Impact of Fading Channel to Energy Harvesting Relay on Cooperative Communication Systems

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***Abstract*—Channel conditions strongly influence the performance of the wireless communication system. Fading is one of the main problems caused by signal propagation via various paths. Recently, cooperative communication systems have been extensively studied to overcome this problem. However, the power consumption in the system relaying information to the destination increases, shortening the network's life. Therefore, this paper analyzes the impact of three Raleigh and Rician fading channel scenarios on cooperative communication performance in which a relay uses energy harvesting based on power splitting (EH-PS). The three scenarios are Rayleigh-Rayleigh fading (I), Rician-Rayleigh fading (II), and Rician-Rician fading (III). Subsequently, the throughput performance and energy efficiency are evaluated based on the maximum power splitting (PS) ratio. The simulation results indicate that the PS ratio in scenario III is higher than in scenarios I and II. Thus, the Rician fading channel can accumulate more energy in the relay due to the line-of-sight path between the source and the relay. Hence, scenario III's throughput and energy efficiency are higher than the other scenarios. The energy efficiency for scenario III is 33.08% and 12.14% higher than scenarios I and II, respectively. Therefore, the EH-PS cooperative communication system with the Rician fading channels has the highest throughput and is promising for future 5G technology.**

***Keywords*—fading channel scenario, energy harvesting, power splitting, energy efficiency, cooperative communication**

I. Introduction

The 5th Generation (5G) mobile communication technology provides several important features, such as high network capacity, low latency, and high energy efficiency [1, 2]. However, 5G technology has several challenges: privacy and security, energy consumption, performance, and QoS [3]. A cooperative communication system fulfills these features in 5G technology and expands the network coverage [4, 5]. The role of relays in cooperative communication systems is crucial as they serve as intermediary devices that transmit information from source to destination. A relay will continuously transmit information from various nearby sources, causing the relay's battery to expire quickly and the energy consumption in a network to increase significantly. Battery-dependent devices have different drawbacks, such as limited size, energy storage, and wasteful extraction of stored energy. Furthermore, most batteries end up in landfills which causes soil and water pollution. In addition, the need for multimedia services on 5G technology with extensive data and high speed will increase energy consumption on the network [6]. The purpose of the cooperative communication system was to overcome the effects of multipath fading, which led to improved network performance and coverage area [7]. However, the current development of 5G technology focuses not only on the performance metrics, such as increasing data rate, throughput, reducing delay, and so on, but also regarding the economic aspect, operational environmental issues, specifically energy efficiency [8]. In addition, wireless devices, in general, are devices with a limited battery capacity. Thus, relays in cooperative communication networks require the power to forward the information to the destination.

One of the solutions to maintain energy availability in relays is to apply Energy Harvesting (EH) techniques [9–12]. The EH technique has been extensively introduced in cooperative communication systems. This technique collects energy from the Radio Frequency (RF), transmitted by the source using wireless devices, carrying the information and energy simultaneously [13]. RF EH is a wireless power transfer technology that converts received RF signals into electricity. Therefore, RF EH devices can deliver an effective solution for wireless devices, empowering them to harvest energy from RF signals within the environment. Generally, the EH technique is performed using the Time-Switching Relaying (TSR) and Power-Splitting Relaying (PSR) protocols [14]. In the TSR protocol, the signal's energy is divided into two transmission time frames; one is used to gather energy from the source, whilst the other is employed to transmit the data.

On the contrary, the PSR protocol equally divides the transmission time frame for receiving nodes in harvesting energy and processing information. As discussed in [15], a comparison was made of the TSR and PSR protocols in a cooperative communication system using an Amplify-and-

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Forward (AF) relay with two transmission modes, namely Delay-Limited Transmission (DLT) and Delay-Tolerant Transmission (DTT). The PSR protocol was revealed to obtain optimum throughput in the two transmission modes. Subsequently, the adaptive EH in cooperative communication systems has also been studied [16]. As a result, the relay can adaptively switch between EH and power splitting at the beginning of each EH time frame and information processing on relays to increase throughput performance opportunistically. Moreover, optimal power splitting by means of information transmission and energy transfer has also been introduced in multi-relay cooperative communication systems [17]. Based on these studies, the PSR protocol has become one of the most studied EH protocols to provide optimum throughput [14]. Thus, the PSR protocol for the EH in the proposed cooperative communication system is also considered in this paper.

The application of RF EH in cooperative communication systems via Rayleigh channels has been universally studied in previous works [18–21]. However, Rayleigh fading channels may not be suitable for transmission from source to relay because EH relays will help forward information if the direct link is blocked due to obstacles. Typically, cooperative communication systems are carried out with the source sending data to a nearby relay [22]. In other words, the relay is closer to the source than the destination. Thus, the source has a good channel quality to the relay because it has a better possibility of available line-of-sight (LOS) paths and multipath spread for the source-relay link. Consequently, the relay channel to the destination may be poor. Subsequently, research in [18–21] focused more on the outage probability performance analysis.

The effect of Rician fading channels on EH for cooperative communication has been investigated in [23–25]. The study conducted in [23] used the EH TSR protocol on the AF relay for cooperative communication systems and confirmed that the throughput of the Rician fading channel was superior to that of the Rayleigh fading. The improvement of the channel was influenced by the LOS component of the Rician fading. In reference [24], the EH PSR protocol is applied in the AF relay by considering two different fading channels; source to relay via Rician fading channels and relay to destination via Rayleigh fading channels. The study results indicate that the LOS component of Rician fading can improve the outage probability performance of the system. The application of EH PSR to Decode-and-Forward (DF) relays by way of detailed fading channels has also been studied in [25] to improve the outage probability performance. However, the study considered a direct line of communication between source and destination, which practically makes it impossible for long-distance LOS path [26]. Recently, a different study [27], the authors took into consideration combining Rayleigh and Rician fading channels in AF and DF relays with EH TSR and PSR mechanisms in cooperative communication systems. The results exhibit that the performance of the DF relay with PSR is better than that of AF with TSR. To the best of our knowledge, few studies consider combined fading channels in EH relays. One of the motivations of this paper is to evaluate the application of EH PSR on DF relays via several scenarios pertaining to fading channels without a direct path between source and destination for the reasons previously mentioned.

Based on the above-mentioned, this paper further examines the effect of several fading channel scenarios on the average throughput and energy efficiency for EH relays in cooperative communication systems. Three fading scenarios for the source-to-relay and relay-to-destination links were investigated: Rayleigh-Rayleigh fading (I), Rician–Rayleigh fading (II), and Rician-Rician fading (III). The considered EH protocol is PSR to maximise the energy collected on the relay [28]. Subsequently, this paper employs the DF mechanism on the relay for optimal performance and reduced energy consumption which is lower than with the AF protocol. The contribution of this paper is given as follows:

- We propose three fading channel scenarios for DF relay with EH PSR in a cooperative communication system without considering a direct path between source and destination.
- We obtain the closed-form of average throughput and energy efficiency for EH PSR in a cooperative communication system.
- We evaluate the effect of fading scenarios on average throughput and energy efficiency based on the maximum PSR value.

II. Channel Scenarios and System Model

A. Fading Channel Scenarios

The cooperative communication system considered in this paper consists of one source, one relay, as well as one destination. EH is applied to relays using the power splitting protocol known as PS-EH. In the system, the source (S) transmits information (contains RF energy) to the relay (R) and then the relay collects energy and forwards the information to the destination (D). This paper proposes three fading channel scenarios for the PS-EH cooperative communication system, as shown in Fig. 1. Each scenario can be explained as follows:

1) Scenario I: The S→R and R→D link employs the same Rayleigh fading channel, as shown in Fig. 1(a). This conventional fading channel is commonly used in cooperative communication systems with EH [29–31]. Rayleigh fading channel has two multipath components, $X(t)$ and $Y(t)$, resulting from the zero-mean complex Gaussian process $X \sim CN(0,\sigma^2)$ and $Y \sim CN(0,\sigma^2)$. Gaussian complex random variables can be expressed [32]:

$$Z = X + jY \tag{1}$$

and comprises an envelope of [31]:

$$R = \sqrt{X^2 + Y^2} \tag{2}$$

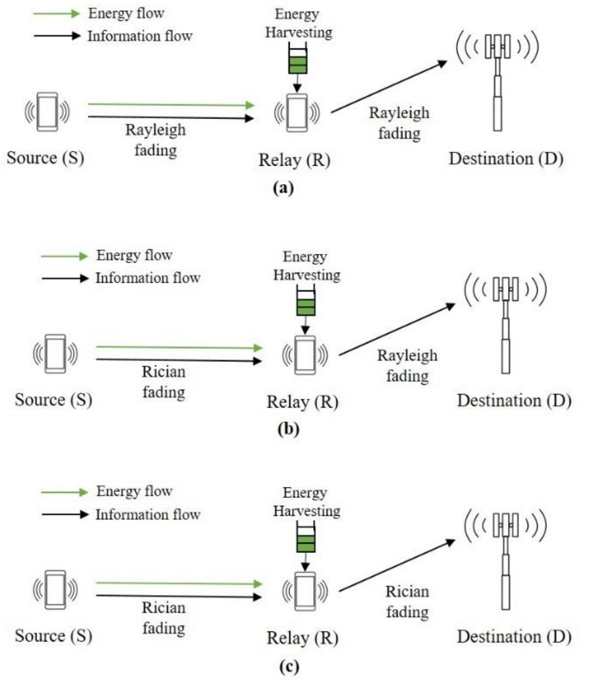


Figure 1. (a) Scenario I; (b) Scenario II and (c) Scenario III.

with a probability density function (PDF) of [32]:

$$f(r) = \frac{r}{\sigma^2} exp\left(-\frac{r^2}{2\sigma^2}\right) \quad (3)$$

where r is the mean and σ^2 is the variance.

2) Scenario II: The S→R link uses the Rician and the R→D link utilises the Rayleigh fading channels, as presented in Fig. 1(b). This scenario uses a combined fading channel in a cooperative communication system. This combined fading channel has not been studied in-depth, notably in the PS-EH cooperative communication system. Thus, it is one of the focal points of this research. The S→R link employs a Rician fading channel because it has a LOS component to optimise the energy harvested by the relay, and the throughput performance can also be increased. Further explanation of the Rician fading channel is provided in point c).
3) Scenario III: The S→R and R→D link use the same fading channel, the Rician fading channels, as illustrated in Fig. 1(c). In Rician fading, there is a dominant component in the form of LOS, considering two Gaussian random variables; $X \sim CN(m_1, \sigma^2)$ and $Y \sim CN(m_2, \sigma^2)$, where m_1 and m_2 are the means of distributions. The non-centrality parameter that determines the values of X and Y is:

$$s = \sqrt{m_1^2 + m_2^2} \quad (4)$$

The non-centrality parameter has an imbalance value of the mean owing to the dominant communication links in Rician fading. Thus, the K factor of the Rician that represents LOS power and non-LOS power (NLOS) [33] is:

$$K = \frac{P_{LOS}}{P_{NLOS}} = \frac{m_1^2 + m_2^2}{2\sigma^2} = \frac{s^2}{2\sigma^2} \quad (5)$$

PDF of Rician fading's envelope is expressed as [34]:

$$f_R(r) = \frac{r}{\sigma^2} exp\left(-\frac{r^2 + s^2}{2\sigma^2}\right) I_0\left(\frac{rs}{\sigma^2}\right) \quad (6)$$

where $I_0(x)$ is a function of Bessel's zero order x.

B. System Model

The system model considered in this paper is a cooperative communication system with EH for several fading channel scenarios, as shown in Fig. 2(a). Firstly, a source transmits the encoded encoder data x_s to the relay. The fading will influence the information signal on the S→R link, where the signal will be convoluted with the fading coefficient, h_{sr}, and noise, n_{sr}. The signal received on the relay, y_{sr}, can be defined as:

$$y_{sr} = x_s h_{sr} + n_{sr} \quad (7)$$

Furthermore, the relay will forward the information signal without using its energy but the energy transferred by the source. The signal received by the relay will be subjected to an EH process based on a power splitting mechanism to minimise energy consumption in the cooperative communication system. The splitter will divide the received power as follows:

- The power ratio of $1 - \rho$ is used to convert signal transmission by means of the signal converter, which is then encoded with the DF relay protocol, where $0 \le \rho \le 1$.
- The power ratio of ρ is applied to collect energy by the energy harvester stored in the battery on the relay.

The entire system block for the information signal process and EH using the power splitting protocol on the relay (T), as shown in Fig. 2(b), is explained below:

- The source transmits information to the relay with a time duration of $T/2$. The ratio of the signal power received by the relay is $1 - \rho$, while the ratio of the energy collected by the relay is ρ.
- The relay communicates with the destination at the time duration of $T/2$.

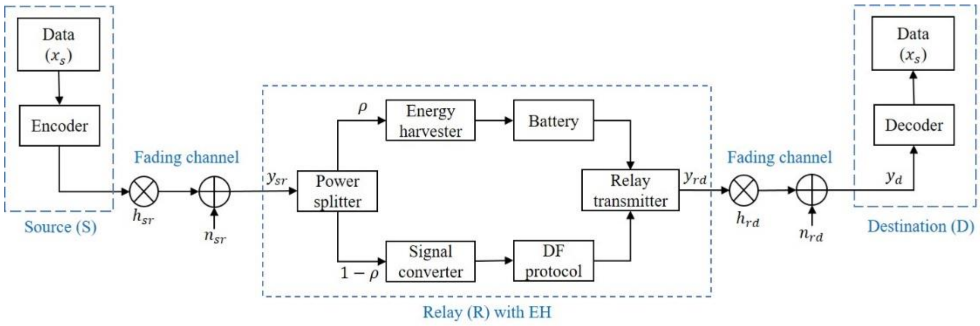
The collected energy using the power splitting EH protocol can be calculated by [15]:

$$E_r = \frac{\eta \rho P |h_{sr}|^2}{d_{sr}^{\alpha_{sr}}}\left(\frac{T}{2}\right) \quad (8)$$

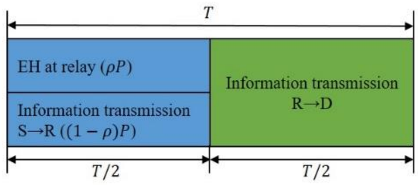
where η is the value of energy conversion efficiency ($0 < \eta < 1$) on the relay, P is the power source, d_{sr} is the distance of the S→R link and α_{sr} is the path loss exponent value in the S→R link. Thus, the output signal of the EH on the relay can be expressed as follows:

$$y_{rd} = \sqrt{1-\rho}\left(\sqrt{\frac{P}{d_{sr}^{\alpha_{sr}}}} x_s h_{sr} + n_{sr}\right) + n_{rc} \quad (9)$$

where n_{rc} is the constant value of the noise converter on the relay. Assuming that the relay uses all the collected energy in the transmission process, the accumulated relay power is calculated by [5]:



(a) System model



(b) Power splitting protocol

Figure 2. (a) System model and (b) Power splitting protocol.

$$P_r = \eta P \frac{|h_{sr}|^2}{d_{sr}^{\alpha_{sr}}} \rho \quad (10)$$

This paper makes use of the DF protocol for cooperative communication. It is assumed that the source information can be corrected appropriately.

III. Performance Analysis

A. Throughput

In this section, the power splitting mechanism of the proposed cooperative communication system model is analysed with the following considerations:

- The relay recognises the condition of the fading channels on the S→R link.
- The relay also recognises the condition of the fading channel on the R→D link.
- The power splitting ratio is determined by maximising the average throughput (effective rate) and is calculated based on the relay's signal-to-noise ratio (SNR) value.

The SNR on the relay and the destination can be determined as [5]:

$$\gamma_{sr}(\rho) = (1+\sigma)\frac{P}{N_{rs}+N_{rc}}\frac{|h_{sr}|^2}{d_{sr}^{\alpha_{sr}}} - \frac{(1+\sigma)\sigma\frac{P}{N_{rs}+N_{rc}}\frac{|h_{sr}|^2}{d_{sr}^{\alpha_{sr}}}}{\rho} \quad (11)$$

and

$$\gamma_d(\rho) = 2\eta\frac{P}{N_{rd}+N_{rc}}\frac{|h_{sr}|^2}{d_{sr}^{\alpha_{sr}}}\frac{|h_{rd}|^2}{d_{rd}^{\alpha_{rd}}} - \eta\frac{P}{N_{rd}+N_{rc}}\frac{|h_{sr}|^2}{d_{sr}^{\alpha_{sr}}}\frac{|h_{rd}|^2}{d_{rd}^{\alpha_{rd}}}\rho - \eta\frac{P}{N_{rd}+N_{rc}}\frac{|h_{sr}|^2}{d_{sr}^{\alpha_{sr}}}\frac{|h_{rd}|^2}{d_{rd}^{\alpha_{rd}}}(1-\sigma) \quad (12)$$

where ($\rho \in [\sigma, 1+\sigma]$) and σ is the noise variance ratio on the antenna compared to the down-converter given by

$$\sigma = \frac{N_{rc}}{N_{sr}} = \frac{N_{rc}}{N_{rd}} \quad (13)$$

Average throughput on the relay and the destination (in nats per channel use (npcu)) are calculated by [35]:

$$E[\tau_{sr}] = E[\tfrac{1}{2}log(1+\gamma_{sr})] \quad (14)$$

and

$$E[\tau_d] = E\left[\tfrac{1}{2}log(1+\gamma_d)\right] \quad (15)$$

Thus, the power splitting is determined by ρ based on the maximum average throughput according to [35]:

$$E[\tau_{df}^{ps}] = arg \max_{x\,\in[\sigma,1+\sigma]} min\{E[\tau_{sr}], E[\tau_d]\} \quad (16)$$

Furthermore, the power splitting ratio for the Rician fading channels is calculated to the K factor value to determine the characteristics of Rician fading. Hence, the power splitting ratio is determined by

$$\rho_{df}^{ps} = 1+\sigma-\rho \quad (17)$$

B. Energy efficiency

Energy efficiency is one crucial performance indicator in relation to EH cooperative communication systems. In this paper, energy efficiency determines the efficiency level of the power splitting on EH in the system. Energy efficiency can be calculated by comparing the average throughput to the total power consumed in the system. Then, the energy efficiency of the cooperative communication system using EH is determined by

$$E_{eff} = \frac{E[\tau_{df}^{ps}]}{P_T} \quad (18)$$

where P_T is the total power consumption in the cooperative communication system consists of source transmission power and power consumption on the circuit [13]. The power consumption of the circuit is described as:

- The power required to process the signal at the source to encode the information at the encoder.
- Power is also required when processing the information signal with the DF protocol at the relay.
- The power required when processing the information signal at the destination, which is the decoding process at the decoder.

Consequently, the total power of the system (in W) can be stated by

$$P_T = \varsigma . P + P_C \quad (19)$$

where ς is the power ratio of the source to transmit the information signal and P_C is the power consumption in the circuit.

IV. Results and Discussion

This section describes the results of computer simulations using MATLAB programming for the average throughput and energy efficiency of the three fading channel scenarios in a cooperative communication system with EH based on the analysis in Section III. The characteristics of Rician fading channels, Rayleigh fading channels, along with combined Rician-Rayleigh fading channels on the EH cooperative communication system are evaluated. The simulation obtains the maximum power splitting EH by referring to each fading channel scenario's average throughput and the highest energy efficiency.

A. Throughput

The average throughput is simulated based on Eq. (16); the value of ρ indicates the power splitting ratio to EH as in Eq. (17). The relay does not collect energy when $\rho = 0$. In other words, all of the energy is used for information transfer. By varying the value ρ, the average throughput is obtained based on the SNR value on the S→R link. Thus, the relay with the highest SNR generates the maximum average throughput. The simulation result of the average throughput to power splitting ratio is shown in Fig. 3, at the distance ratio S→R of 0.5 or when the relay is in the middle between S→D. At a PSR of 0.25, the maximum average throughput for the fading channel scenarios I and II are 0.3138 and 0.4078 npcu, respectively. While the maximum average throughput value for the fading channel scenario III is 0.4906 npcu, obtained at a PSR of 0.3.

Based on the simulation result, it is established that the Rician fading channel (scenario III) can produce an average throughput higher than the other two scenarios. Because the Rician fading channel transmits information signals in LOS conditions, a high SNR value improves the quality. However, fading channels scenario II with the S→R link uses Rician fading better than scenario I. Furthermore, in scenario III, the relay collects more energy than in scenarios I and II. The maximum average throughput for scenario III is achieved at the PSR of 0.3. The relay can collect 30% of the energy, of which 70% is utilised for information transfer. Although scenarios II and III have a maximum average throughput of PSR of 0.25, each relay can only collect 25% of the energy. Therefore, in power splitting EH, Rician link fading (S→R and R→D) can produce a relatively high average throughput and collect more energy.

By considering the same simulation parameters as in Fig. 3, the average throughput to the distance ratio of the S→R link for the three fading channel scenarios is presented in Fig. 4. In this simulation, the PSR is the ratio that yields the highest average throughput for scenario I, II, and III, which are 0.25, 0.25, and 0.3, respectively. The simulation results indicate that changes in the S→R link's distance ratio affect the average throughput value; the closer the distance ratio to 1, the smaller the average throughput value. The highest average throughput for the three scenarios is obtained when the relay is closest to the source. For example, at the distance ratio of the S→R link equal to 0.1, the source has a high probability of transmitting data successfully to the destination due to low fading and low noise compared to a higher distance ratio. The average throughput for scenarios I, II, and III at this distance ratio are 2.004, 2.224, and 2.665 npcu, respectively. Conversely, relays located far from the source or close to the destination, for example, at a distance ratio SR link of 0.9, have a higher probability of transmission failure, resulting in low average throughput.

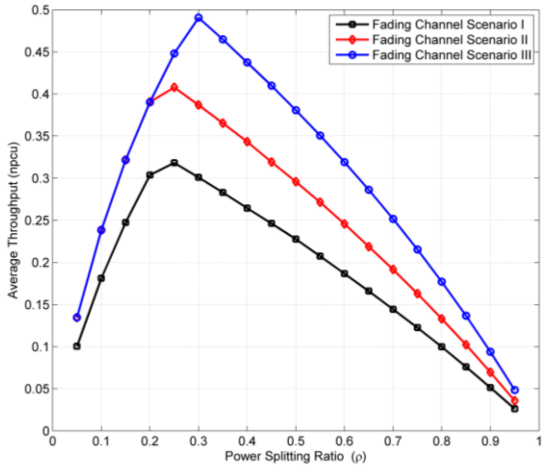


Figure 3. The average throughput versus power splitting ratio for three fading channels in the cooperative communication system.

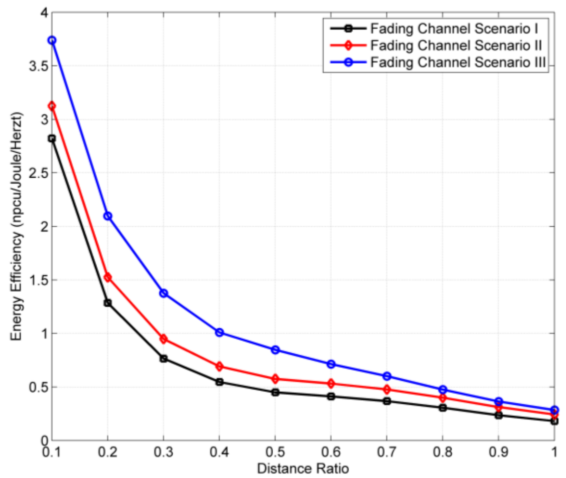


Figure 4. The average throughput versus distance ratio for the three fading scenarios in the cooperative communication system.

The average throughput for scenarios I, II, and III at this distance ratio are 0.168, 0.2231, and 0.2604 npcu, respectively. The average throughput of fading channel scenario III is higher than those of the other scenarios for the reason that this scenario can collect more energy in the relay, increasing the system's average throughput. The effect of LOS conditions on the Rician channel can also improve the average throughput of the system. On the contrary, Rayleigh fading channels with NLOS components will significantly affect the average throughput of the system. Fig. 5 exhibits the simulation results of the relationship between the PSR and the distance ratio of the S→R link. The increased distance ratio requires a more significant power splitting ratio as a result of the attenuation in the S→R communication link. Therefore, the harvested power at the relay will increase the throughput due to the S→R link's distance ratio. Therefore, it is essential to determine the maximum PSR for maximum average throughput.

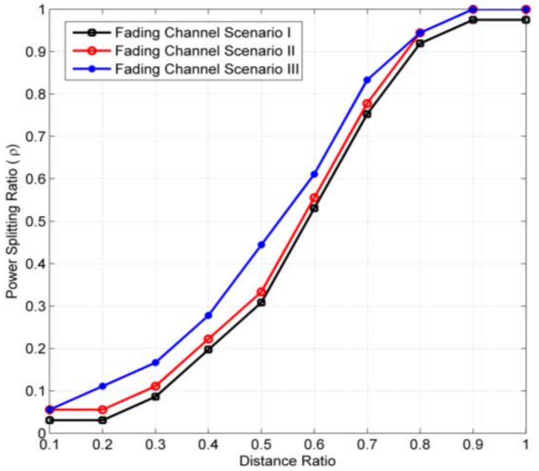


Figure 5. The power splitting ratio versus distance ratio for the three fading scenarios in the cooperative communication system.

B. *Energy Efficiency*

Energy efficiency is assessed based on the Analysis of Section III and the system model described in Section II. In the simulation, information from source to destination is imposed using three fading channel scenarios and the parameters in Section IV-A. The energy efficiency is simulated against the PSR and is calculated based on Eq. (18). Total power consumption is determined by applying Eq. (19), where the signal processing causes the value of the power consumption in the circuit to be 160 mW [13]. In this cooperative communication network, the relay does not use its own power but rather the power collected from the source. In other words, the source transfers power to the relay by dividing it in a specific ratio. Hence, the system is energy efficient while maintaining high performance by maximising the average throughput.

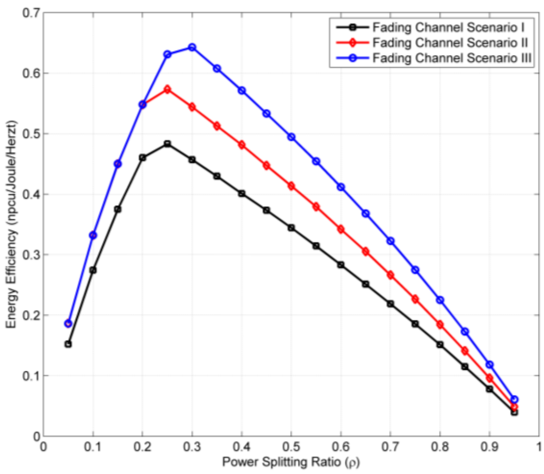


Figure 6. Energy efficiency versus power splitting ratio for the three fading scenarios in the cooperative communication system.

The simulation result of the energy efficiency to PSR for the three fading channel scenarios is demonstrated in Fig. 6. Simulations were conducted at a distance ratio of S→R link of 0.5; energy efficiency increased for all scenarios at $\rho \leq 0.3$ and reduced when the PSR increased, $\rho > 0.3$. As a result, the maximum energy efficiency in the system with $\rho = 0.25$ for scenarios I and II are 0.483 and 0.5732 npcu/Joule/Hertz, respectively. Simultaneously, the maximum energy efficiency of scenario III with $\rho = 0.3$ is 0.6428 npcu/Joule/Hertz. Hence, the energy efficiency pertaining to fading channel scenario III is 33.08% higher than fading channel scenario I and 12.14% higher than the fading channel scenario II. Energy efficiency results related to other ρ values also exhibit similar indications. Thus, the Rician fading channels with a LOS component significantly affect the harvested energy on the relay.

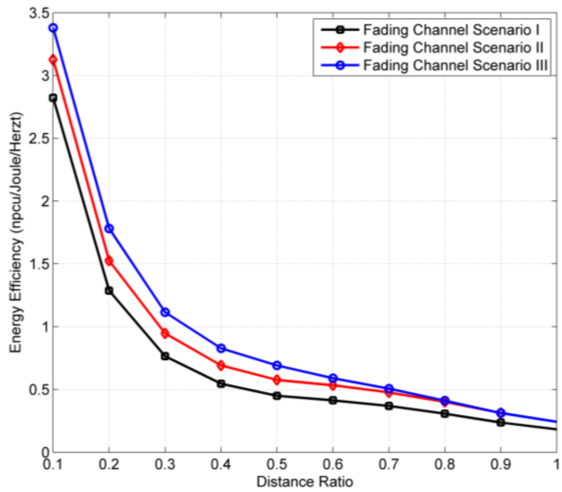


Figure 7. The energy efficiency versus distance ratio for three fading channels in the cooperative communication system.

The energy efficiency to distance link for the three fading scenarios is shown in Fig. 7. The simulated PSR is based on a distance ratio that can produce maximum average throughput and high energy efficiency, i.e., ρ=0.25 for fading channel scenarios I and II and ρ=0.3 for fading channel scenario III.

In general, the distance ratio of the S→R link affects the level of energy efficiency in the system, where relays closer to the source collect more energy than they consume. On the contrary, relays far from the source consume more energy than they collect, reducing energy efficiency. The energy efficiency of Fading channel scenario III is higher than that of the other two scenarios. This is due to the fact that in scenario III, the S→R and the R→D links use Rician fading channels with LOS components that can gather more energy. The energy efficiency at the distance ratio of the S→R link of 0.3 for scenarios I, II, and III are 0.7651, 0.9481, and 1.375 npcu/Joule/Hertz, respectively. At this distance ratio, the energy efficiency for scenario III is 79.71% higher than that of scenario I and 45.02% higher than scenario II. Therefore, the optimal PSR determines the EH's throughput performance and energy efficiency in a cooperative communication system.

V. Conclusion

This paper has analyzed the impact of fading channel scenarios and power splitting-based EH on cooperative communication performance in terms of maximum average throughput and energy efficiency. First, we introduced three-channel fading scenarios and a system model with power splitting-based EH for cooperative communication systems. The system performance has been analyzed regarding the average throughput and energy efficiency. Then, based on the proposed scenarios and EH system, the simulation was conducted by considering the maximum PSR for the high performance of a cooperative communication system. The simulation results reveal that the fading channel scenario III provides the highest average throughput and energy efficiency at the optimal PSR compared to the other two fading channel scenarios in the cooperative communication systems. Moreover, the fading scenario III, which uses fading Rician for both links S→R and R→D, consists of a LOS component in the system that is capable of harvesting more energy at the relay than those of the Rayleigh channel or mixed channel fading (Rician-Rayleigh). In addition, the distance link S→R also affects the performance of the cooperative system with EH. The relay that is closest to the source can harvest more energy, increasing energy efficiency. In contrast, further relays tend to consume more energy than they can harvest due to increased attenuation and noise, resulting in lower average throughput and energy efficiency.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Each of the authors has contributed. Nasaruddin Nasaruddin conducted research, analysed the model system, and wrote the paper; Elizar Elizar prepared the simulation and also was involved in writing the paper, whilst Afdhal Afdhal analysed the simulation results and proofread the paper.

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