Energy Harvesting AF Relaying in the Presence of Interference and Nakagami-m Fading

Yunfei Chen, *Senior Member, IEEE*

***Abstract*—Energy harvesting relaying is a promising solution to the extra energy requirement at the relay. It can transfer energy from the source to the relay. This will encourage more idle nodes to be involved in relaying. In this paper, the outage probability and the throughput of an amplify-and-forward relaying system using energy harvesting are analyzed. Both time switching and power splitting harvesting schemes are considered. The analysis takes into account both the Nakagami-m fading caused by signal propagation and the interference caused by other transmitters. Numerical results show that time switching is more sensitive to system parameters than power splitting. Also, the system performance is more sensitive to the transmission rate requirement, the signal-to-interference-plus-noise ratio in the first hop and the relaying method.**

***Index Terms*—Amplify-and-forward, energy harvesting, interference, performance analysis, power splitting, time switching.**

I. Introduction

Wireless relaying can extend the network coverage without the need for (or without requiring) any extra infrastructure. It can also provide distributed multiple-input-multiple-output with improved diversity gain [1]. Among all the relaying protocols, the amplify-and-forward (AF) protocol only needs to amplify the received signal from the source without any further processing. Hence, AF relaying has attracted great research interest. Despite this, the amplification and forwarding operations at the relay still consume extra energy. For relay nodes connected to the power grid, such extra energy is not a serious concern. However, for relay nodes powered by batteries, such as mobile devices, due to the limited battery life, such extra energy may cause great concern and therefore, may discourage them from performing any relaying.

To tackle this problem, recently, energy harvesting AF relaying has been proposed [2] - [8]. For example, in [2], assuming a stationary and ergodic process for the energy harvested by the relay, the symbol error rate was derived by considering energy-constrained and energy-unconstrained relays. In this case, the energy could be harvested from any source. In [3], the authors studied two harvest-and-forward protocols using power splitting or time switching, where the relay harvests the transmitted energy from the source node to amplify and forward the signal. In [4], a harvest-use structure was studied, where the relay does not have energy storage capability. The optimal tradeoff between harvesting time and relaying time was derived by considering half-duplex relays as well as full-duplex relays. In [5], the authors studied the optimal power allocation problem for energy harvesting relays, where relays can harvest energies from multiple source nodes and the total harvested energy was then allocated for transmissions of signals to different destinations. It was found in this work that it is better to allocate the total harvested energy among all transmissions. Similarly, in [6], stochastic geometry was used to study the effect of random locations of relays on the relaying performance, where relays harvest energy from the source node. The authors in [7] considered a joint power splitting and antenna selection scheme, where the relay is equipped with multiple antennas to harvest the energy from the source node and hence, it can choose the best portion of power splitting and the best antenna to maximize the achievable rate. In [8], the authors derived optimal power allocations that maximize the throughput when different knowledge of harvested energy and channel state is available.

All the aforementioned works have provided beneficial insights on various aspects of AF relaying using energy harvesting. However, none of them has considered the effect of interference. Reference [9] considered the interference from other source nodes and optimized the power splitting factors using game theory, while reference [10] considered the network interference for Rayleigh fading channels. In a practical network, the relaying process is subject to interference and may suffer from Nakagami-m fading at the same time. Thus, it is of great interest to see how energy harvesting relays perform in Nakagami-m fading channels when they suffer from interference.

In this paper, the performance of energy harvesting AF relaying is analyzed by deriving the outage probability and the throughput in Nakagami-m fading channels, when both the relay and the destination suffer from interference. In this energy harvesting system, the relay is powered by harvesting radio frequency energy from the source and other interferers in the environment. The source and destination nodes do not rely on harvested energy for transmission and reception. The analysis considers power splitting (PS) as well as time switching (TS). Both fixed gain relaying and variable gain relaying are studied. Numerical results also show that time switching is more sensitive to system parameters than power splitting and that the system performance is more sensitive to the transmission rate requirement, the signal-to-interference-plus-noise ratio in the first hop and the relaying method.

The rest of the paper is organized as follows. In Section II, the system model used in this paper will be introduced. In Sections III and IV, detailed derivations of the outage probability and the throughput, respectively, will be presented. Section V will give the numerical examples used to examine the effects of the system parameters, followed by some conclusions in Section VI.

Yunfei Chen is with the School of Engineering, University of Warwick, Coventry, U.K. CV4 7AL (e-mail: Yunfei.Chen@warwick.ac.uk).

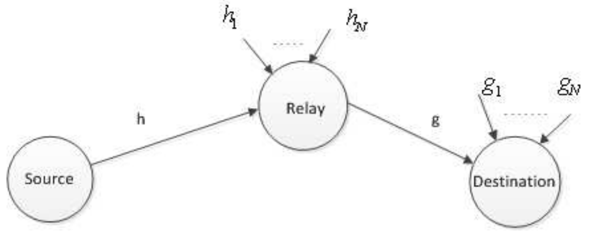

Fig. 1. A diagram of the considered system

II. System Model

Consider a three-node relaying system where the source sends the information and energy to the relay and the relay uses the received energy to forward the received information to the destination. There is no direct link. Each node has a single antenna and operates in half-duplex mode. The source-to-relay and relay-to-destination links are made orthogonal in time by transmitting signals at different times. Assume that the total communication time is T. Two energy harvesting schemes are considered: TS and PS. Diagrams of the TS and PS processes can be found in [3, Fig. 2] and [3, Fig. 3]. Due to the limited space, they are not repeated here. Fig. 1 shows the diagram of the relaying system.

A. Time Switching (TS)

In TS, a faction of the total time αT is used for energy harvesting at the relay, followed by $(1-\alpha)\frac{T}{2}$ for information reception at the relay and $(1-\alpha)\frac{T}{2}$ for information reception at the destination. Thus, the received signal at the relay is given by [3]

$$y_r[k] = \sqrt{P_S} h s[k] + \sum_{i=1}^{N} \sqrt{P_i} h_i s_i[k] + n_{ra}[k] + n_{rc}[k] \quad (1)$$

where P_S is the transmission power of the source, h is the small-scale fading gain of the source-to-relay link, $s[k]$ is the transmitted symbol of the source, N is the number of interferers at the relay, P_i is the transmission power of the i-th interferer, h_i is the small-scale fading gain of the link from the i-th interferer to the relay, $s_i[k]$ is the transmitted symbol of the i-th interferer, $n_{ra}[k]$ is the additive white Gaussian noise (AWGN) due to the antenna and $n_{rc}[k]$ is the AWGN due to the RF-to-baseband conversion [11]. In this paper, Nakagami-m small-scale fading is assumed such that $|h|^2$ and $|h_i|^2$, $i = 1, 2, \cdots, N$, follow Gamma distributions with probability density functions (PDFs)

$$f_{|h|^2}(x) = \left(\frac{m_1}{\Omega_1}\right)^{m_1} \frac{x^{m_1-1}}{\Gamma(m_1)} e^{-\frac{m_1}{\Omega_1}x}, x > 0 \quad (2)$$

and

$$f_{|h_i|^2}(x) = \left(\frac{m_{I1}}{\Omega_{I1}}\right)^{m_{I1}} \frac{x^{m_{I1}-1}}{\Gamma(m_{I1})} e^{-\frac{m_{I1}}{\Omega_{I1}}x}, x > 0 \quad (3)$$

respectively, where m_1 and Ω_1 are the m parameter and the average fading power in the source-to-relay link, respectively, and m_{I1} and Ω_{I1} are the m parameter and the average fading power in the link from the i-th interferer to the relay, respectively. In this case, the channel fading gains from the interferers to the relay are assumed to be independent and identically distributed. The case of non-identically distributed interferers will be discussed later. The signalling scheme is assumed to be binary phase shift keying (BPSK) such that $s[k] = 1$ and $s[k] = -1$ occur with equal probabilities. So do $s_i[k] = 1$ and $s_i[k] = -1$. Finally, the AWGN terms $n_{ra}[k]$ and $n_{rc}[k]$ have zero mean and variances of σ_{ra}^2 and σ_{rc}^2, respectively. From (1), the energy harvested from the source and the interferers is given by $E_h = \eta(P_s|h|^2 + \sum_{i=1}^{N} P_i|h_i|^2)\alpha T$, where η is the conversion efficiency of the energy harvester at the relay, $(P_s|h|^2 + \sum_{i=1}^{N} P_i|h_i|^2)$ is the total input power at the harvester, and αT is the total harvesting time. Then, the signal in (1) is amplified and forwarded to the destination as

$$y_d[k] = \sqrt{P_r} a g y_r[k] + \sum_{j=1}^{N} \sqrt{Q_j} g_j s'_j[k] + n_{da}[k] + n_{dc}[k] \quad (4)$$

where $P_r = \frac{E_h}{(1-\alpha)\frac{T}{2}} = \frac{2\alpha\eta}{1-\alpha}(P_s|h|^2 + \sum_{i=1}^{N} P_i|h_i|^2)$ is the transmission power of the relay, a is the amplification factor of the relay, g is the small-scale fading gain of the relay-to-destination link, Q_j is the transmission power of the j-th interferer to the destination, g_j is the small-scale fading gain of the link from the j-th interferer to the destination in the relaying phase, $s'_j[k]$ is the transmitted BSPK symbol of the j-th interferer, $n_{da}[k]$ is the AWGN at the antenna and $n_{dc}[k]$ is the AWGN due to RF-to-baseband conversion with zero mean and variances of σ_{da}^2 and σ_{dc}^2, respectively. The transmission power Q_j may be different from P_i, as adaptive power control may be employed at the interfering sources such that their transmission powers are changing. If no power control is used, Q_j could be set the same as P_i. The amplification factor depends on the method of AF relaying. In this paper, we consider two methods: fixed gain relaying and variable gain relaying [12] - [14]. In fixed gain relaying, a is a constant and without loss of generality, $a = 1$. In variable gain relaying, a varies with the fading gain such that for TS one has

$$a = \frac{1}{\sqrt{P_s|h|^2 + \sigma_{ra}^2 + \sigma_{rc}^2}}. \quad (5)$$

Remark. *Note that, in general, the power consumed at the relay is a function of the transmission power. Their actual relationship is mainly determined by the efficiency and non-linearity of the power amplifier. In this work, the consumed power is also limited to the amount of harvested power by the signal from the source as the main source of power. Although the amount of harvested power is the same for different relaying schemes, the consumed power of* $P_r a^2 E\{|y_r[k]|^2\}$ *and therefore the transmission power is different for different relaying schemes. Also, it is assumed that the circuit power at the relay can be ignored. Note also that the interference power in the denominator of (5) is not used, as this knowledge may be difficult to obtain in practice such that practical amplification factor may not scale the power of the received signal at the relay perfectly.*

The small-scale fading gains in this case are again assumed to be Nakagami-m distributed such that their powers follow

Gamma distributions with m_2 and Ω_2 being the m parameter and the average fading power in the relay-to-destination link for $|g|^2$, respectively, and m_{I2} and Ω_{I2} being the m parameter and the average fading power in the link from the j-th interferer to the destination for $|g_j|^2$, respectively.

B. Power Splitting (PS)

In PS, a fraction of the received signal energy is harvested without any dedicated harvesting time. Thus, the transmission from the source to the relay takes $\frac{T}{2}$ seconds and the received information signal at the relay is given by [3]

$$y_r[k] = \sqrt{(1-\rho)P_s}hs[k] + \sqrt{1-\rho}\sum_{i=1}^{N}\sqrt{P_i}h_i s_i[k] + \sqrt{1-\rho}n_{ra}[k] + n_{rc}[k] \quad (6)$$

where ρ is the PS factor. Then, the harvested energy is $E_h = \eta\rho(P_s|h|^2 + \sum_{i=1}^N P_i|h_i|^2)\frac{T}{2}$. Note that in this case, the harvested energy from the noise is assumed to be a small constant and therefore can be ignored (see the derivations of (5) - (13) in [11]). Thus, the noise term does not appear in the harvested energy. The transmission power of the relay is $P_r = \frac{E_h}{T/2} = \eta\rho(P_s|h|^2 + \sum_{i=1}^N P_i|h_i|^2)$ and the amplification factor for variable gain relaying is $a = \frac{1}{\sqrt{(1-\rho)P_S|h|^2+(1-\rho)\sigma_{ra}^2+\sigma_{rc}^2}}$ in this case.

The above model ignores the path loss, as it is included in the average fading power. However, if one wishes to consider the path loss explicitly, it can be easily accommodated in the above model by replacing h with $\frac{h}{\sqrt{d_1^v}}$, h_i with $\frac{h_i}{\sqrt{d_{1i}^v}}$, g with $\frac{g}{\sqrt{d_2^v}}$, g_j with $\frac{g_j}{\sqrt{d_{2j}^v}}$, where v is the path loss exponent and d_1, d_2, d_{1i} and d_{d_2j} are the distances. Also, knowledge of h and g is required in the signal detection and can be obtained by using either cascaded channel estimation or disintegrated channel estimation [15].

III. Outage Probability

A. Time Switching (TS)

For TS, the received signal at the destination is given in (4). Let the signal-to-interference-plus-noise ratio (SINR) in the source-to-relay link be $\gamma_1 = \frac{|h|^2}{\sum_{i=1}^N P_i|h_i|^2+\sigma_{ra}^2+\sigma_{rc}^2}$ and the SINR in the relay-to-destination link be $\gamma_2 = \frac{|g|^2}{\sum_{j=1}^N Q_j|g_j|^2+\sigma_{da}^2+\sigma_{dc}^2}$. From (4), the end-to-end SINR can be derived as

$$\gamma = \frac{P_s P_r a^2\gamma_1\gamma_2}{P_r a^2\gamma_2 + \frac{1}{\sum_{i=1}^N P_i|h_i|^2+\sigma_{ra}^2+\sigma_{rc}^2}}. \quad (7)$$

The expression in (7) actually applies to both relaying with energy harvesting and relaying without energy harvesting. From (7), if the conventional relay without energy harvesting has a transmission power larger than that P_r with energy harvesting, it will have a larger end-to-end SINR and thus better performance than relaying with energy harvesting.

For fixed gain relaying, using P_r and $a = 1$, one has

$$\gamma^{TS-FG} = \frac{P_s\gamma_1\gamma_2}{\gamma_2 + \frac{(1-\alpha)/(2\alpha\eta)}{(\sum_{i=1}^N P_i|h_i|^2+\sigma_{ra}^2+\sigma_{rc}^2)(P_s|h|^2+\sum_{i=1}^N P_i|h_i|^2)}}. \quad (8)$$

For variable gain relaying, a is given in (5). Using P_r and (5), the end-to-end SINR can be derived as

$$\gamma^{TS-VG} = \frac{P_s\gamma_1\gamma_2}{\gamma_2 + \frac{(1-\alpha)(P_s|h|^2+\sigma_{ra}^2+\sigma_{rc}^2)/(2\alpha\eta)}{(\sum_{i=1}^N P_i|h_i|^2+\sigma_{ra}^2+\sigma_{rc}^2)(P_s|h|^2+\sum_{i=1}^N P_i|h_i|^2)}}. \quad (9)$$

One sees that the end-to-end SINR of the energy harvesting AF relaying is different from that of the conventional AF relaying in that there is an additional term of $\frac{1-\alpha}{2\alpha\eta(P_s|h|^2+\sum_{i=1}^N P_i|h_i|^2)}$ in the denominator. This term comes from energy harvesting and causes the difficulty in the derivation. There have been a lot of works on the capacity over Nakagami-m fading channels in the literature, such as [16] and [17]. However, none of these works considered energy harvesting. As can be seen from (9), the end-to-end SINR with energy harvesting is much more complicated, which is the contribution of this work.

The outage probability is defined as the probability that the SINR is below a certain threshold γ_0. For fixed gain relaying, P_{out} is derived in Appendix A as (10). For variable gain relaying, using a similar method, the outage probability can be derived in the same form as (10), except that $X_{TS-FG}(y,z)$ is replaced by $X_{TS-VG}(y,z) = \frac{1-\alpha}{2\alpha\eta}\frac{\gamma_0(y+\sigma_{ra}^2+\sigma_{rc}^2)}{(y+z)(y-\gamma_0 z-\gamma_0\sigma_{ra}^2-\gamma_0\sigma_{rc}^2)}$.

In the special case when there is no interference at the relay or the destination, one has

$$P_{out}^{TS-FG} = 1 - (\frac{m_1}{P_s\Omega_1})^{m_1}\frac{1}{\Gamma(m_1)}\sum_{l=0}^{m_2-1}\frac{1}{l!}(\frac{m_2}{\Omega_2})^l \int_{\gamma_0(\sigma_{ra}^2+\sigma_{rc}^2)}^{\infty} e^{-\frac{m_2}{\Omega_2}U_{TS-FG}-\frac{m_1}{P_s\Omega_1}y} y^{m_1-1}U_{TS-FG}^l dy \quad (11)$$

where $U_{TS-FG} = \frac{1-\alpha}{2\alpha\eta}\frac{\gamma_0(\sigma_{da}^2+\sigma_{dc}^2)}{y(y-\gamma_0\sigma_{ra}^2-\gamma_0\sigma_{rc}^2)}$ for fixed gain relaying. For variable gain relaying, P_{out}^{TS-VG} can be obtained by replacing U_{TS-FG} with $U_{TS-VG} = \frac{1-\alpha}{2\alpha\eta}\frac{\gamma_0(\sigma_{da}^2+\sigma_{dc}^2)(y+\sigma_{ra}^2+\sigma_{rc}^2)}{y(y-\gamma_0\sigma_{ra}^2-\gamma_0\sigma_{rc}^2)}$ in (11). Also, in the special case when there is no interference at the relay and only interference at the destination, the outage probability can be simplified as a one-dimensional integral by setting $z = 0$ and removing the integration over z in (10).

In addition, for variable gain relaying, when the noise at the relay is very weak such that $\sigma_{ra}^2 + \sigma_{rc}^2 \approx 0$, one further has

$$P_{out}^{TS-VG} \approx 1 - (\frac{m_1}{P_s\Omega_1})^{m_1}\frac{2}{\Gamma(m_1)}\sum_{l=0}^{m_2-1}\frac{1}{l!}(\frac{m_2}{\Omega_2})^l [\frac{1-\alpha}{2\alpha\eta}\gamma_0(\sigma_{da}^2+\sigma_{dc}^2)]^{\frac{m_1-1+l}{2}}(\frac{m_2 P_s\Omega_1}{\Omega_2 m_1})^{\frac{m_1-1-l}{2}} K_{m_1-1-l}\left(2\sqrt{\frac{m_2(1-\alpha)\gamma_0(\sigma_{da}^2+\sigma_{dc}^2)m_1}{2\alpha\eta\Omega_2 P_s\Omega_1}}\right) \quad (12)$$

where [18, eq. (3.471.9)] is used and $K_{m_1-1-l}(\cdot)$ is the (m_1-1-l)-th order modified Bessel function of the second kind.

The asymptotic results can also be obtained. When $\gamma_2 \to \infty$, from (8) and (9), one has $\gamma^{TS-FG} \to P_s\gamma_1$ and $\gamma^{TS-VG} \to P_s\gamma_1$. Also, when $\gamma_1 \to \infty$, from (8) and (9), one has $\gamma^{TS-FG} \to P_s\gamma_1$ and $\gamma^{TS-VG} \to \frac{P_s\gamma_1\gamma_2}{\gamma_2+\frac{1-\alpha}{2\alpha\eta(\sum_{i=1}^N P_i|h_i|^2+\sigma_{ra}^2+\sigma_{rc}^2)}}$. For the first case $P_s\gamma_1$, the outage probability can be derived by using the same method for X_2

$$
\begin{aligned}
P_{out}^{TS-FG} &= 1-\left(\frac{m_{I1}}{P_{I1}\Omega_{I1}}\right)^{Nm_{I1}}\left(\frac{m_1}{P_S\Omega_1}\right)^{m_1}\left(\frac{m_{I2}}{Q_{I2}\Omega_{I2}}\right)^{Nm_{I2}}\frac{1}{\Gamma(Nm_{I1})\Gamma(m_1)\Gamma(Nm_{I2})} \\
& \sum_{l=0}^{m_2-1}\sum_{l'=0}^{l}\frac{(m_2/\Omega_2)^l\binom{l'}{l}(\sigma_{da}^2+\sigma_{dc}^2)^{l-l'}(Nm_{I2}+l'-1)!}{l!} \\
&\times \int_0^\infty\int_{\gamma_0 z+\gamma_0\sigma_{ra}^2+\gamma_0\sigma_{rc}^2}^\infty e^{-\frac{m_2(\sigma_{da}^2+\sigma_{dc}^2)}{\Omega_2}X_{TS-FG}(y,z)-\frac{m_1}{P_s\Omega_1}y-\frac{m_{I1}}{P_{I1}\Omega_{I1}}z} \\
&\times \frac{(X_{TS-FG}(y,z))^l y^{m_1-1}z^{Nm_{I1}-1}}{(\frac{m_{I2}}{Q_{I2}\Omega_{I2}}+\frac{m_2X_{TS-FG}(y,z)}{\Omega_2})^{Nm_{I2}+l'}}dydz. \qquad (10)
\end{aligned}
$$

in (29), except that m_{I2}, Q_{I2}, Ω_{I2}, σ_{da}^2, σ_{dc}^2, m_2, Ω_2, x are replaced by m_{I1}, P_{I1}, Ω_{I1}, σ_{ra}^2, σ_{rc}^2, m_1, Ω_1, γ_0, respectively. For the second case of variable gain using TS, its outage probability is derived in Appendix B as

$$
\begin{aligned}
P_{out}^{TS-VG} &\approx 1-\frac{(m_{I1}/P_{i1}/\Omega_{I1})^{Nm_{I1}}}{\Gamma(Nm_{I1})}\sum_{l=0}^{m_1-1}\sum_{l'=0}^{l} \\
&\frac{\binom{l}{l'}(Nm_{I1}+l'-1)!(\frac{m_1\gamma_0}{P_s\Omega_1})^l e^{-\frac{m_1\gamma_0}{P_s\Omega_1}(\sigma_{ra}^2+\sigma_{rc}^2)}}{l!(\frac{m_1\gamma_0}{P_s\Omega_1}+\frac{m_{I1}}{P_{I1}\Omega_{I1}})^{Nm_{I1}+l'}} \qquad (13) \\
&\int_0^\infty(\sigma_{ra}^2+\sigma_{rc}^2+\frac{1-\alpha}{2\alpha\eta}w)^{l-l'}e^{-\frac{m_1\gamma_0(1-\alpha)}{2P_s\Omega_1\alpha\eta}w}f_W(w)dw
\end{aligned}
$$

where $f_W(w)$ is closed-form in (39) in Appendix B.

B. Power Splitting (PS)

In this case, denote $\gamma_3 = \frac{|h|^2}{\sum_{i=1}^N P_i|h_i|^2+\sigma_{ra}^2+\sigma_{rc}^2/(1-\rho)}$. One has the end-to-end SINR as

$$
\gamma = \frac{P_S P_r a^2\gamma_2\gamma_3}{P_r a^2\gamma_2+\frac{1}{(1-\rho)\sum_{i=1}^N P_i|h_i|^2+(1-\rho)\sigma_{ra}^2+\sigma_{rc}^2}}. \qquad (14)
$$

Note that [9] derived an expression similar to (14) in [9, eq. (5)] using their system models. For fixed gain relaying, using P_r and $a=1$, the end-to-end SINR is obtained as

$$
\gamma^{PS-FG} = \frac{P_S\gamma_2\gamma_3}{\gamma_2+\frac{1/(\eta\rho(1-\rho))}{[\sum_{i=1}^N P_i|h_i|^2+\sigma_{ra}^2+\frac{\sigma_{rc}^2}{1-\rho}](P_S|h|^2+\sum_{i=1}^N P_i|h_i|^2)}}. \qquad (15)
$$

For variable gain relaying, using P_r and a, the end-to-end SINR is

$$
\gamma^{PS-VG} = \frac{P_S\gamma_2\gamma_3}{\gamma_2+\frac{(P_S|h|^2+\sigma_{ra}^2+\frac{\sigma_{rc}^2}{1-\rho})/(\eta\rho)}{[\sum_{i=1}^N P_i|h_i|^2+\sigma_{ra}^2+\frac{\sigma_{rc}^2}{1-\rho}](P_S|h|^2+\sum_{i=1}^N P_i|h_i|^2)}}. \qquad (16)
$$

When $\sigma_{rc}^2 \approx 0$, it can be shown that the relay without energy harvesting has a larger end-to-end SINR and a better performance than the relay with energy harvesting, when its transmission power is larger than $(1-\rho)P_r$ for fixed gain and P_r for variable gain in PS.

Using (15) and (16), the outage probability for fixed gain relaying using PS can be derived in Appendix A as (17), and the outage probability for variable gain relaying is obtained by replacing $X_{PS-FG}(y,z)$ with $X_{PS-VG}(y,z) = \frac{\gamma_0}{\eta\rho}\frac{y+\sigma_{ra}^2+\sigma_{rc}^2/(1-\rho)}{(y+z)(y-\gamma_0 z-\gamma_0\sigma_{ra}^2-\gamma_0\sigma_{rc}^2/(1-\rho))}$. In the special case when there is no interference, the outage probability can be derived as

$$
\begin{aligned}
P_{out}^{TS-FG} &= 1-(\frac{m_1}{P_s\Omega_1})^{m_1}\frac{1}{\Gamma(m_1)}\sum_{l=0}^{m_2-1}\frac{1}{l!}(\frac{m_2}{\Omega_2})^l \qquad (18) \\
&\int_{\gamma_0(\sigma_{ra}^2+\frac{\sigma_{rc}^2}{1-\rho})}^\infty e^{-\frac{m_2}{\Omega_2}U_{PS-FG}-\frac{m_1}{P_s\Omega_1}y}y^{m_1-1}U_{PS-FG}^l dy
\end{aligned}
$$

where $U_{PS-FG} = \frac{\gamma_0(\sigma_{da}^2+\sigma_{dc}^2)}{\eta\rho(1-\rho)y(y-\gamma_0\sigma_{ra}^2-\gamma_0\sigma_{rc}^2/(1-\rho))}$ for fixed gain relaying. For variable gain relaying, one can replace U_{PS-FG} with $U_{PS-VG} = \frac{\gamma_0(\sigma_{da}^2+\sigma_{dc}^2)((1-\rho)y+(1-\rho)\sigma_{ra}^2+\sigma_{rc}^2)}{\eta\rho(1-\rho)y(y-\gamma_0\sigma_{ra}^2-\gamma_0\sigma_{rc}^2/(1-\rho))}$ in (18). Moreover, when the noise at the relay is very weak, for variable gain relaying, the outage probability can be approximated by replacing $\frac{1-\alpha}{2\alpha\eta}$ with $\frac{1}{\eta\rho}$ in (12). Similarly, in the special case when there is no interference at the relay but interference at the destination, the outage probability can be simplified as a one-dimensional integral by setting $z=0$ and removing the integration over z in (17). For the asymptotic results when $\gamma_2\to\infty$ or $\gamma_3\to\infty$, they can be obtained by replacing σ_{rc}^2 with $\frac{\sigma_{rc}^2}{1-\rho}$ and $\frac{1-\alpha}{2\eta\alpha}$ with $\frac{1}{\eta\rho}$ in the results for TS.

IV. Throughput

Let R be a fixed transmission rate that the source needs to satisfy such that $R=\log_2(1+\gamma_0)$. Then, one has $\gamma_0 = 2^R-1$.

A. Time Switching (TS)

In this case, from [3], the throughput for TS is given by

$$
\tau = (1-P_{out})R\frac{(1-\alpha)T/2}{T} = \frac{R}{2}(1-\alpha)(1-P_{out}) \qquad (19)
$$

where T is the total time and $(1-\alpha)T/2$ is the effective transmission time. When α increases, from (9), γ increases. When γ increases, P_{out} decreases. Thus, when α increases, $(1-P_{out})$ in (19) increases. On the other hand, when α increases, $(1-\alpha)$ in (19) decreases. Thus, there may exist an optimum value of α that maximizes (19) as a product of $(1-P_{out})$ and $(1-\alpha)$. Using the outage probabilities derived above to replace P_{out} in (19), the throughput for energy harvesting relaying using TS can be derived.

$$
\begin{aligned}
P_{out}^{PS-FG} &= 1-\left(\frac{m_{I1}}{P_{I1}\Omega_{I1}}\right)^{Nm_{I1}}\left(\frac{m_1}{P_S\Omega_1}\right)^{m_1}\left(\frac{m_{I2}}{Q_{I2}\Omega_{I2}}\right)^{Nm_{I2}}\frac{1}{\Gamma(Nm_{I1})\Gamma(m_1)\Gamma(Nm_{I2})}\\
&\sum_{l=0}^{m_2-1}\sum_{l'=0}^{l}\frac{(m_2/\Omega_2)^l\binom{l'}{l}(\sigma_{da}^2+\sigma_{dc}^2)^{l-l'}(Nm_{I2}+l'-1)!}{l!}\\
&\times \int_0^{\infty}\int_{\gamma_0 z+\gamma_0\sigma_{ra}^2+\gamma_0\sigma_{rc}^2/(1-\rho)}^{\infty} e^{-\frac{m_2(\sigma_{da}^2+\sigma_{dc}^2)}{\Omega_2}X_{PS-FG}(y,z)-\frac{m_1}{P_S\Omega_1}y-\frac{m_{I1}}{P_{I1}\Omega_{I1}}z}\\
&\times \frac{(X_{PS-FG}(y,z))^l y^{m_1-1}z^{Nm_{I1}-1}}{(\frac{m_{I2}}{Q_{I2}\Omega_{I2}}+\frac{m_2X_{PS-FG}(y,z)}{\Omega_2})^{Nm_{I2}+l'}}dydz. \qquad (17)
\end{aligned}
$$

B. Power Splitting (PS)

For PS, the throughput is given by

$$\tau=(1-P_{out})R\frac{T/2}{T}=\frac{R}{2}(1-P_{out}) \qquad (20)$$

as there is no time penalty incurred by energy harvesting and only the penalty of the relaying time needs to be considered.

Also, using the outage probabilities derived above to replace P_{out} in (20), the throughput for energy harvesting relaying using PS can be derived.

C. Extensions

An extension can be made when the fading channels are independent but non-identically distributed. This is the case, for example, when the pass losses caused by different transmission distances need to be considered explicitly such that P_i are different for $i=1,2,\cdots,N$ and Q_j are different for $j=1,2,\cdots,N$. In this case, using [19, eq. (2)], the PDF of Z_1 can be derived as

$$
\begin{aligned}
f_{Z_1}(x)=\prod_{i=1}^{N}\left(\frac{\beta_{min}}{\beta_i}\right)^{m_{I1}^{(i)}}\\
\sum_{k=0}^{\infty}\frac{\delta_k x^{\sum_{i=1}^N m_{I1}^{(i)}+k-1}e^{-\frac{x}{\beta_{min}}}}{\beta_{min}^{\sum_{i=1}^N m_{I1}^{(i)}+k}\Gamma(\sum_{i=1}^N m_{I1}^{(i)}+k)} \qquad (21)
\end{aligned}
$$

where $\beta_{min}=\min\{\beta_i\}$, $\beta_i=\frac{m_{I1}^{(i)}}{P_i\Omega_{I1}^{(i)}}$, $m_{I1}^{(i)}$ is the m parameter of the channel from the i-th interferer to the relay, $P_i\Omega_{I1}^{(i)}$ is the average fading power of the channel from the i-th interferer to the relay, and δ_k can be calculated as [19, eq. (3)]

$$\delta_{k+1}=\frac{1}{k+1}\sum_{n=1}^{k+1}\sum_{i=1}^{N}m_{I1}^{(i)}(1-\frac{\beta_{min}}{\beta_i})^n\delta_{k+1-n} \qquad (22)$$

for $k=0,1,2,\cdots$ with $\delta_0=1$. Similarly, the PDF of Z_2 can be derived by replacing $m_{I1}^{(i)}$ with $m_{I2}^{(i)}$, P_i with Q_i and $\Omega_{I1}^{(i)}$ with $\Omega_{I2}^{(i)}$ in (21) and (22). Comparing (21) with (32), one sees that, when the channels are non-identically distributed, the PDFs are similar to those for identical channels, both of which consist of a power function multiplied by an exponential function. Thus, by substituting corresponding parameters in the results for identical channels, for example, replacing Nm_{I1} with $\sum_{i=1}^N m_{I1}^{(i)}+k$ and $\frac{m_{I1}}{P_{I1}\Omega_{I1}}$ with $\frac{1}{\beta_{min}}$, results for non-identical channels can be obtained, only with an extra infinite series.

Another extension can be made when there is a direct link such that selective relaying can be used as $\gamma_{total}=\max\{\gamma,\gamma_d\}$, where γ is the end-to-end SINR of the relaying link derived as before and $\gamma_d=\frac{P_S|f|^2}{\sum_{j=1}^N Q_j|f_j|^2+\sigma_{da}^2+\sigma_{dc}^2}$ is the SINR of the direct link, with f being the small-scale Nakagami-m fading gain of the source-to-destination link and f_j is the small-scale Nakagami-m fading gain from the j-th interferer to the destination in the broadcasting phase. Following the same assumptions as before for the relaying link, the SINR of γ_d has the same CDF as X_2 in (28), except that the relevant parameters in (28) are replaced by the corresponding parameters in the direct link. Then, the overall outage probability will be calculated as $P_{out}^{TS-FG}F_{\gamma_d}(\gamma_0)$, $P_{out}^{TS-VG}F_{\gamma_d}(\gamma_0)$, $P_{out}^{PS-FG}F_{\gamma_d}(\gamma_0)$, or $P_{out}^{PS-VG}F_{\gamma_d}(\gamma_0)$, which can be used to derive the throughput in (19) and (20).

Using the results obtained in this paper the aforementioned extensions are quite straightforward and, for the sake of brevity, is not presented here.

V. Numerical Results and Discussion

In this section, the effects of several important system parameters are examined. We set $\sigma_{ra}^2=\sigma_{rc}^2=\sigma_{da}^2=\sigma_{dc}^2=1$, $P_S=P_{I1}=Q_{I2}=\Omega_{I1}=\Omega_{I2}=1$, while Ω_1 and Ω_2 vary with the average SINRs $\Delta_1=\frac{\Omega_1}{NP_{I1}\Omega_{I1}+\sigma_{ra}^2+\sigma_{rc}^2}$ and $\Delta_2=\frac{\Omega_2}{NQ_{I2}\Omega_{I2}+\sigma_{ra}^2+\sigma_{rc}^2}$, respectively, unless stated otherwise. The value of α is tested from 0.01 to 0.50 with a step size of 0.01 and the value of ρ is tested from 0.01 to 0.99 with a step size of 0.01. All simulation results are represented by the diamond markers in the curves.

Figs. 2 and 3 show the throughput versus α using TS. Several observations can be made. Firstly, from Fig. 2, the throughput increases when η increases, as expected, as larger values of η lead to more harvested energy. Numerically, from (8) and (9), the end-to-end SINR increases when η increases. Since $P_{out}=Pr\{\gamma<\gamma_0\}$, for fixed γ_0, the outage probability decreases when the end-to-end SINR increases. Thus, from (19), the throughput increases when η increases. Also, from Fig. 2, the throughput increases when N increases. The end-to-end SINRs are determined by γ_1, γ_2 and $\sum_{i=1}^N P_i|h_i|^2$ in (8) and (9). In the figure, Δ_1 and Δ_2 that determine γ_1

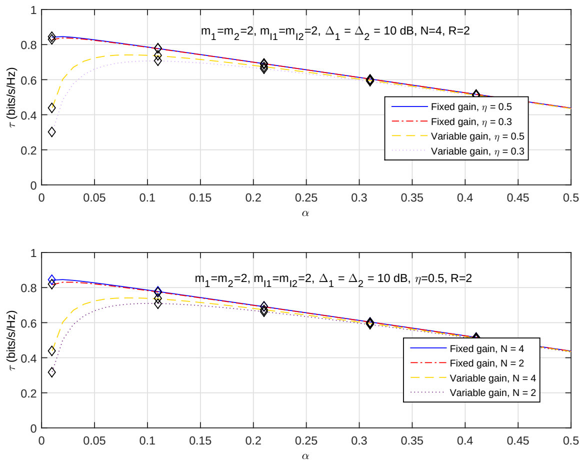

Fig. 2. Throughput vs. α for different η and N using TS in Nakagami-m fading with Nakagami-m interferers.

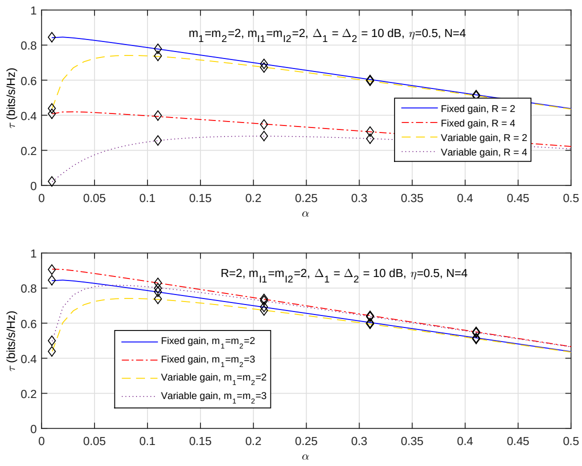

Fig. 3. Throughput vs. α for different R and m parameter using TS in Nakagami-m fading with Nakagami-m interferers.

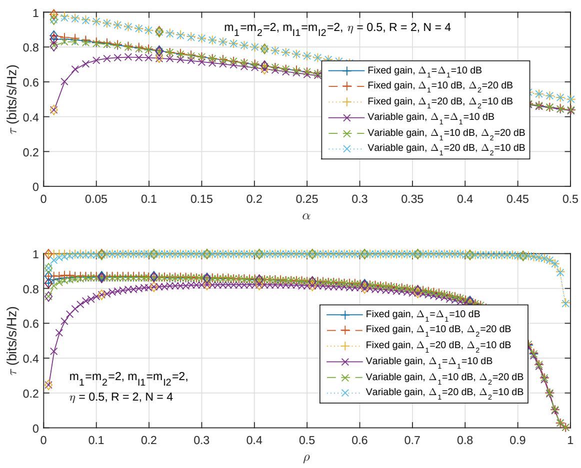

Fig. 4. Throughput vs. α or ρ for different Δ_1 and Δ_2 using TS or PS in Nakagami-m fading with Nakagami-m interferers.

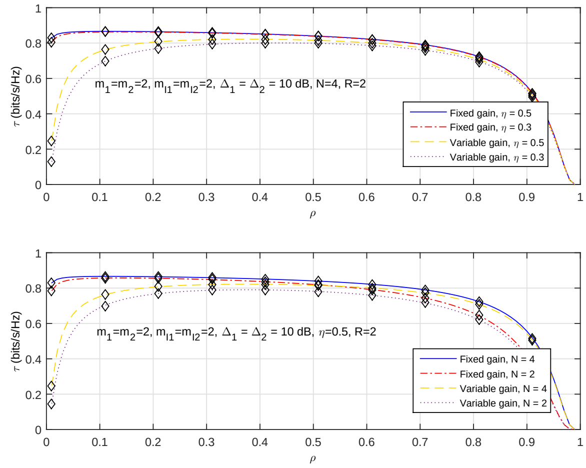

Fig. 5. Throughput vs. ρ for different η and N using PS in Nakagami-m fading with Nakagami-m interferers.

and γ_2, respectively, are fixed. Thus, when N increases, the term of $\sum_{i=1}^{N} P_i|h_i|^2$ increases such that the end-to-end SINR increases, leading to an improved performance due to more harvested interferences. Secondly, from Fig. 3, the throughput decreases when R increases. From (19), τ is determined by R and $1-P_{out}$ or $Pr\{\gamma > 2^R-1\}$. When R increases, $1-P_{out}$ or $Pr\{\gamma > 2^R-1\}$ decreases at a higher rate than R such that the overall throughput decreases. Also, the throughput increases when m parameter increases, as the channel conditions get better for larger m parameter. Thirdly, fixed gain has higher throughput than variable gain, as comparing (8) with (9), fixed gain relaying has a larger end-to-end SINR. Also, from Fig. 4, one sees that the throughput generally increases when Δ_1 or Δ_2 increase. However, the improvement is larger for an increased Δ_1 than Δ_2. This is because the first hop signal is used for information transmission as well as energy transfer such that a larger Δ_1 benefits both information and energy reception at the relay. In summary, the throughput is more sensitive to R, Δ_1 and the relaying method than to η, N, Δ_2 and m parameter.

Figs. 5 and 6 show the throughput versus ρ using PS. Similar to TS, the throughput of PS increases when η increases, N increases, R decreases, m parameter increases, Δ_1 increases or Δ_2 increases. Also, the throughput is more sensitive to R, Δ_1 and the relaying method than to η, N, m parameter, Δ_2. Also, comparing Figs. 2 and 3 with Figs. 5 and 6, one sees that the throughput of PS is less sensitive to ρ than the throughput of TS to α. In fact, in most curves, there is a flat area where a large range of ρ can achieve almost the same throughput, indicating that there is a greater flexibility in the choice of ρ. From (10) and (17), the difference of TS and PS lies in the value of X. Comparing X^{TS-FG} in (25) with X^{PS-FG} in (34), X^{TS-FG} has a term of $\frac{1-\alpha}{2\alpha}$ and X^{PS-FG} has a term of $\frac{1}{\rho(1-\rho)}$. It can be shown that $\frac{1-\alpha}{2\alpha}$ changes more dramatically with α than $\frac{1}{\rho(1-\rho)}$ with ρ. Also, X^{TS-VG} has a term of $\frac{1-\alpha}{2\alpha}$, while X^{PS-VG} has a term of $\frac{1}{\rho}$. Again, $\frac{1-\alpha}{2\alpha}$ changes more dramatically with α than $\frac{1}{\rho}$ with ρ. Table I gives the optimum values of α and ρ in these figures. One sees that α_{opt}^{FG} is very

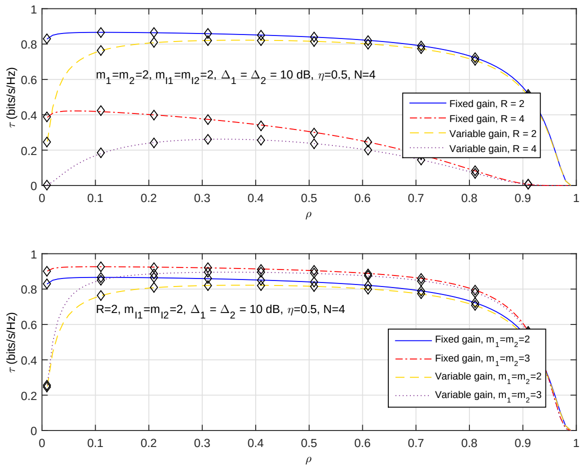

Fig. 6. Throughput vs. ρ for different R and m parameter using PS in Nakagami-m fading with Nakagami-m interferers.

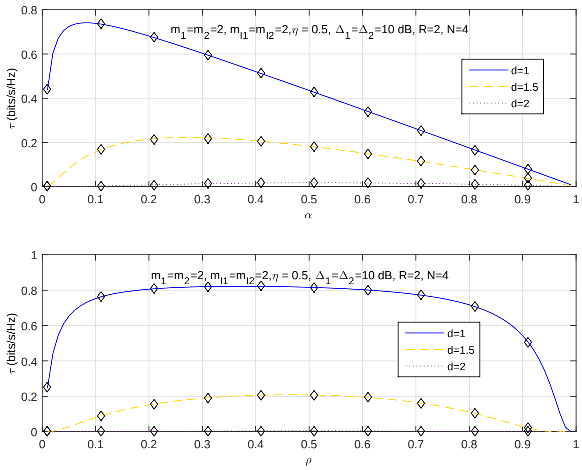

Fig. 7. The effect of the distance on τ using TS and PS in Nakagami-m fading with Nakagami-m interferers.

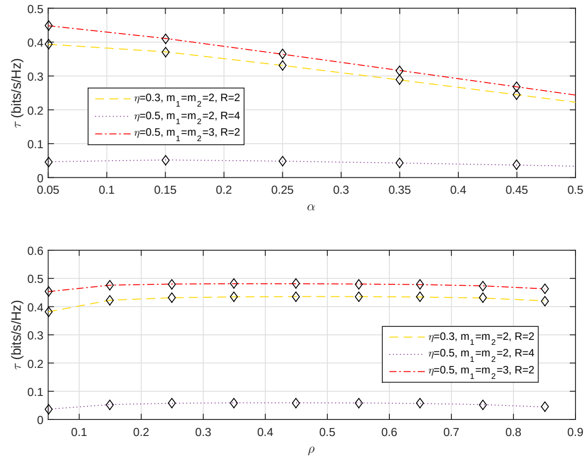

Fig. 8. The throughput of variable gain relaying with independent and non-identically distributed Nakagami-m interferers when $m_{I1} = m_{I2} = 2$, $N = 4$ and $\Delta_1 = \Delta_2 = 20dB$.

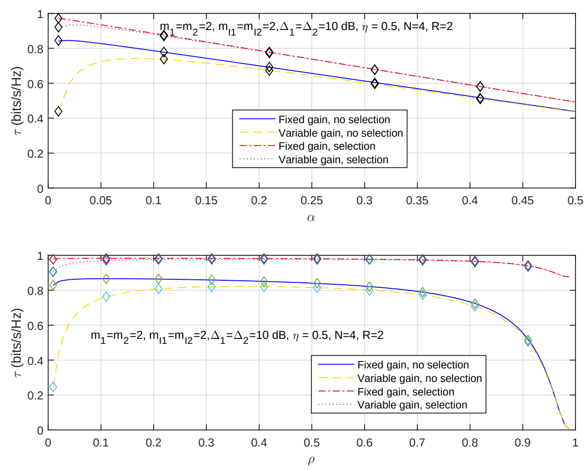

Fig. 9. Comparison of selective relaying with direct link and relaying without direct link.

small in all the cases. The value of α_{opt}^{VG} increases when η decreases, N decreases, R increases, m, Δ_1 or Δ_2 decreases. The value of ρ_{opt}^{FG} has similar trend to α_{opt}^{VG}, except that it decreases when R increases. The value of ρ_{opt}^{VG} has similar trend to ρ_{opt}^{FG}, except that it increases when Δ_1 increases.

Fig. 7 shows the effect of distance using variable gain relaying. In this case, the hop SINR is defined as $\gamma_1 = \frac{|h|^2/d^v}{\sum_{i=1}^{N} P_i|h_i|^2+\sigma_{ra}^2+\sigma_{rc}^2}$ and $\gamma_2 = \frac{|g|^2/d^v}{\sum_{j=1}^{N} Q_j|g_j|^2+\sigma_{da}^2+\sigma_{dc}^2}$, where d is the distance and v is the path loss exponent. In Fig. 7, $v = 3$. The path loss of the interference is ignored for simplicity. One sees that the throughput decreases quickly as the distance increases, as expected, as the end-to-end SINR decreases when the path loss increases due to an increased distance. Fig. 8 shows the throughput using variable gain relaying with independent and non-identically distributed interferers. In the figure, $\Omega_{I1}^{(1)} = \Omega_{I2}^{(1)} = \frac{1}{1^v}$, $\Omega_{I1}^{(2)} = \Omega_{I2}^{(2)} = \frac{1}{1.5^v}$, $\Omega_{I1}^{(3)} = \Omega_{I2}^{(3)} = \frac{1}{2^v}$ and $\Omega_{I1}^{(4)} = \Omega_{I2}^{(4)} = \frac{1}{2.5^v}$, and the infinite series in (21) is truncated to 30 terms. In this case, the throughput of TS monotonically decreases when α increases, while the throughput of PS is flat in most cases. Fig. 9 compares selective relaying with direct link and that without direct link. Here, f is assumed to have the same parameters as h and f_j is assumed to have the same parameters as g_j. One sees that the addition of the direct link improves the throughput due to diversity gain.

Note that in all cases, simulation results match very well with theoretical results. Also, the above results only con-

TABLE I
OPTIMUM VALUES OF α AND ρ IN FIGS. 2 - 6.

$(\eta,\ N,\ R,\ m,\ \Delta_1,\ \Delta_2)$	α_{opt}^{FG}	α_{opt}^{VG}	ρ_{opt}^{FG}	ρ_{opt}^{VG}
(0.5,4,2,2,10,10)	0.02	0.08	0.11	0.37
(0.3,4,2,2,10,10)	0.02	0.11	0.13	0.43
(0.5,2,2,2,10,10)	0.02	0.10	0.13	0.37
(0.5,4,4,2,10,10)	0.03	0.20	0.06	0.34
(0.5,4,2,3,10,10)	0.01	0.07	0.09	0.34
(0.5,4,2,2,10,20)	0.01	0.03	0.04	0.34
(0.5,4,2,2,20,10)	0.01	0.02	0.06	0.33

sider a fixed number of interferers. This is the case when a fixed-access wireless system with low or little mobility is studied, where wireless interconnection is mainly used to replace wires. This case has also been studied in the literature for relaying without harvesting (see for example [20] and references therein). On the other hand, references [10], [21] and [22] considered a random number of interferers by using stochastic geometry for wireless systems with high mobility. In particular, [10] considered energy harvesting. However, it is quite challenging to use these methods to extend our results to random interferers. This could be a potential generalization of this paper in the future.

VI. Conclusions

The performance of energy harvesting AF relaying has been evaluated in terms of the outage probability and the throughput. Analytical expressions have been derived considering both TS and PS harvesters when the channels suffer from interferences and Nakagami-m fading. Numerical results show that TS is more sensitive to energy harvesting than PS and that the throughput is more sensitive to N, R, Δ_1 and m_1 than to η, Δ_2 and the relaying method.

Appendix A Derivation of (10) and (17)

Define $Y_1 = P_s|h|^2$ and $Z_1 = \sum_{i=1}^{N} P_i|h_i|^2$, $Y_2 = |g|^2$ and $Z_2 = \sum_{i=1}^{N} Q_j|g_j|^2$, $X_1 = \frac{Y_1}{Z_1+\sigma_{ra}^2+\sigma_{rc}^2}$, $X_2 = \frac{Y_2}{Z_2+\sigma_{da}^2+\sigma_{dc}^2}$. Using (8), one has

$$P_{out}^{TS-FG} = Pr\{\frac{2\alpha\eta X_2 Y_1(Y_1+Z_1)}{(1-\alpha)(Z_1+\sigma_{ra}^2+\sigma_{rc}^2)} < \frac{2\alpha\eta\gamma_0 X_2(Y_1+Z_1)}{1-\alpha} + \frac{\gamma_0}{Z_1+\sigma_{ra}^2+\sigma_{rc}^2}\} \quad (23)$$

which gives

$$P_{out}^{TS-FG} = Pr\{\frac{2\alpha\eta}{1-\alpha}(Y_1+Z_1)(X_1-\gamma_0)X_2 < \frac{\gamma_0}{Z_1+\sigma_{ra}^2+\sigma_{rc}^2}\} = I_1 + I_2 \quad (24)$$

where $I_1 = Pr\{X_1 < \gamma_0\}$ and $I_2 = Pr\{X_2 < X_{TS-FG}(Y_1, Z_1), X_1 > \gamma_0\}$ with

$$X_{TS-FG}(Y_1,Z_1) = \frac{\frac{1-\alpha}{2\alpha\eta}\gamma_0}{(Y_1+Z_1)(Y_1-\gamma_0 Z_1-\gamma_0\sigma_{ra}^2-\gamma_0\sigma_{rc}^2)}. \quad (25)$$

In (24), the second equation is obtained using the total probability theorem by conditioning on $X_1 < \gamma_0$ and $X_1 > \gamma_0$.

Since $Y_2 = |g|^2$ is a Gamma random variable, its cumulative distribution function (CDF) can be derived as

$$F_{Y_2}(x) = \frac{1}{\Gamma(m_2)}\gamma(m_2, \frac{m_2}{\Omega_2}x), x > 0 \quad (26)$$

where $\gamma(\cdot,\cdot)$ is the lower incomplete Gamma function [18, (8.350.1)]. Also, assume $Q_j = Q_{I2}$ for $j = 1, 2, \cdots, N$. Then, the PDF of $Z_2 = \sum_{j=1}^{N} Q_j|g_j|^2$ is given by

$$f_{Z_2}(x) = \left(\frac{m_{I2}}{Q_{I2}\Omega_{I2}}\right)^{Nm_{I2}} \frac{x^{Nm_{I2}-1}}{\Gamma(Nm_{I2})} e^{-\frac{m_{I2}}{Q_{I2}\Omega_{I2}}x}, x > 0. \quad (27)$$

Thus, one has the CDF of X_2 as

$$F_{X_2}(x) = \int_0^\infty F_{Y_2}(x(t+\sigma_{da}^2+\sigma_{dc}^2)) f_{Z_2}(t)dt. \quad (28)$$

Using [18, (8.352.1)] and [18, (3.381.4)], this integration can be solved to give

$$F_{X_2}(x) = 1 - \left(\frac{m_{I2}}{Q_{I2}\Omega_{I2}}\right)^{Nm_{I2}} \frac{e^{-\frac{m_2(\sigma_{da}^2+\sigma_{dc}^2)}{\Omega_2}x}}{\Gamma(Nm_{I2})} \sum_{l=0}^{m_2-1}\sum_{l'=0}^{l} (m_2 x/\Omega_2)^l \binom{l'}{l} \frac{(\sigma_{da}^2+\sigma_{dc}^2)^{l-l'}(Nm_{I2}+l'-1)!}{l!(\frac{m_{I2}}{Q_{I2}\Omega_{I2}}+\frac{m_2 x}{\Omega_2})^{Nm_{I2}+l'}}. \quad (29)$$

Thus,

$$I_2 = 1 - I_1 - \int_0^\infty \int_{\gamma_0 z+\gamma_0\sigma_{ra}^2+\gamma_0\sigma_{rc}^2}^\infty \left(\frac{m_{I2}}{Q_{I2}\Omega_{I2}}\right)^{Nm_{I2}} \frac{e^{-\frac{m_2(\sigma_{da}^2+\sigma_{dc}^2)}{\Omega_2}X_{TS-FG}(y,z)}}{\Gamma(Nm_{I2})} \sum_{l=0}^{m_2-1}\sum_{l'=0}^{l} \frac{(m_2 X_{TS-FG}(y,z)/\Omega_2)^l}{l!(\frac{m_{I2}}{Q_{I2}\Omega_{I2}}+\frac{m_2 X_{TS-FG}(y,z)}{\Omega_2})^{Nm_{I2}+l'}} \binom{l'}{l}(\sigma_{da}^2+\sigma_{dc}^2)^{l-l'}(Nm_{I2}+l'-1)! f_{Y_1}(y) f_{Z_1}(z) dydz \quad (30)$$

where $\binom{l'}{l}$ is the binomial coefficient of choosing l' out of l and $(\cdot)!$ is the factorial operation. Since $Y_1 = P_S|h|^2$, the PDF of Y_1 can be derived as

$$f_{Y_1}(x) = \left(\frac{m_1}{P_S\Omega_1}\right)^{m_1} \frac{x^{m_1-1}}{\Gamma(m_1)} e^{-\frac{m_1}{P_S\Omega_1}x}, x > 0. \quad (31)$$

Also, assume $P_i = P_{I1}$ for $i = 1, 2, \cdots, N$. Thus, Z_1 has

$$f_{Z_1}(x) = \left(\frac{m_{I1}}{P_{I1}\Omega_{I1}}\right)^{Nm_{I1}} \frac{x^{Nm_{I1}-1}}{\Gamma(Nm_{I1})} e^{-\frac{m_{I1}}{P_{I1}\Omega_{I1}}x}, x > 0. \quad (32)$$

Finally, using (30) - (32) in (24), the outage probability for fixed gain relaying using TS energy harvesting can be derived as (10).

Define $X_3 = \frac{Y_1}{Z_1+\sigma_{ra}^2+\sigma_{rc}^2/(1-\rho)}$. For PS, the outage probability for fixed gain relaying can be derived as

$$P_{out}^{PS-FG} = Pr\{\eta\rho(1-\rho)(Y_1+Z_1)(X_3-\gamma_0)X_2 < \frac{\gamma_0}{Z_1+\sigma_{ra}^2+\sigma_{rc}^2/(1-\rho)}\} = I_1 + I_2 \quad (33)$$

where $I_1 = Pr\{X_3 < \gamma_0\}$ and $I_2 = Pr\{X_2 < X_{PS-FG}(Y_1, Z_1), X_3 > \gamma_0$ with

$$X_{PS-FG}(Y_1,Z_1) = \frac{\gamma_0}{\eta\rho(1-\rho)}\frac{1}{(Y_1+Z_1)} \frac{1}{(Y_1-\gamma_0 Z_1-\gamma_0\sigma_{ra}^2-\gamma_0\sigma_{rc}^2/(1-\rho))}. \quad (34)$$

The second equation in (33) is also obtained by using the total probability theorem conditioned on $X_3 < \gamma_0$ or $X_3 > \gamma_0$. Using the CDF of X_2 in (29), the outage probability can be calculated as (17).

APPENDIX B DERIVATION OF (13)

One has $\gamma^{TS-VG} \approx \frac{Y_1 X_2}{X_2(Z_1+\sigma_{ra}^2+\sigma_{rc}^2)+\frac{1-\alpha}{2\alpha\eta}}$ when $\gamma_1 \to \infty$. This gives

$$P_{out}^{TS-VG} \approx Pr\{Y_1 < \gamma_0 Z_1 + \gamma_0\sigma_{ra}^2 + \gamma_0\sigma_{rc}^2 + \gamma_0\frac{1-\alpha}{2\alpha\eta}W\} \quad (35)$$

where $W = \frac{1}{X_2} = \frac{Z_2+\sigma_{da}^2+\sigma_{dc}^2}{Y_2}$. Using the PDF of Y_1 in (31) and [18, eq. (8.352.1)], one further has

$$\begin{aligned} P_{out}^{TS-VG} &\approx 1 - \sum_{l=0}^{m_1-1} \frac{(\frac{m_1\gamma_0}{P_s\Omega_1})^l}{l!} \\ &\int_0^\infty \int_0^\infty f_{Z_1}(z) f_W(w) \\ &(z+\sigma_{ra}^2+\sigma_{rc}^2+\frac{1-\alpha}{2\alpha\eta}w)^l \\ \times \quad & e^{-\frac{m_1\gamma_0}{P_s\Omega_1}(z+\sigma_{ra}^2+\sigma_{rc}^2+\frac{1-\alpha}{2\alpha\eta}w)} dzdw. \end{aligned} \quad (36)$$

By using the binomial expansion and [18, (3.381.4)] to solve the integration over z, one has (13). Next, we need the PDF of W. For $T = Z_2+\sigma_{da}^2+\sigma_{dc}^2$, using (27), one has

$$\begin{aligned} f_T(t) &= \left(\frac{m_{I2}}{Q_{I2}\Omega_{I2}}\right)^{Nm_{I2}} \frac{(t-\sigma_{da}^2-\sigma_{dc}^2)^{Nm_{I2}-1}}{\Gamma(Nm_{I2})} \\ &\times e^{-\frac{m_{I2}}{Q_{I2}\Omega_{I2}}(t-\sigma_{da}^2-\sigma_{dc}^2)}, t > \sigma_{da}^2+\sigma_{dc}^2. \end{aligned} \quad (37)$$

Also, since $W = \frac{T}{Y_2}$, one has

$$f_W(w) = \int_{\frac{\sigma_{da}^2+\sigma_{dc}^2}{w}}^\infty y f_T(wy) f_{Y_2}(y) dy. \quad (38)$$

Finally, using (37) and (26) in (38), one can solve the integration as

$$\begin{aligned} f_W(w) &= \frac{(\frac{m_2}{\Omega_2})^{m_2}(\frac{m_{I2}}{Q_{I2}\Omega_{I2}})^{m_{I2}}}{\Gamma(m_2)\Gamma(Nm_{I2})} \\ &\sum_{n=0}^{m_2} \binom{m_2}{n} (\sigma_{da}^2+\sigma_{dc}^2)^{m_2-n} \\ &\times \frac{(Nm_{I2}+n-1)! e^{-\frac{m_2(\sigma_{da}^2+\sigma_{dc}^2)}{\Omega_2 w}}}{w^{m_2}(\frac{m_{I2}}{Q_{I2}\Omega_{I2}}+\frac{m_2}{\Omega_2}w)^{Nm_{I2}+n}}. \end{aligned} \quad (39)$$

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