \) relay during the transmission of energy.

Noise power \( n_{r_i} \) (Signal transmission phase) indicates White Gaussian Noise at the \( i^{th} \) relay during signal transmission and has an expression \( n_r \sim \mathcal{CN}(0,\delta) \).

Noise power \( n_d \) White Gaussian Noise at the destination \( D \), which can be modeled as \( n_d \sim \mathcal{CN}(0,\delta) \).

Energy harvesting efficiency \( \mu \)

\[ 0 \leq \mu \leq 1 \]

**Figure 1.** System model

\[ y_{r_i} = \omega_{H_i} h_{r_i} x_s + n_{r_i} \quad (3) \]

From (3), \( y_{r_i} \) is the signal that is received by the \( i^{th} \) relay, in the first half \((1-\alpha)T/2\) with power \( P_{r_i} \). In order to receive the best transmission signal, we use the Maximal ratio transmission technology (MRT) and the Maximal ratio combining technology (MRC) to the \( S \) and the \( D \) respectively [16]. We can know \( \omega_{h_i} = \frac{h_{r_i}}{\|h_{r_i}\|} \).

In the second half \((1-\alpha)T/2\), the \( i^{th} \) relay transmits the signal to the \( D \), so the received signal at the destination \( D \) is

\[ y_{d_i} = \omega_{H_i} h_{r_i} y_{r_i} + n_d \quad (4) \]

From (4), \( y_{d_i} \) is the received signal from the \( D \) to the \( i^{th} \) relay. We use the Maximal ratio combining (MRC) technology on the \( D \), so \( \omega_{h} = \frac{h_{d_i}}{\|h_{d_i}\|} \). We assume that the whole harvested energy is used for transmitting the signal, and the \( P_{r_i} \) expression can be derived as follows:
From (5), \( \varepsilon = \frac{\mu \alpha}{1 - \alpha} \).

3. Performance analysis

In this section, we derive the closed-form expressions of the outage probability and signal-to-noise for the consider system, and the progressive solution.

3.1. The End-to-End SNR of The System

From (3), the signal to noise ratio (SNR) of the first hop \((1 - \alpha)T/2\) is given by

\[
\gamma_{1i} = \frac{\text{Tr}(\mathbf{H}_i \mathbf{x}_i)}{\delta_i^2} = \frac{\mathbf{h}_{ii}^2 P}{\delta_i^2} \tag{6}
\]

From (4), the SNR of the second hop \((1 - \alpha)T/2\) is given by

\[
\gamma_{2i} = \frac{\text{Tr}(\mathbf{H}_2 \mathbf{x}_i)}{\delta_d^2} = \frac{\mathbf{h}_{2i}^2 P}{\delta_d^2} \tag{7}
\]

Substituting (5) into (7) and after some simplifications, \( \gamma_{2i} \) is given by (8),

\[
\gamma_{2i} = \frac{2\varepsilon |\mathbf{h}_{2i}|^2 |\mathbf{h}_{ii}|^2 P}{\delta_d^2} \tag{8}
\]

In this part, we use opportunistic and partial relay selection schemes [17]. When we use partial relay selection scheme, the SNR of the first hop can be derived as

\[
\gamma_1 = \max_{i=1, 2, \ldots, N} \left( \gamma_{1i} \right) = \max_{i=1, 2, \ldots, N} \left( \frac{\mathbf{h}_{ii}^2 P}{\delta_i^2} \right) \tag{9}
\]

We consider to use the decoding and forwarding protocol in relay node, so the SNR of the \( D \) can be derived as

\[
\gamma_e = \min \left( \gamma_1, \gamma_{1i} \right) \tag{10}
\]

When we use the opportunity relay selection scheme, the SNR of the \( i \)th link can be derived as

\[
\gamma_{ei} = \min \left( \gamma_{1i}, \gamma_{2i} \right) \tag{11}
\]

Finally, the SNR of the \( D \) is given by

\[
\gamma_e = \max_{i=1, 2, \ldots, N} \left( \gamma_{ei} \right) \tag{12}
\]

3.2. Outage performance

Before analysing the outage probability of the system, we give the probability density function of the link, and define \( \lambda_i = \frac{|\mathbf{h}_{ii}|^2 P}{\delta_i^2} \).

With the help of [18], we can get the Probability density function (PDF) of \( \gamma_{1i} \) and \( \lambda_i \) as

\[
f_{\gamma_{1i}}(x) = \frac{-M_i}{(M_i - 1)!} x^{M_i - 1} e^{-x} \gamma_{1i} \tag{13}
\]
\[
f_{\lambda_1}(x) = \frac{\lambda_1^{-M_1} x^{M_1-1} e^{-x/\lambda_1}}{(M_1-1)!}
\]  
(14)

From (13) and (14), \( \bar{\gamma}_v \) is the average SNR of the S→R link and \( \bar{\lambda}_2 \) is the average SNR of the R→D link.

By [19], the cumulative distribution function (CDF) of \( \gamma_1 \) and \( \bar{\lambda}_2 \) can be given as

\[
F_{\gamma_1}(x) = 1 - \sum_{k_1=0}^{M_1-1} \frac{1}{k_1!} \left( \frac{x}{\gamma_1} \right)^{k_1} e^{-x/\gamma_1}
\]  
(15)

\[
F_{\lambda_2}(x) = 1 - \sum_{k_2=0}^{M_2-1} \frac{1}{k_2!} \left( \frac{x}{\lambda_2} \right)^{k_2} e^{-x/\lambda_2}
\]  
(16)

One of the important indicators of system performance is the probability of outage, it is an important prerequisite for other components analysis of the system [14]. The outage probability is defined as the probability that the instantaneous end-to-end SNR of the system falls below a predefined threshold, which can be expressed as (17).

\[
P_{\text{out}}(\gamma_{th}) = \Pr(\gamma_1 \leq \gamma_{th})
\]  
(17)

From (17), \( \gamma_{th} \) is the interruption threshold.

We use opportunistic and partial relay selection schemes. Firstly, we analyse the partial relay selection scheme, (17) can be rewritten as (18)

\[
P_{\text{out}}(\gamma_{th}) = \Pr(\gamma_1 \leq \gamma_{th})
\]

\[= \Pr \left[ \min (\gamma_1, \gamma_{2i}) \leq \gamma_{th} \right]
\]

\[= \Pr(\gamma_1 \leq \gamma_{th}) + \Pr(\gamma_{2i} \leq \gamma_{th}) - \Pr(\gamma_1 \leq \gamma_{th}) \Pr(\gamma_{2i} \leq \gamma_{th})
\]  
(18)

From (9), \( \Pr(\gamma_1 \leq \gamma_{th}) \) can be expressed as

\[
\Pr(\gamma_1 \leq \gamma_{th}) = \left[ \Pr(\gamma_1 \leq \gamma_{th}) \right]^N
\]  
(19)

Substituting (19) into (18), (18) is rewritten as (20)

\[
P_{\text{out}}(\gamma_{th}) = \left[ \Pr(\gamma_1 \leq \gamma_{th}) \right]^N + \Pr(\gamma_{2i} \leq \gamma_{th}) - \left[ \Pr(\gamma_1 \leq \gamma_{th}) \right]^N \Pr(\gamma_{2i} \leq \gamma_{th})
\]  
(20)

Secondly, we analyse the opportunity relay selection scheme, (17) is rewritten as (21)

\[
P_{\text{out}}(\gamma_{th}) = \Pr(\gamma_1 \leq \gamma_{th})
\]

\[= \Pr \left[ \max_{i \in \{1, K\}} (\gamma_{ei}) \leq \gamma_{th} \right]
\]

\[= \left[ \Pr(\gamma_{ei} \leq \gamma_{th}) \right]^N
\]

\[= \left[ \Pr(\gamma_1 \leq \gamma_{ah}) + \Pr(\gamma_{2i} \leq \gamma_{th}) - \Pr(\gamma_1 \leq \gamma_{ah}) \Pr(\gamma_{2i} \leq \gamma_{ah}) \right]^N
\]  
(21)

Then, (8) will be rewritten as

\[
\gamma_{2i} = \frac{2e^{\delta_2^2} |\mathbf{h}_2^\dagger \mathbf{h}_1|}{\delta_2^2} \frac{|\mathbf{h}_1^\dagger \mathbf{h}_2|}{P} + \frac{2e^{\delta_2^2} \gamma_1 \bar{\lambda}_2}{P}
\]  
(22)
With the help of (6), \( \Pr \left( \gamma_i \leq \gamma_{th} \right) \) is derived as

\[
\Pr \left( \gamma_i \leq \gamma_{th} \right) = 1 - \sum_{k_i=0}^{N_i-1} \left( \frac{1}{k_i!} \right) \left( \frac{\gamma_{th}}{\gamma_i} \right)^{k_i} e^{-\frac{\gamma_{th}}{\gamma_i}} \]

(23)

\( \Pr \left( \gamma_{2i} \leq \gamma_{th} \right) \) can be expressed as

\[
\Pr \left( \gamma_{2i} \leq \gamma_{th} \right) = \Pr \left( \frac{\gamma_{th} \lambda_{2i}}{P} \leq \gamma_{th} \right)
\]

\[
= \int_0^\infty \int_0^{\frac{\gamma_{th} \lambda_{2i}}{y}} f_{\gamma_i}(y) f_{\lambda_{2i}}(y) \, dy 
\]

(24)

\[
= \int_0^\infty F_{\lambda_{2i}} \left( \frac{\gamma_{th} \lambda_{2i}}{y} \right) f_{\gamma_i}(y) \, dy 
\]

\[
= \int_0^\infty \left[ 1 - \sum_{k_i=0}^{N_i-1} \left( \frac{\gamma_{th} \lambda_{2i}}{y^{N_i} 2\sigma_i^2} \right)^{k_i} \right] \frac{1}{k_i!} \left( \frac{\gamma_{th} \lambda_{2i}}{y \gamma_i} \right)^{k_i} e^{-\frac{\gamma_{th} \lambda_{2i}}{y \gamma_i}} 
\]

\[
\times \int_0^\infty y^{M_{2i}-1} \frac{\gamma_{th} \lambda_{2i}}{y \gamma_i} \, dy 
\]

(25)

From (25), \( A = \frac{\gamma_{th} \lambda_{2i}}{\gamma_i \gamma_{th}^2} \), \( B = \frac{1}{\lambda_{2i}} \), \( K_{M_{2i}-k_i} (\gamma) \) is \( M_{2i} - k_i \) order Bessel function.

Inserting (23) and (25) into (20), the outage probability expression under partial relay scheme is derived as

\[
P_{\text{out}} (\gamma_{th}) = \left[ 1 - \sum_{k_i=0}^{N_i-1} \left( \frac{1}{k_i!} \right) \left( \frac{\gamma_{th} \lambda_{2i}}{\gamma_i} \right)^{k_i} e^{-\frac{\gamma_{th} \lambda_{2i}}{\gamma_i}} \right]^{N_i} 
\]

\[
\times \left[ 1 - \sum_{k_i=0}^{N_i-1} \left( \frac{1}{k_i!} \right) \left( \frac{\gamma_{th} \lambda_{2i}}{\gamma_i} \right)^{k_i} e^{-\frac{\gamma_{th} \lambda_{2i}}{\gamma_i}} \right]^{N_i} 
\]

(26)

Inserting (23) and (25) into (21), the outage probability expression of the system under the opportunity relay selection scheme is derived as

\[
P_{\text{out}} (\gamma_{th}) = \left[ 1 - \sum_{k_i=0}^{N_i-1} \sum_{k_{th}=0}^{N_{th}-1} \left( \frac{1}{k_i!} \right) \left( \frac{\gamma_{th} \lambda_{2i}}{\gamma_i} \right)^{k_{th}} e^{-\frac{\gamma_{th} \lambda_{2i}}{\gamma_i}} \right]^{N_i} 
\]

\[
\times \left[ 1 - \sum_{k_i=0}^{N_i-1} \sum_{k_{th}=0}^{N_{th}-1} \left( \frac{1}{k_i!} \right) \left( \frac{\gamma_{th} \lambda_{2i}}{\gamma_i} \right)^{k_{th}} e^{-\frac{2\gamma_{th} \lambda_{2i}}{\gamma_i}} \right]^{N_i} 
\]

(27)

4. Simulation

In this section, we combine MATLAB simulation tool and the thought of Monte Carlo simulations to verify our analysis results [20, 21]. Firstly, we assume \( \sigma_i^2 = \sigma_{th}^2 = 1 \) and \( \gamma_i = \lambda_{th} = \gamma \). Second, verifying the theoretical analysis according to the simulation results. Finally, we analyse the influence of relays, energy collection factor and antennas etc for system performance.
Figure 2. Interrupt probability under partial relay selection scheme for different antenna numbers. \( N=2 \) and \( \alpha=1/4 \)

Figure 3. Interrupt probability under the opportunity relay selection scheme for different antenna numbers. \( N=2 \) and \( \alpha=1/4 \)

Figure 4. Outage probability of partial relay selection scheme under different number of relays. \( M=3 \) and \( \alpha=1/4 \)
Figure 5. Outage probability under the opportunity relay selection scheme for different number of relays. $M=3$ and $\alpha=1/4$

Figure 6. Interrupt probability under different antenna numbers and lower partial relay selection scheme. $N=3$ and $R_n=3dB$

Figure 7. Number of different antennas and outage probability under the next opportunity relay selection scheme. $N=3$ and $R_n=3dB$
Figure 2 plots the outage probability of the system under the partial relay selection scheme for different antenna numbers. Figure 3 plots the outage probability of the system under opportunity relay selection scheme for different antenna numbers. In Figure 2 and Figure 3, \( N=2 \), \( \alpha =1/4 \) is assumed. As shown in Figure 2 and Figure 3, we can know that the larger the \( \alpha \), the lower the outage probability. They also depict that, with the increasing number of antennas, the outage performance of opportunistic relay is getting better and better than partial relay. It shows the advantage of an opportunity relaying selection scheme. From the theoretical analysis, we can know, when the system use the opportunity relay selection scheme, it will select the best link among the two links \( S \rightarrow R \), \( R \rightarrow D \), it has better performance in the whole network, when the system use the partial relay selection, it only selects the best one hop link among the \( S \rightarrow R \). So, in the link of \( R \rightarrow D \), the opportunity relay selection scheme has more advantage.

In Figure 4 and Figure 5, \( M =3 \), \( \alpha =1/4 \) is assumed. They plot that the outage performance of different \( \alpha \) under different selection schemes. In the partial relay selection if the SNR is low in \( S \rightarrow R \), the larger \( \alpha \) is, the lower outage probability is. But if the SNR is large in \( S \rightarrow R \), the outage probability is not changed significantly with the \( N \). This is because that, When the SNR increases to a threshold, the quality of every connection in the first link is good enough, the performance is similar between the best connection and one connection of all. In the opportunity relay selection scheme, if the SNR is large in \( S \rightarrow R \), the larger \( \alpha \) is, the lower outage probability is.

In Figure 6 and Figure 7, \( N=3 \), \( R_o =3dB \) is assumed. Figure 6 and Figure 7 plot the outage probability of different \( \alpha \) under different relay selection schemes. From Figure 6 and Figure 7, the larger \( \alpha \) is, the lower outage probability is, this is because when \( \alpha \) becomes larger, the power of relay becomes larger simultaneously. That verifies the advantage of the opportunity relay selection again.

5. Conclusion
In summary, the transmission scheme and probability etc of the energy harvesting relay network with Multi-antenna Multi-relay were investigated. Firstly, we designed the network model of energy harvesting. Secondly, we analysed the model theoretically and derived the exact closed-form expression of the outage probability. Finally, the theoretical design results were verified by simulation. Moreover, the analysis of the simulation results gave us the way to choose the parameter. Simultaneously, the system performance of opportunistic relay selection was better to the partial relay selection, however the implementation complexity was the opposite.

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