DOCTORAL DISSERTATION

# Design and analysis of adaptive cooperative energy harvesting wireless relay networks

研究題名の和訳　環境発電を用い
た適応的協調無線中継ネットワークの設計と解析

*Author:*
Vikash SINGH

*Supervisor:*
Professor Hideki OCHIAI

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YOKOHAMA NATIONAL UNIVERSITY

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YNU 横浜国立大学
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# Abstract

For severely energy constrained and low complexity wireless networks such as mobile ad hoc wireless networks and wireless sensor networks, multihop transmission is a viable option to overcome wireless impairments and efficiently enhance network coverage. But for the energy constrained relay nodes, relaying the information of the source could be subject to severe energy limitation and thus may reduce the lifetime of such networks. In such scenario, a radio-frequency (RF) energy harvesting (EH) technique can be a viable option to prolong the lifetime of such energy-constrained wireless networks; where the relay can harvest energy from the information source to assist the source transmission. It is thus important for the system designer to design and analyze the throughput efficient energy harvesting protocols to enhance the lifetime of such energy constrained wireless networks.

In this work we propose a Adaptive time switching (ATS), TS and adaptive power splitting (TS-APS), and ATS-and-APS (ATS-APS) protocols and analyze the system performance in terms of the outage probability, effective transmission rate, and network throughput. Through extensive numerical analysis, we show that the proposed schemes can substantially outperform the conventional energy harvesting schemes proposed so far. Furthermore, we have also proposed a Clustering-based multi hop relaying with the partial relay selection (PRS) scheme for an EH relaying network and analyze the performance in the framework of the decode-and-forward (DF) relaying and APS protocol. Through extensive numerical analysis, we show that the proposed scheme can substantially outperform the conventional multi hop relaying without clustering as well as direct transmission, which suggests that the proposed scheme can be used to extend the network coverage without any extra energy from the network. We also demonstrate that the proposed scheme can compensate for the performance loss due to poor RF-to-DC conversion efficiency as well as path loss by exploiting the gain associated with multi hop relaying as well as the diversity gain achieved through the PRS scheme.

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# CHAPTER 1

# Introduction

The conventional networks are designed based on principle of point-to-point communications, where isolated pairs of communicated node communicate with each other, without any support or assistance from the neighboring nodes. Whereas in the cooperative networks, neighboring nodes assists each other in relaying information. The advantage of such networks is that even energy constrained and low complexity wireless networks such as mobile ad-hoc and wireless sensor networks where deployment of MIMO techniques is not feasible, can also harness the spatial diversity (also know as cooperative diversity) by exploiting the broadcast nature of wireless transmission, through cooperative communication. As a result, the overall quality of the wireless transmission, such as decoding reliability, power efficiency, network capacity and coverage can be enhanced significantly [1–3].

Apart from all these advantages, one of the major disadvantage of these cooperative networks is that in such cooperation the cooperative node may exhaust their battery while helping other nodes. This could reduce the over all network life time. In such scenarios, one critical question arises, whether to enhance network reliability and coverage by cooperating or to prolong the life time by saving the power by refraining from such cooperation, clear trade off exist.

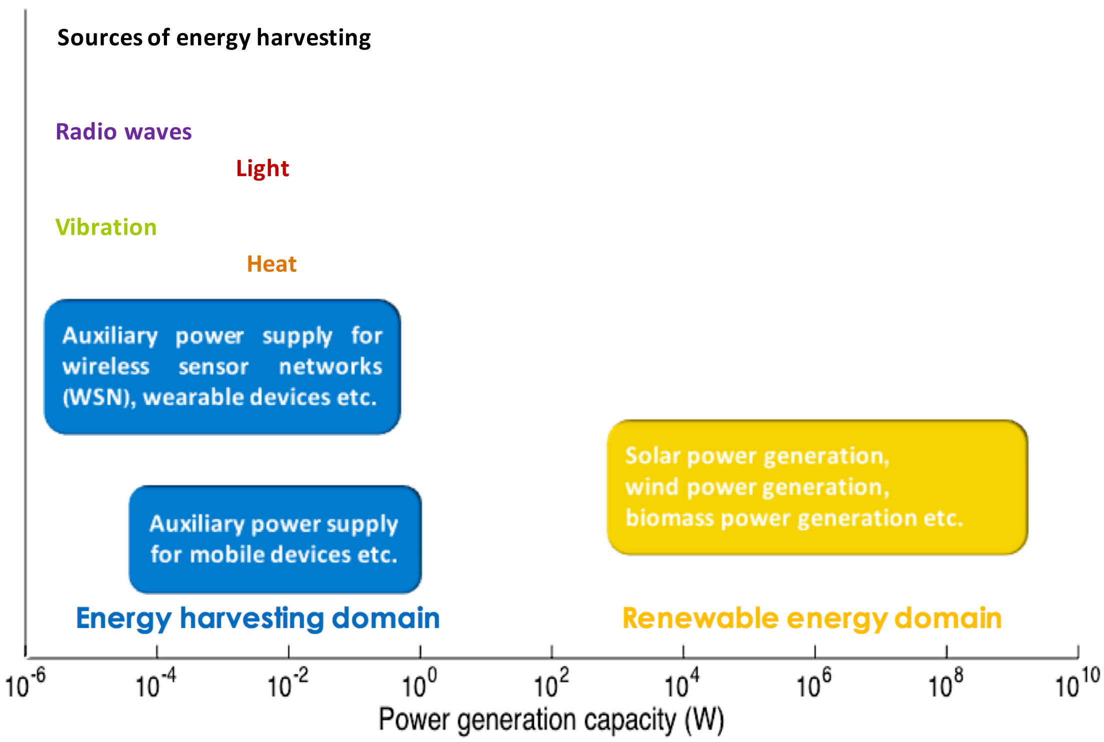


Figure 1.1: Alternative energy sources [4]

In such a scenario, energy harvesting (EH) from the environment can be a viable solution to prolong the life time of such energy constrained networks. The potential energy sources could be, solar, thermal, wind and ambient radio signals. From Fig. 1.1, it can be observe that for small and power constraints devices like sensor nodes, energy harvesting from radio signal is also possible. As a matter of fact, wireless devices powered by energy harvested from the ambient radio signals have been successfully implemented, e.g., the RFID ID tags known as PCT100 and PCT200 produced by Powercast are capable of harvesting energy from the RF signal transmitted by the any standard UHF RFID reader [5, 6]. In view of the fact that radio signal can carry information and energy at the same time, a fascinating new research direction, the so called simultaneous wireless information and power transfer (SWIPT), has recently been pursued [7–9].

The concept of simultaneously wireless information and power transfer (SWIPT) was first introduced in [9] and further explored in [10, 11]. All the aforementioned papers base their analyses on the assumption that a receiver can decode information and harvest energy from the same signal. However, this may not be feasible given the current state-of-the-art of electronic circuits [8]. In [7] therefore, a time switching (TS) and power splitting (PS) schemes were proposed as the practical receiver designs for an EH system. In [12], a TS based relaying (TSR) and PS based relaying (PSR) protocols were proposed to enable energy harvesting and information processing at the relay and the throughput and ergodic capacity were derived in the framework of Amplify-and-Forward AF) relaying. Similarly in [13], these protocols were analyzed in the framework of Decode-and-Forward (DF) relaying. In [14, 15], an interference aided EH scheme was proposed, where the relay harvests energy from the received information signal and co-channel interference signals. The closed form expression for ergodic and outage capacities were derived in the framework of DF relaying. In [16], the analytical results for the optimum TS and PS ratios for TSR and PSR schemes were derived in the framework of DF relaying, respectively. Similarly the optimum TS ratio of TSR scheme in the framework of AF relaying was derived in [17]. In [18], a multi-relay assisted two-hop EH relay system, with PSR scheme were analyzed and the optimization problems of power splitting ratios at the relays were formulated for DF and AF relaying protocols and Efficient algorithms were proposed to find the optimal solutions. In [19, 20], the outage behavior of a partial relay selection (PRS) and the opportunist relay selection (ORS) schemes, in the framework of the DF relaying and TS EH protocol were analyzed and analytical expression for the outage probability was derived in a closed form. The comparative studies of TSR and PSR protocol was carried out in [12, 13, 15] where, it was reported that the PSR protocol outperforms the TSR protocol at high SNR region and vice-versa is true at lower SNR region, since then various hybrid approaches where the relay can switch between the TSR and PSR protocols has been proposed in [19, 21–24].

Th major drawback of the aforementioned hybrid protocols is that the processing power required for the relaying circuitry were assumed to be negligible and hence neglected in the numerical analysis [19, 21–24]. If the relaying circuit power is also taken into the consideration then the switching strategies and optimization techniques of hybrid and adaptive relaying scheme proposed in [24] and [23] needs to be revised. Due to causality principle of energy, i.e., the energy cannot be used before it is harvested, simultaneous EH and information decoding with the same harvested energy may not be feasible in practice [21, 22], which makes the traditional PSR scheme infeasible and impractical for the EH relay nodes, which operate with harvested energy and has no other embedded energy supply [21, 22]. Apart from that the performance of the traditional TSR, PSR and hybrid (which uses both) schemes depends on the value of the PS and TS ratios. For optimum performance these should be optimized [12, 13, 16, 17, 24]. Though the analytical results for the optimum PS and TS were derived in [16, 17], and various other papers, but the results obtained for one scenario or channel realization may not work for other, and for optimization also centralized processing unit is required (i.e., relay cannot perform on its own) which makes these scheme very unattractive and unsuitable for the distributed relaying networks, where the relay needs to operate independently with very minimal help (in most of the cases no help at all) and coordination from the centralized processing unity.

Motivated by these issues, in this research work, we have proposed an adaptive time switching (ATS) and ATS with adaptive power splitting (ATS-APS) relaying scheme, where the relay can dynamically adjust their respective TS and PS ratios, according to their local channel sate information (CSI) (i.e. single hop CSI) Apart from that unlike the traditional PSR, the propose ATS-APS scheme, respect energy causality principle and first harvest energy before any information processing takes place, i.e., first harvest the minimum required energy to power relay circuit by operating in energy harvesting mode and then switches to the PS mode for simultaneously EH and information decoding. The interesting part is that in the proposed ATS-APS scheme, relay can dynamically adjust their respective Ts and PS ratios as per their local CSI, without any external help, i.e., in distributed manner. Through rigors numerical analysis we have also shown that the proposed schemes can outperforms the traditional one, without any need of optimization. Though with optimization, the performance of the proposed scheme can be further enhanced, but our goal in this research work is to propose the relaying protocols for energy harvesting relay node, which can achieve better performance than the traditional schemes with just local CSI , i.e., without any assistance or extra information from any external source.

All the above-mentioned studies, however, deal with the dual-hop relaying, which may not be necessarily practical for low-power wireless sensor networks where the communication link between the source and destination may not be supported by a single relay due to severe path loss, shadowing, and fading. For the conventional multi hop relaying networks without EH (i.e., the networks with fully powered relays), extensive work has been done, which can be found in [25–30] and references therein. On the other hand, the studies on multi hop relaying with WIPT are rather scarce; the performance of multi hop relaying with EH relays is evaluated in [31] under the framework of TS and PS EH protocols. Through numerical simulations, it is shown that in order to extend the network coverage, the TS along with AF relaying is a better combination. However, it does not provide any analytical expression for the outage probability or the achievable throughput. Apart from that, the above reference [31] deals with multi hop relaying as a wireless network of a cascaded point-to-point links and, as a consequence, the average throughput diminishes as the number of nodes increases toward infinity [32].

Motivated by the above observation, in this research work we propose a clustering-based multi hop relaying with the partial relay selection (PRS) scheme for the EH relay networks, which can improve the performance of the multi hop relaying with WIPT, by combining the benefits of the multi hop relaying (i.e., gain achieved by the path loss reduction) and relay selection (i.e., diversity gain) [27, 28, 33].

## 1.1 Thesis Outline

This thesis is devoted to design and analysis of relaying protocol for the distributed sensor networks with energy harvesting relay nodes. The outline of this thesis is summarized in Fig. 1.2.

Chapter 2, reviews the fundament of cooperative networks, like relaying protocols and relay selection schemes. Apart from that it also provide the basis of energy harvesting cooperative networks, like energy harvesting techniques and relaying schemes.

In Chapter 3, A hybrid relaying protocol to enable referred to as time switching and adaptive power splitting protocol (TS-APS) based on the combination of conventional time switching (TS) and adaptive power splitting (APS) protocol is proposed and the performance metric such as outage probability, effective transmission rate and network throughput are derived in closed form. Apart from that a comparative study of the proposed and existing protocols are also presented.

In Chapter 4, other relaying protocols, called adaptive time switching (ATS) relaying and ATS-and-adaptive power splitting (ATS-APS) relaying protocols to enable energy harvesting and information processing at the relay of energy harvesting (EH) relay networks are proposed. Where the relay nodes only requires local channel state information (CSI) for the optimization.

In Chapter 5, cluster based multi hop relaying scheme is proposed and analytical results for outage probability and network throughput in the framework of decode-and-forward (DF) relaying and partial relay selection (PRS) scheme are derived in the closed form. More over, the effect of number of hops, relay nodes, and energy harvesting efficiency on the performance of proposed scheme are also investigated.

Finally, concluding remarks are given in Chapter 6.

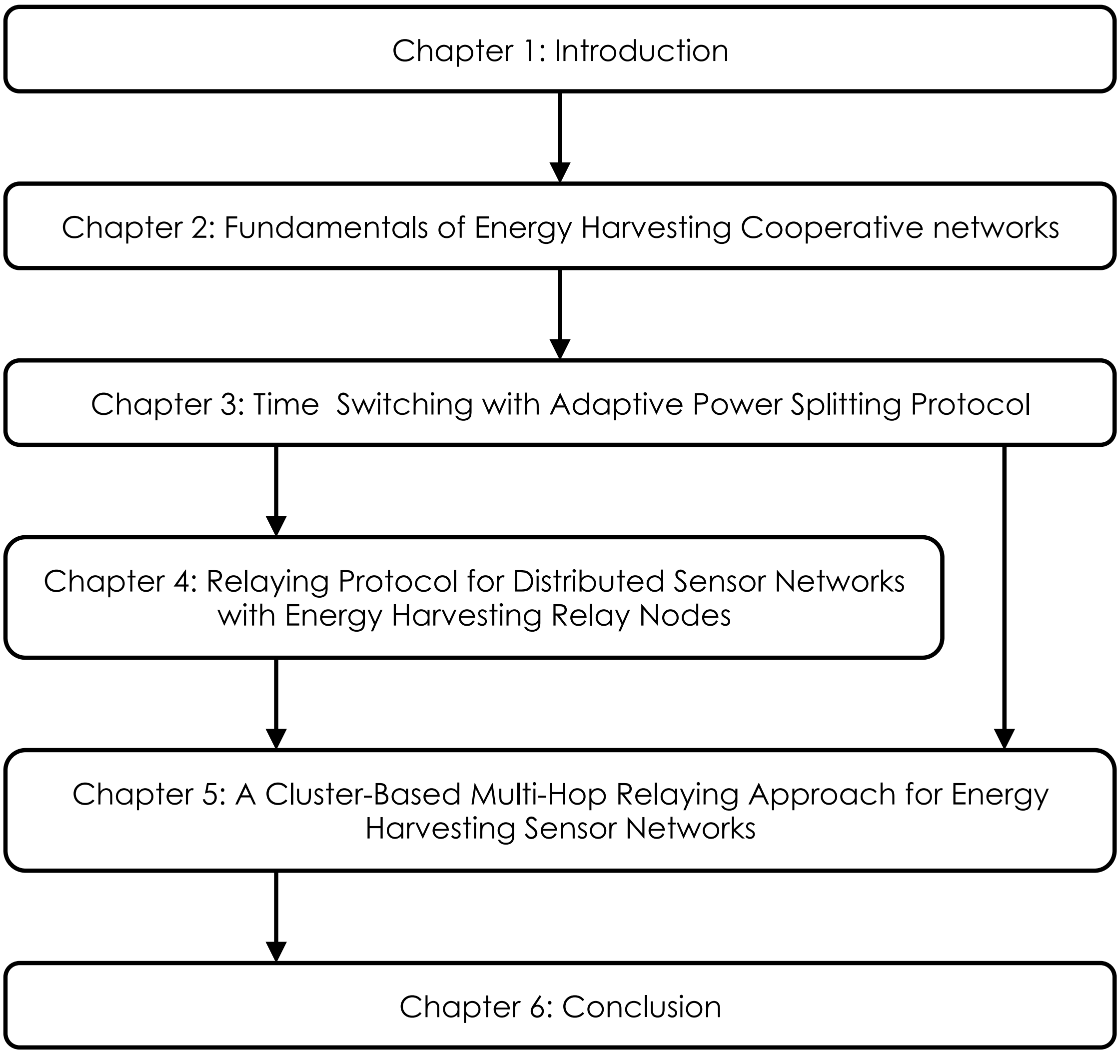


Figure 1.2: Outline of this thesis

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# CHAPTER 2

# Fundamental of Energy Harvesting Cooperative Networks

In this chapter, the fundamental of cooperative networks, like relaying protocols and relay selection schemes are presented. The concept of energy harvesting cooperative networks is also introduced; where the basis energy harvesting schemes and relaying protocols are explained.

## 2.1 Cooperative Networks

The conventional networks are designed based on principle of point-to-point communications, where isloated pairs of communicated node communicate with each other, without any support or assistance from the neighboring nodes. Whereas in the cooperative networks, neighboring nodes assists each other in relaying information. The advantage of such networks is that even energy constrained and low complexity wireless networks such as mobile ad-hoc and wireless sensor networks, where deployment of MIMO techniques is not feasible, can also harness the spatial diversity (also know as cooperative diversity) by exploiting the broadcast nature of wireless transmission, through cooperative communication. As a result, the overall quality of the wireless transmission, such as decoding reliability, power efficiency, network capacity and coverage can be enhanced significantly [1–3]. Apart from the wireless sensor networks, the concept of cooperative communication can also be implemented in infrastructure based networks, e.g., 3GPP LTE-Advanced (LTE-A) [34].

### 2.1.1 A classic three-node cooperative network

A classic three-node cooperative network is shown in Fig. 2.1, which is consists of three terminals; a source ($S$), relay ($R$), and destination ($D$), where the $R$ assists $S$ to communicate with the $D$. In principle, the $R$ can assist $S$ in two different modes, i.e., *half duplexing* (HD) and *full duplexing* (FD) modes, as shownn in Fig. 2.1. In FD mode, the relay can receive and transmit signal simultaneously [35], in HD mode, the cooperation is divided into two stage, in stage I, the $S$ transmits its message to the $R$ and $D$ and in the second stage the $R$ forward the message recived in stage I to the $D$. Due to practical limitations FD is infeasible [1], so we shall not deal with FD mode any further, interested readers can refer to [36–41].

The concept of cooperative diversity was first introduced in [42, 43], since then various protocols for the information relaying have been proposed [44, 45], but all these protocols can be broadly classified into two categories; Amplify-and-Forward (AF) and Decode-and-Forward (DF), which are shown in Fig. 2.2(a) and Fig. 2.2(b), respectively. In AF protocol the relay simply retransmits a scaled version of the received signal [46], and in DF protocol, the relay first decodes the received signal before retransmitting it [47]. In this research work, we are intrested in the DF protocol.

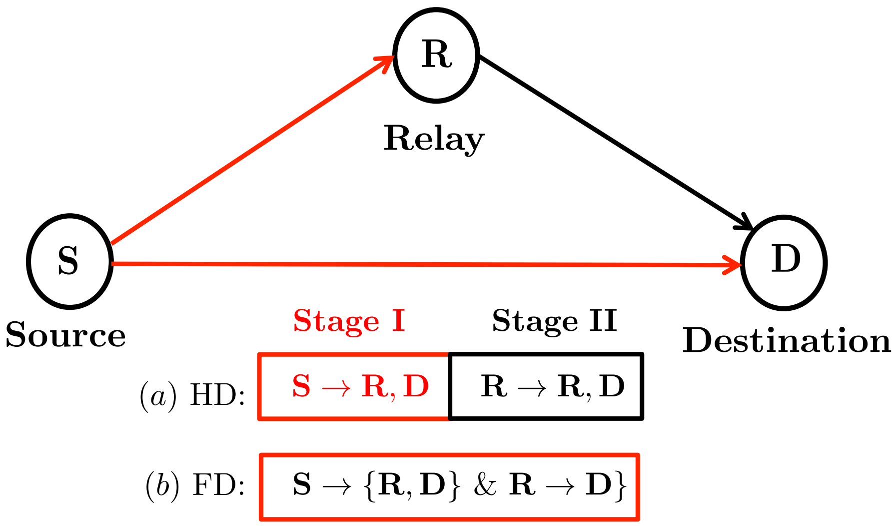



Figure 2.1: A classic thre-node cooperative network

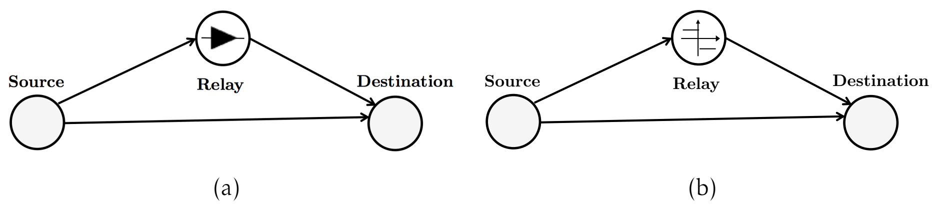



Figure 2.2: Relaying protocols for cooperative networks (a) AF and (b) DF Protocols.

### 2.1.2 Decode-and-Forward Protocol

In this section, the channel capacity of DF relaying with HD constraints are derived, The results derived in this section are not unique, these have been reported before in various papers [1, 45]. As shown in Fig. 2.2(b), In the DF relaying mode, the relay decodes its received message, re-encodes it, and forwards it to the destination. In the proposed system, we require the relay to successfully decode the received message before further processing [46]. The mutual information between $S \to R$, $S \to D$, and $R \to D$ links can be expressed as

$$C_{i,j} = \frac{1}{2}\log_2\left(1 + |H_{i,j}|^2 \frac{P_i}{\sigma_j^2}\right) \tag{2.1}$$

where $P_i$ is the transmission power of node $i$, $\sigma_j^2$ is the variance of Additive white Gaussian noise (AWGN) at node $j$ and $|H_{i,j}|^2$ is the channel gain for $i \to j$ link, with $i \in \{S, R\}$ and $j \in \{R, D\}$. In the DF protocol, the system is said to be in outage in the following events; (i) when the link between $S \to R$ as well as $S \to D$ are in outage, or (ii) when the link between $S \to R$ is not in outage, but the mutual inforamtinn at the destination is less than the required rate R. Which is equivalent to [45]

$$P_{out} = \mathbb{P}\left[\{(C_{S,R} < \mathsf{R}) \cap (C_{S,D} < \mathsf{R})\} \cup \{(C_{S,R} \geq \mathsf{R}) \cap (C_{SR,D} < \mathsf{R})\}\right] \tag{2.2}$$

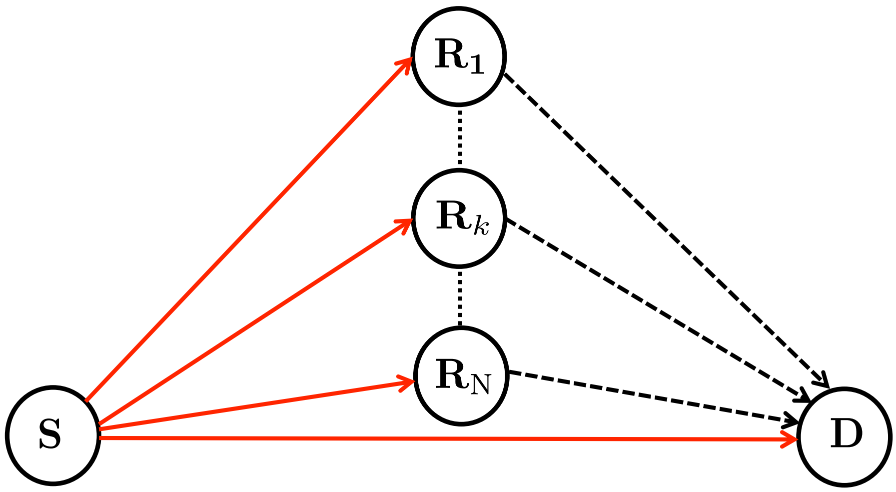



Figure 2.3: Cooperative network with multihple relay nodes

where $C_{SR,D}$ is the mutula information at the destination, when $S \rightarrow R$ link is not in outage, which can be caluclated as

$$C_{SR,D} = \frac{1}{2}\log_2\left(1 + |H_{R,D}|^2\frac{P_R}{\sigma_D^2} + |H_{S,D}|^2\frac{P_S}{\sigma_D^2},\right) \tag{2.3}$$

where $\sigma_D^2$ is the variance of the AWGN at $D$, $P_S$ and $P_R$ are the transmission power of the $S$ and $R$ nodes, respectively. With the help of (2.2), the network throughput can be expressed as

$$\tau = \mathsf{R} \times P_{out} \tag{2.4}$$

where R is the targated data rate.

### 2.1.3 Cooperative network with multihple relay nodes

In pratical scenario, there could be multiple relay nodes in the network, as shown in Fig. 2.3, which can be used in different ways to improve system performance. In [45, 48] a repetition based algorithms were proposed, where each relay node was provided with dedicated orthogonal subchannel (time slot) for repetition. However, the spectral efficiency of these algorithms decreases as number of relay increases. In [49], a distributed space-time coding (DSTC) algorithm, was proposed, where the relays which can successful decode the source transmission, were allowed to forward the decoded information simultaneously using space time code. However, in practice, such code design is very complex. In [50], an opportunist relay selection (ORS) scheme was proposed, where one relay with best end-to-end channel gain is selected, and it was shown that such approach can achive same diversity order as that of DSTC, with less system complexity. However, for the resource constrained and low complexity sensor networks, monitoring the connectivity among all links could limit the network lifetime [51]. In such a scenario, partial relay selection (PRS) scheme, could be a better option, where the relay is selected on the basis of single hop channel information.

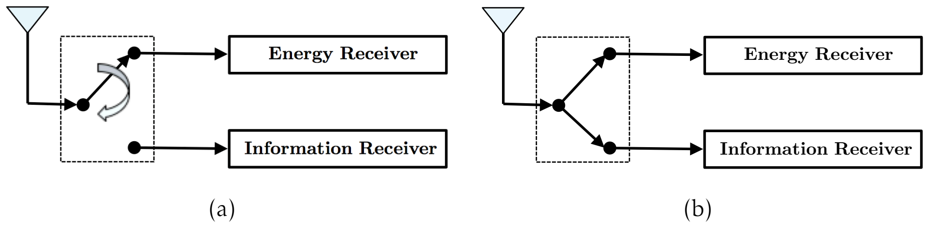



Figure 2.4: Energy harvesting schemes for SWIPT (a) TS and (b) PS schemes.

## 2.2 Energy harvesting cooperative networks

For severely energy-constrained wireless networks such as mobile ad-hoc wireless networks and wireless sensor networks, cooperative relaying is a viable option to overcome wireless impairments and efficiently enhance the network coverage [45, 48, 49, 51]. In the cooperative relaying, the communication between the source and destination is established with the help of intermediate nodes that relay the information of the source to the destination. For the energy-constrained relay nodes, relaying the information of the source could be subject to severe energy limitation, which may considerably affect the lifetime of such cooperative networks [52, 53]. A radio-frequency (RF) energy harvesting (EH) technique can be a viable option to prolong the lifetime of such energy-constrained wireless networks, where the relay harvest energy from the information source to assist the source transmission.

### 2.2.1 Practical reciver design for SWIT based system

The concept of simultaneously wireless information and power transfer (SWIPT) was first introduced in [9] and furter explored in [10, 11]. All the aforementioned papers base their analyses on the assumption that a receiver can decode information and harvest energy from the same signal. However, this may not be feasible given the current state-of-the-art of electronic circuits [8]. Therefore, in [7] the time switching (TS) and power splitting (PS) schemes were proposed as the practical receiver designs for an energy harvesting system. In the TS scheme, antenna at the receiver periodically switches between energy harvester and information decoder units, while in the PS scheme, the receiver splits the received signal into two streams and provide each stream to energy harvester and information decoder units as shown in Fig. 2.4(a) and 2.4(b), respectively. Based on TS and PS receiver architetures, two relaying protocols, called, a TS based relaying (TSR) and PS based relaying (PSR) protocols were proposed to enable energy harvesting and information processing at the relay in [12].

### 2.2.2 Relaying Protocols for SWIPT based cooperative network

In this section, we have presented the tow basis relaying protocols, i.e., TSR and PSR, proposed for SWIPT based cooperative relaying networks [12].

▷ *Time Switching Relaying Protocol*

The TSR protocol is shown in Fig. 2.5(a), where the block time is divided into three time slots; in the first time slot $\alpha T$, relay operates in the EH mode, in the second time slot $(1-\alpha)T/2$, the relay operates in the information decoding mode, and in the third time slot $(1-\alpha)T/2$ the relay re-encode the successfully decoded signal and forward it to the

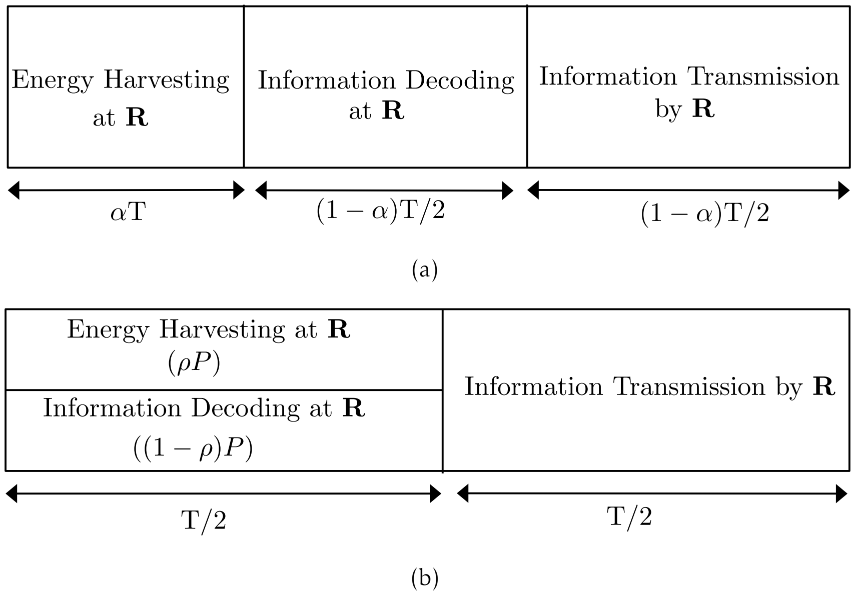



Figure 2.5: Relaying protocols for energy harvesting relay (a) TSR and (b) PSR protocols.

destination, with all the harvested energy, as it cannot hold the harvested energy for the later use, due to leakage in the relay battery, this type of reciver is called *harvest-and-use* (HU) architecture [12, 13, 15–17, 31, 41, 54–56]. For the three node cooperative model shown in Fig. 2.1 and TS energy harvesting scheme shown in Fig. 2.4(b), the energy harvested at the relay can be expressed as

$$E = \eta\alpha|H_{S,R}|^2 P_S T \tag{2.5}$$

where $|H_{S,R}|^2$ is the channel gain of $S \to R$ link, $\alpha T$ is the amount of time dedicated for the energy harvesting, $P_S$ is the transmission power of the relay node, and $\eta \in (0,1)$ is the energy harvesting efficiency. As relay always transmits with all the available energy, hence the transmission power of the relay node can be expressed as

$$P_R = \frac{2E}{T}. \tag{2.6}$$

For the TSR protocol, channel capacity at the relay can be expressed as

$$C_{S,R} = (1-\alpha)\frac{T}{2}\log_2\left(1 + \frac{P_S|H_{S,R}|^2}{\sigma_R^2}\right) \tag{2.7}$$

where $\alpha$ is the portion of total block time $T$ assigned for the energy harvesting, $P_S$ is the transmission power of the source, $|H_{S,R}|^2$ is the channel gain of the $S \to R$ link, and $\sigma_R^2$ is the variance of AWGN at the relay. Simillarly, the capacity of $R \to D$ link can be calculated as

$$C_{R,D} = \frac{T}{2}\log_2\left(1 + \frac{P_R|H_{R,D}|^2}{\sigma_D^2}\right) \tag{2.8}$$

where $P_R$ is the transmission power of the relay node mentioned in (2.6), $|H_{R,D}|^2$ is the channel gain of the $R \to D$ link, and $\sigma_D^2$ is the variance of AWGN at the destination. The outage probability for the TSR protocol can be calculated as mentioned in (2.2)

▷ *Power Splitting Relaying Protocol*

The PSR protocol is shown in Fig. 2.5(b), where the transmission block time $T$ is equally divided for the $S \to R$ and $R \to D$ information transmission, as in DF relaying protocol introduced in section 2.1.2. The only difference is that in the PRS protocol, the relay node splits the signal received in the first half of the block time, into two streams, i.e., $\rho P$ for the energy harvesting and $(1-\rho)P$ for the information decoding, where $\rho \in (0,1)$ is a PS ratio. The amount of energy harvested by the relay node for given $\rho$ can be expressed as

$$E = \eta\rho|H_{S,R}|^2 P_S \frac{T}{2} \tag{2.9}$$

similarly, the channel capacity at the relay can be calculated as

$$C_{S,R} = \frac{T}{2}\log_2\left(1 + \rho|H_{S,R}|^2 \frac{P_S}{\sigma_R^2}\right). \tag{2.10}$$

As in the TSR protocol, the relay always transmits with all harvested energy, thus the transmission power of $R$ and the channel capacity of $S \to D$ link, can be calculated as in (2.6) and (2.8), respectively. The outage probability for the PSR protocol can be calculated as mentioned in (2.2).

CHAPTER 3

# Time Switching with Adaptive Power Splitting Protocol

A new time switching protocol referred to as TS-APS is proposed for the energy harvesting (EH) relay networks based on the combination of conventional time switching (TS) protocol and adaptive power splitting (APS). In the framework of the decode and forward (DF) relaying with multiple relays, we derive the closed form expression for the outage probability of the proposed scheme and discuss its effective transmission rate considering the random relay selection (RRS) and opportunistic relay selection (ORS) scenarios. Through numerical analysis, we show that the proposed scheme can achieve better outage performance and the effective transmission rate as compared to the TS and power splitting (PS) schemes proposed in the literature, irrespective of relay selection scenarios. By properly selecting time switching (TS) ratio, we demonstrate that the effective transmission rate of the proposed protocol can be optimized only with partial knowledge of channel gains in the network, which makes the proposed approach suitable for the distributed relay selection scenarios. All the theoretical results developed here are confirmed by numerical simulations.

## 3.1 Introduction

In view of the fact that radio signal can carry information and energy at the same time, a fascinating new research direction, the so called *simultaneous wireless information and power transfer* (SWIPT), has recently been pursued [7, 8]. In [7], the *time switching* (TS) and *power splitting* (PS) protocols are proposed as practical receiver designs for an EH system. The TS EH protocol is further analyzed and optimal as well as suboptimal switching protocols are proposed in [8, 57]. Recently, the SWIPT technique is also applied to relay networks. In [58], the SWIPT concept for a three-node cooperative network with an EH relay node is studied. The greedy switching (GS) policy is proposed, where a relay node transmits when its residual energy can support decoding at the destination, and analyzed in terms of the outage probability for a battery model with dicretized levels. The outage probability and the ergodic capacity for the TS EH and PS EH protocols in the framework of amplify-and-forward (AF) and decode-and-forward (DF) are derived in [12, 13]. In [16] the outage probability expressions for the PS relaying and TS relaying protocols with the given PS and TS ratios are derived in the framework of DF relaying and the optimal ratios that maximize the transmission rate are obtained for both the PS and TS relaying protocols. In [17], closed-form expressions for the average SNR, outage probability, and network throughput are derived for the TS EH protocol in the framework of DF relaying, and an expression for the optimal TS ratio is obtained. The results are also extended for an opportunistic relay selection (ORS) scenario. In [20, 59], the outage behavior of a partial relay selection (PRS) and the ORS scenarios, in the framework of the DF relaying and TS EH protocol, is analyzed and analytical expression for the outage probability is derived in a closed form.

In [60] a dynamic power splitting approach in the framework of AF relaying is proposed, where the relay dynamically calculates the optimum PS ratio with the help of instantaneous channel state information (CSI) such that the outage probability is minimized. When the relay has partial CSI, i.e., the first hop instantaneous CSI and statistic characteristics of the second hop channel, the optimum PS ratio may be the one that provides the best average outage probability. When the relay has global CSI, the optimum PS ratio may be the one that provides the highest SNR at the destination. In [24] adaptive relaying (AR) protocol for wireless power transfer and information processing is proposed where the block time dedicated for the source to destination is divided into three phases; in the first phase the relay harvests energy through received signal (i.e., TS), in the second phase the relay splits the received signal for relaying and EH (i.e., PS), and in the third phase it transmits the received signal. It is shown that with optimized TS and PS ratios, the proposed approach outperforms each of the TS and PS approaches around the point in which there is throughput crossover for both PS and TS relaying protocols.

In this chapter, we propose a time switching protocol with adaptive power splitting (TS-APS) for EH relay networks. The proposed TS-APS protocol is a hybrid form of the TS and APS protocols proposed in [7] and [61], respectively. When the entire block time allocated for the source-to-destination channel is equally divided into the source-to-relay and relay-to-destination transmission, the TS-APS protocol is equivalent to the APS protocol. In [61], an approximate expression for the outage probability of the APS protocol is derived, whereas in this work we obtain the exact closed-form expression for both the outage probability and effective transmission rate. Furthermore, the obtained results are extended for the opportunistic relay selection scenario. Through numerical analyses, we demonstrate that the proposed TS-APS protocol can provide better effective transmission rate than those presented in [13, 16, 17].

The rest of the chapter is organized as follows. The system model is presented in Section 5.2. In Section 3.3, the proposed TS-APS protocol is described and analyzed for a given selected relay. Section 3.4 deals with the ORS scheme. Numerical and simulation results are presented in Section 3.5. Finally, conclusion is given in Section 5.5.

## 3.2 System Model

### 3.2.1 Relay Network Model

We consider a decode-and-forward (DF) relay network with one source ($S$), one destination ($D$), and $N$ EH relays denoted by $R_k$ with $k \in \{1, \ldots, N\}$. The corresponding network model is illustrated in Fig. 5.1, where each node is assumed to be equipped with a single antenna and half duplex, i.e., it cannot transmit and receive at the same time, as is often the case with low-cost sensor networks [62]. The source is modeled as an energy unconstrained node and it transmits with a constant power $P_0$. We assume that the direct link from the source to destination does not exist due to the shielding and shadowing effects caused by obstacles, which forces that the communication can be established only through the relay nodes. For simplicity of our subsequent analyses, all the physical links between the nodes are assumed to be frequency flat block fading, where the fading coefficient remains constant during one entire time slot but changes independently from one slot to another. We also assume Rayleigh fading for each link. Therefore, the complex-valued fading coefficients follow statistically independent circularly symmetric complex Gaussian random variables with zero mean and variance $\sigma_{i,j}^2 = \mathbb{E}(|H_{i,j}|^2)$, where

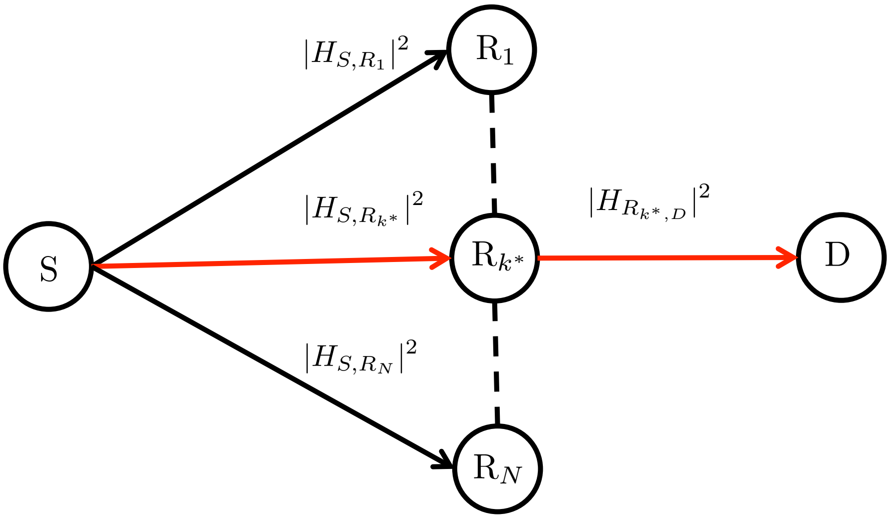



Figure 3.1: Relay network model.

$\mathbb{E}(\cdot)$ is an expectation operation and $H_{i,j}$ denotes the fading coefficient of the channel from the node $i$ to node $j$ with $i \in \{S, R_k\}$ and $j \in \{R_k, D\}$, respectively, and $k \in \{1, \ldots, N\}$ is consistently used as the index of the relay node in this work. Let $w_j$ be the AWGN observed at node $j$ with its variance $\sigma_j^2$, where $j \in \{R_k, D\}$. Furthermore, we assume for simplicity that the relay nodes have an identical noise level, i.e., $\sigma_{R_k}^2 = \sigma_R^2$ for any $k \in \{1, \ldots, N\}$.

In order to simplify the notation in our subsequent analyses, we define the path gain associated with fading between the different nodes as $g_k \triangleq |H_{S,R_k}|^2$ and $h_k \triangleq |H_{R_k,D}|^2$ for the relay node $k \in \{1, \ldots, N\}$. According to [63], the path gains are exponential random variables with its probability density function (pdf) expressed as $p(x) = \lambda \exp(-\lambda x)$, where the parameter $\lambda$ is given by $\lambda_{S,R_k} = 1/\sigma_{S,R_k}^2$ and $\lambda_{R_k,D} = 1/\sigma_{R_k,D}^2$. For simplicity, the statistical properties of the path gains are assumed to be identical, i.e., $\lambda_{S,R_k} = \lambda_1$ and $\lambda_{R_k,D} = \lambda_2$ for all $k$. Let us denote $d_{S,R_k}$ and $d_{R_k,D}$ as the distances between $S \to R_k$ and between $R_k \to D$, respectively. We further assume that $d_{S,R_k} = d_1$ and $d_{R_k,D} = d_2$ for all $k$, since the relay nodes are often grouped in a cluster by clustering algorithm based on the geographical proximity of nodes [28, 64].

### 3.2.2 Battery Model

It is assumed that the relay node is equipped with a discrete level energy battery of size $E_b$, which can hold energy for an immediate use only, due to leakage. Thus, all the harvested energy should be used in the same information block. The battery level is discretized in $L$ energy levels $\epsilon^{(i)} \triangleq iE_b/L$ with $i \in \{1, \ldots, L\}$. We define $L$ corresponding energy states, $s_i$, with $i \in \{1, \ldots, L\}$, and thus the battery is said to be in the state $s_i$ when its stored energy is equal to $\epsilon^{(i)}$. Let $p_i$ denote the probability that the battery state is $s_i$, i.e., $p_i = \mathbb{P}\{s_i\}$.

## 3.3 Time Splitting and Adaptive Power Splitting Protocol

The proposed time splitting and adaptive power splitting (TS-APS) protocol is shown in Fig. 3.2, where the block time $T$ is divided into two different time slots. In this section,

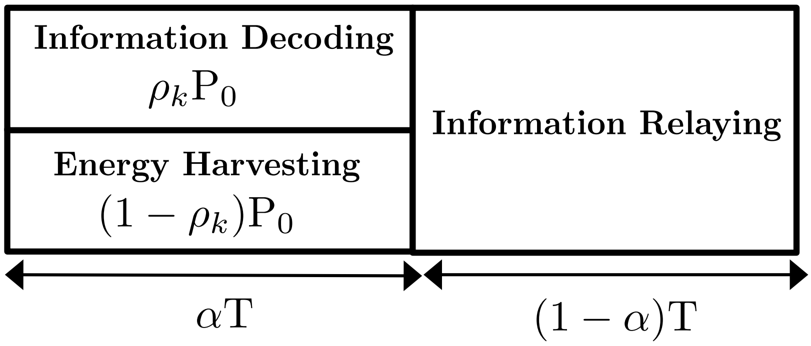



Figure 3.2: TS-APS protocol

we focus on the capability of a given single relay node $R_k$, which corresponds to the scenario often referred to as a random relay selection (RRS). In the first time slot with $\alpha T$, the source broadcasts its information, where $\alpha \in (0,1)$. In the second time slot with $(1-\alpha)T$, the relay node assists the source node by decoding-and-forwarding the received signal. In the first time slot, the EH relay will dynamically split the recieved signal into the two streams with power splitting ratio $\rho_k$ and $(1-\rho_k)$ for infromation decoding and energy EH respectively. The energy harvested at $k$th relay can be given by

$$E_k = \frac{\zeta(1-\rho_k)g_k\eta T P_0}{d_1^m}, \tag{3.1}$$

where $P_0$ is the average power transmitted by the source node, $T$ is the block time reserved for the entire link from the source to destination, $\alpha \in (0,1)$ is the portion of the block time dedicated for the $S \to R_k$ transmission, $\zeta \in (0,\ 1]$ denotes the conversion efficiency, $\rho_k \in (0,\ 1)$ is the PS ratio, and $m$ is the path loss exponent.

By definition, the battery of all energy harvesting relays are discrete and finite. Therefore, the energy of the $k$th relay can be expressed as

$$\epsilon_k = \max_{i\in\{1,\ldots,L\}} \epsilon^{(i)} \quad \text{where} \quad \epsilon^{(i)} \leq E_k. \tag{3.2}$$

We also assume that the relay node uses harvested energy for the infromation decoding, re-encoding, and transmission, thus the transmission power of the $k$th relay can be expressed as

$$P_{R_k} = \max\left(\frac{\epsilon_k - E_C}{(1-\alpha)T}\right) \tag{3.3}$$

where $E_C$ is the energy counsumed by the receiver circuit of the $k$th relay for information decoding and re-encoding, and $\epsilon_k$ is the discrete-level energy harvested by the $k$th relay defined in (5.6). For the TS-APS protocol, the data rate supported by the $S \to R_k$ link can be expressed as

$$C_{S,R_k} = \alpha T \log_2\left(1 + \rho_k \frac{P_0 g_k}{\sigma_R^2 d_1^m}\right). \tag{3.4}$$

The PS ratio $\rho_k$, required to ensure successful detection at the relay given a targeted data rate $\mathsf{R}$, can be expressed as

$$\rho_k = \min\left(1, \frac{2^{\frac{\mathsf{R}}{\alpha T}} - 1}{g_k \gamma_k}\right) \tag{3.5}$$

where

$$\gamma_k = \frac{P_0}{\sigma_R^2 d_1^m}. \tag{3.6}$$

From (5.5) and (3.5), it can be observed that when the selected relay cannot decode the received signal successfully (i.e., $\rho_k \geq 1$), it will not harvest any energy as it cannot retain the harvested energy for the later use. When $\rho_k < 1$, then the relay first feeds the $(1-\rho_k)$ portion of the recived signal to the EH unit, and if the harvested energy satisfies $\epsilon_k > E_C$ (i.e., the harvested energy is higher than that required for the information decoding and re-encoding), then the inforamtion decoding unit utilizes the harvested energy to decode the received signal. Due to leakage, the relay always transmits with all available energy. Thus, the channel capacity of $R_k \to D$ link can be expressed as

$$C_{R_k,D} = (1-\alpha)T \log_2\left(1 + \frac{P_{R_k} h_k}{\sigma_D^2 d_2^m}\right) \tag{3.7}$$

where $\sigma_D^2$ is the variance of additive white Gaussian noise (AWGN) at the destination. When the wireless channel experiences a deep fading and the channel cannot support the transmission rate, the channel is said to be in outage [65]. In the TS-APS protocol, for the selected relay $R_k$, the outage event at the destination is caused by the following conditions; 1) the $S \to R_k$ link is in outage (i.e., $\epsilon_k < E_C$) or 2) the $S \to R_k$ link is not in outage but the $R_k \to D$ link is in outage. Therefore, the overall outage event can be expressed as

$$\begin{aligned} P_{\text{out}} &= \mathbb{P}\Big[(\epsilon_k \leq E_C) \cup \Big\{(\epsilon_k > E_C) \cap (C_{R_k,D} < \mathsf{R})\Big\}\Big] \\ &= 1 - \mathbb{P}\Big\{(\epsilon_k > E_C) \cap (C_{R_k,D} \geq \mathsf{R})\Big\} \end{aligned} \tag{3.8}$$

where $\mathsf{R}$ is the targeted transmission rate. From (5.11) it can be observed that $C_{R_k,D}$ depends on $h_k$ and $g_k$ through (3.5) and (3.7), which makes our mathematical analysis intractable. Nevertheless, the discrete-level battery model introduced in the previous section would make the subsequent analysis mathematically tractable. The channel gain required to harvest $\epsilon^{(i)} = iE_b/L$ units of energy for the infromation relaying or equivalently, to reach the state $s_i$, can be given by

$$\Gamma_i = \left(2^{\frac{\mathsf{R}}{\alpha T}} - 1\right)\frac{\sigma_R^2 d_1^m}{P_0} + \frac{(\epsilon^{(i)} + E_C) d_1^m}{\alpha T \zeta P_0} \tag{3.9}$$

where the first part represents channel gain required to ensure the successful decoding of the received signal and the second part denotes the channel gain required to harvest $(\epsilon^{(i)} + E_C)$ units of energy, where $\epsilon^i$ denotes the amount of energy left after information decoding and re-encoding. We derive the probability of harvesting $\epsilon^{(i)}$ amount of energy, or the probability $p_i = \mathbb{P}(s_i)$, by separately considering the following two cases.

1. **Probability of battery being partially charged (i.e., $1 \le i < L$):**

   When the harvested energy is greater than or equal to $\epsilon^{(1)}$ and less than $\epsilon^{(L)}$, the battery is said to be partially charged. The corresponding probability $p_i$ can be expressed as

$$\begin{aligned} p_i &= \mathbb{P}(\Gamma_i \le g_k < \Gamma_{i+1}) \\ &= F_{g_k}(\Gamma_{i+1}) - F_{g_k}(\Gamma_i) \\ &= \exp(-\lambda_1 \Gamma_i) - \exp(-\lambda_1 \Gamma_{i+1}) \end{aligned} \tag{3.10}$$

   where $F_X = 1 - \exp(-x\lambda_X)$ is the cumulative distribution function (cdf) of the exponential random variable $X$ with parameter $\lambda_X$.

2. **Probability of battery being fully charged (i.e., $i = L$):** When the harvestable energy is greater than or equal to $\epsilon^{(L)}$, the battery is called to be fully charged. The corresponding probability $p_i = p_L$ can be calculated as

$$p_L = \mathbb{P}(g_k \ge \Gamma_L) = \bar{F}_{g_k}(\Gamma_L) \tag{3.11}$$

   where $\bar{F}_X \triangleq 1 - F_X = \exp(-x\lambda_X)$.

### 3.3.1 Outage Probability

The channel gain required to successfully decode the signal at the destination, provided that the power of the relay is given by $P_{R_k} = \frac{\epsilon^{(i)}}{(1-\alpha)T}$ with $i \in \{1, \ldots, L\}$, is

$$\Gamma_i^D = \left(2^{\frac{\mathsf{R}}{(1-\alpha)T}} - 1\right) \frac{\sigma_D^2 d_2^m (1-\alpha)T}{\epsilon^{(i)}}. \tag{3.12}$$

With the help of (5.11), (3.10), and (3.11), the outage probability of the TS-APS protocol for a given TS ratio $\alpha$ can be expressed as

$$\begin{aligned} P_{\text{out}}(\alpha) &= 1 - \sum_{i=1}^{L} p_i \bar{F}_{h_k}(\Gamma_i^D) \\ &= 1 - \sum_{i=1}^{L} p_i \exp(-\lambda_2 \Gamma_i^D). \end{aligned} \tag{3.13}$$

### 3.3.2 Effective Transmission Rate

For the fixed transmission rate $\mathsf{R}$ and the outage probability $P_{\text{out}}(\alpha)$, the effective transmission rate can be defined as [55]

$$\tau(\alpha) = \mathsf{R}(1 - P_{\text{out}}(\alpha)) \tag{3.14}$$

where $\alpha$ denotes the portion of the block time $T$ dedicated for the $S \to R_k$ transmission.

From (3.14), it can be observed that the effective transmission rate $\tau$ depends on $\alpha$, hence by optimizing it the effective transmission rate of the proposed scheme can be enhanced. The fraction $\alpha$ for which the effective transmission rate of the system is maximized is said to be optimal, which can be calculated as

$$\alpha_{\text{opt}} = \arg \max_{\alpha \in (0,1)} \tau(\alpha). \tag{3.15}$$

For the proposed scheme, derivation of the closed-form expressions for the optimal value of $\tau$ appears to be challenging. Therefore, we resort to the optimization based on numerical evaluation of $\alpha_{\text{opt}}$.

## 3.4 Opportunistic Relay Selection (ORS)

In the ORS scheme, a single relay among a set of $N$ relays that can provide best end-to-end SNR is selected, and for the relay selection the distributed algorithm proposed in [50] is considered here. It is assumed that the relays overhear a signal transmission of a ready-to-send (RTS) packet and a clear-to-send (CTS) packet from the source and the destination, respectively. According to reciprocity theorem, the forward and backward channels can be assumed to be the same [66]. Thus, the transmission of RTS and CTS from the source and destination allows for the estimation of the instantaneous channel gain $g_k = |H_{S,R_k}|^2$ (i.e., channel gain of $S \to R_k$) and $h_k = |H_{R_k,D}|^2$ (i.e., channel gain of $R_k \to D$), where $k \in \{1,\ldots,N\}$. As soon as the relay receives the RTS packet from the source, it starts a timer, with the following waiting time

$$T_k = \frac{\Delta}{\min\{g_k, h_k\}} \tag{3.16}$$

where $\Delta$ has a unit of time [50]. Note that, with the above definition, the shorter waiting time indicates the better channel realization achieved by the relay. To incorporate the power constraint of each relay, which depends on the amount of the energy harvested during $S \to R_k$ transmission, we modify the selection function to be

$$T_k = \frac{\Delta}{\min\{g_k P_0, h_k P_{R_k}\}} \tag{3.17}$$

where $P_{R_k}$ is the power of the $k$th relay node described in (4.7). The relay whose waiting time expires first raises its flag, and all the other relays who listen to the flag should take a back-off. We assume that there is no hidden relay and all relay can hear each other. In this case, the relay with the minimum waiting time will be selected, and the corresponding waiting time will be expressed as

$$T^* = \min\{T_k\}, \quad k \in \{1,\ldots,N\}. \tag{3.18}$$

### 3.4.1 Outage Probability

The system is said to be in outage when the selected relay cannot decode the information successfully or the destination fails to decode the signal transmitted by the selected relay. It is assumed that at any given time instant there are $N$ relays competing to facilitate the source. Hence, the closed form expression for the ORS scheme can be calculated using (3.13) as

$$P_{\text{out}}(\alpha) = \left(1 - \sum_{i=1}^{L} p_i \exp\left(-\lambda_2 \Gamma_i^D\right)\right)^N \tag{3.19}$$

where $p_i$ is given in (3.10) for $i < L$ and (3.11) for $i = L$, and $\Gamma_i^D$ is derived in (3.12).

## 3.5 Numerical Results and Discussions

In this section, we present several numerical results and their interpretations based on theoretical analysis carried out in the previous sections. The effective transmission rate

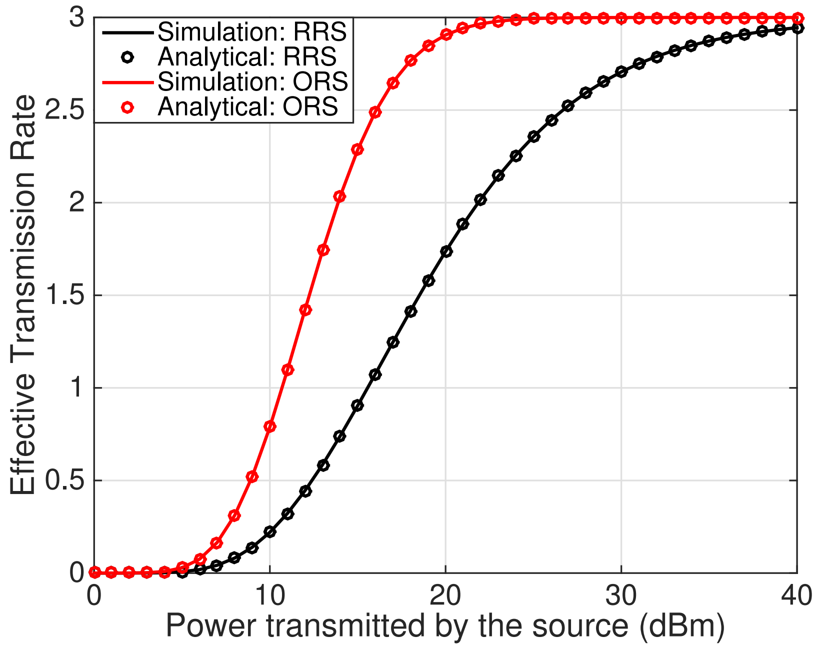



Figure 3.3: Effective transmission rate versus transmitted power by the source (solid lines: simulation, circle marks: theoretical analysis). Parameters: R = 3, $\zeta = 1$, $\lambda_1 = \lambda_2 = 1$, $d_1 = 1, d_2 = 5 - d_1$, $\sigma_D^2 = \sigma_R^2 = -20$ dBm, $L = 1000$, $P_C = \frac{P_0}{1000}$, and $N = 4$.

is used as our performance measure. The accuracy of the developed analytical results are also verified using Monte Carlo simulation. For the subsequent numerical results, the following parameters are chosen unless otherwise stated; targeted data rate R = 3 bits per channel use, the EH efficiency $\zeta = 1$, the number of relays $N = \{1, 4\}$, the distances ($S \rightarrow R$ and $R \rightarrow D$) $d_1 = 1$, $d_2 = 5 - d_1$, the noise powers $\sigma_R^2 = \sigma_D^2 = -20$ dBm, average power transmitted by the source $P_0 = 20$ dBm, the circuit power is $P_C = \frac{P_0}{1000}$ (i.e., 0.1 % of the transmission power of the source), $L = 1000$ levels, and the path loss exponent $m = 2.7$.

Fig. 3.3 evaluates the performance in term of effective transmission rate, based on both the theoretical analysis (indicated by circle marks) and the corresponding simulations (solid lines). From the figure, it can be observed that the analytical results obtained for the effective transmission rate are very tight irrespective of the source power $P_0$ and relay selection schemes, which validates our theoretical analysis.

Fig. 3.4 shows the effective transmission rate of the PS, TS, and TS-APS schemes, with respect to PS ratio for PS and TS ratio for TS and TS-APS schemes, respectively. In the PS scheme, PS ratio represents the portion of received signal used for the EH. In the TS and TS-APS schemes, TS ratios represent the portion of block time $T$, dedicated for the EH and $S \rightarrow R_k$ transmission, respectively. The result shows that for carefully selected system parameters, the maximum effective transmission rate of the TS-APS scheme can be higher than those achievable by the TS and PS schemes proposed in [13, 16], which shows the effectiveness of the proposed scheme.

The effective transmission rate for the RRS (solid line) and ORS (dashed line) schemes are compared in Fig. 3.5 as a function of the power transmitted by the source. From

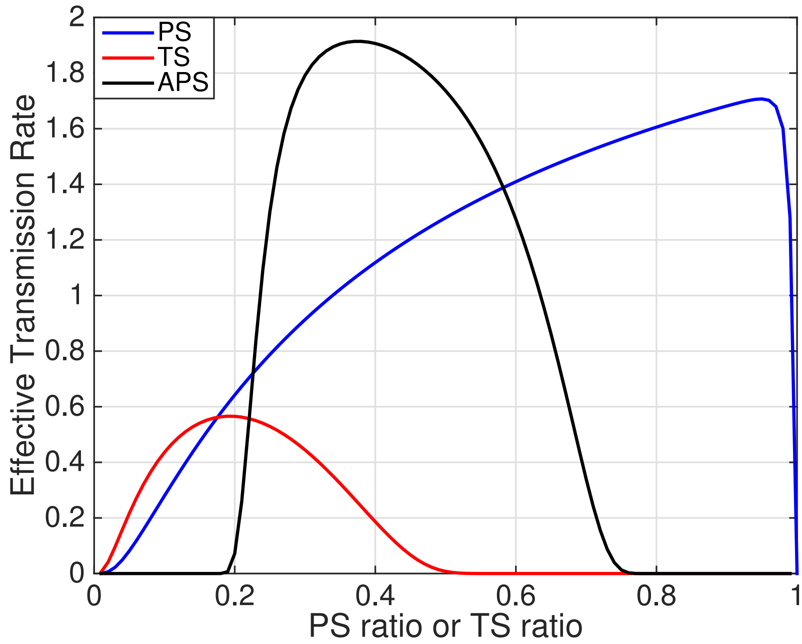



Figure 3.4: Effective transmission rate with respect to PS ratio for the PS scheme and TS ratio for the TS and TS-APS schemes. Parameters: R = 3, $\zeta = 1$, $P_0 = 20$ dBm $\lambda_1 = \lambda_2 = 1$, $\sigma_D^2 = \sigma_R^2 = -20$ dBm, $d_1 = 1$, $d_2 = 5 - d_1$, $L = 1000$, $P_C = \frac{P_0}{1000}$ and $N = 1$.

the results, it can be observed that irrespective of $P_0$ and relay selection methods the proposed scheme can easily outperform the conventinoal TS and PS schemes.

The effective transmission rates for the TS, PS and TS-APS schemes are compared in Fig. 3.6 for the case of ORS scheme, where solid lines represent the results with optimized system parameter and dash lines with out any optimization. Irrespective of the optimization and value of the RF to DC conversion efficiency, the proposed scheme is better than the conventional schemes.

In Fig. 3.7, the effective transmission rate of the TS, PS and TS-APS are compared as a function of distance between the source to relay ($d_1$) for the RRS scheme. The corresponding optimal TS ratio for the proposed protocol is plotted in Fig. 3.8. From these results it can be concluded that irrespective of the value of $d_1$, the proposed scheme outperforms the conventional schemes. As in the proposed scheme the relay can adjust the $\alpha$ to enhance the effective transmission rate. When it is near to relay, it decreases the $\alpha$ and vice versa, as shown in Fig. 3.8.

Furthermore, from (3.5), we can observe that the selected relay in the proposed scheme can dynamically calculate the optimum PS ratio with the help of the first hop CSI, and only requires the statistic characteristics of the second hop channel to calculate $\alpha_{\text{opt}}$ in (3.15). This property makes the proposed approach suitable for the distributed relay networks, where the relay selection is done locally as in [50]. The proposed scheme can be easily extended to the multi-relay selection scheme without any modification, with very low cost as compared to [18] where all the relays in the network require the global CSI to calculate the optimum PS ratio.

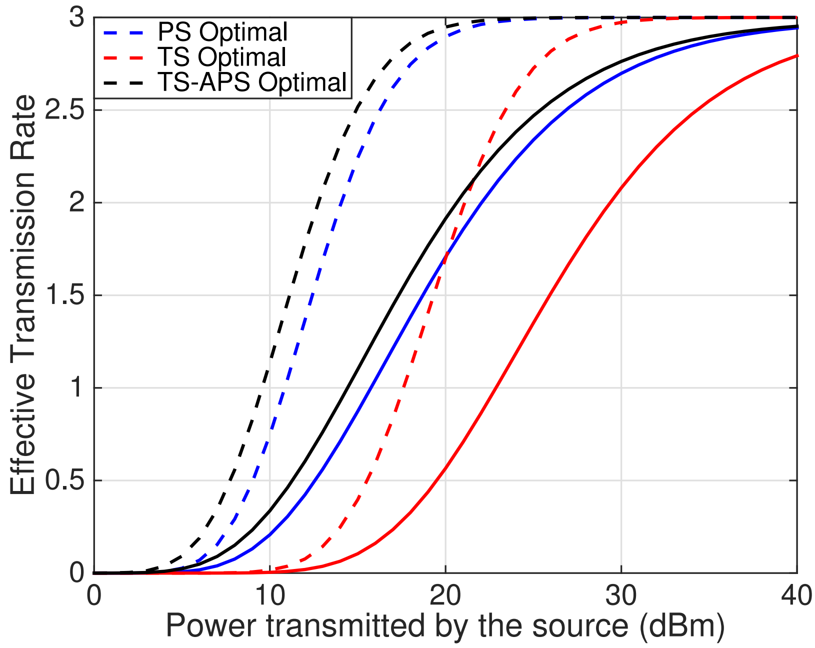



Figure 3.5: Effective transmission rate versus transmitted power by the source (solid lines: with RRS selection, dashed lines: with ORS). Parameters: R = 3, $\zeta = 1$, $\lambda_1 = \lambda_2 = 1$, $d_1 = 1$, $d_2 = 5 - d_1$, $N = 4$, $\sigma_D^2 = \sigma_R^2 = -10$ dBm, $L = 1000$, and $P_C = \frac{P_0}{1000}$.

## 3.6 Conclusion

We have proposed a TS-APS protocol for EH relay networks where the relays are powered only by the RF signal of the source, and we have derived closed-form expressions for its outage probability and effective transmission rate, under the DF framework with random and opportunistic relay selection scenarios. Based on the numerical comparison in terms of theoretical analysis and simulations, we have shown that the proposed TS-APS approach with properly optimized TS ratio can achieve better effective transmission rate than the TS and PS schemes proposed in [13, 16, 17], irrespective of the relay selection schemes. Furthermore, we have elaborated that for the proposed scheme, the relay can dynamically calculate the optimum PS ratio with the help of local CSI (i.e., CSI of the first hop) and as a result, only TS ratio is required to be optimized to enhance the system performance, which can be carried out with the help of partial knowledge of channel gains, and this property makes the proposed protocol very attractive for the distributed relay networks.

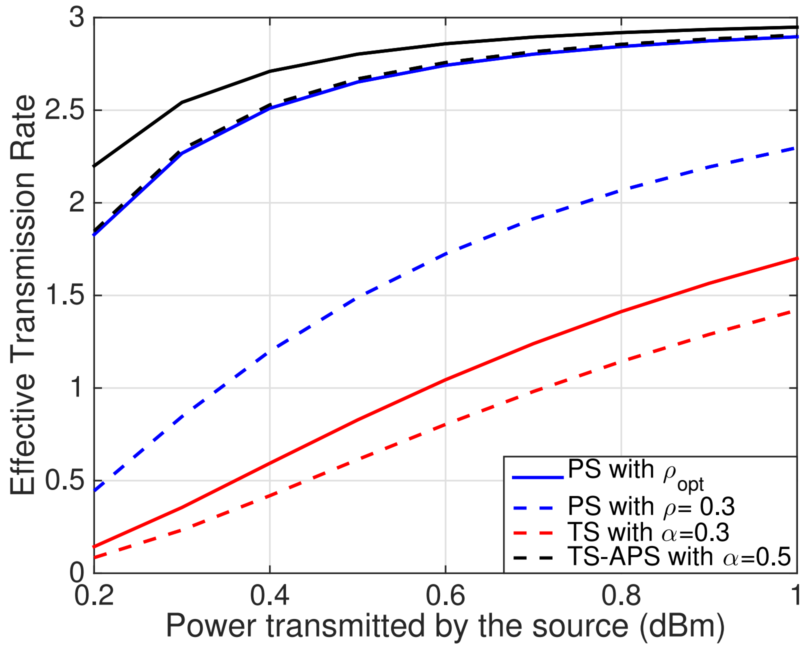



Figure 3.6: Effective transmission rate versus RF to DC conversion efficiency (solid lines: with optimization, dashed lines: without optimization). Parameters: R = 3, $\zeta = 1$, $\lambda_1 = \lambda_2 = 1$, $\sigma_D^2 = \sigma_R^2 = -20$ dBm, $P_0 = 20$ dBm $d_1 = 1$, $d_2 = 5 - d_1$, $L = 1000$, $P_C = \frac{P_0}{1000}$, and $N = 4$.

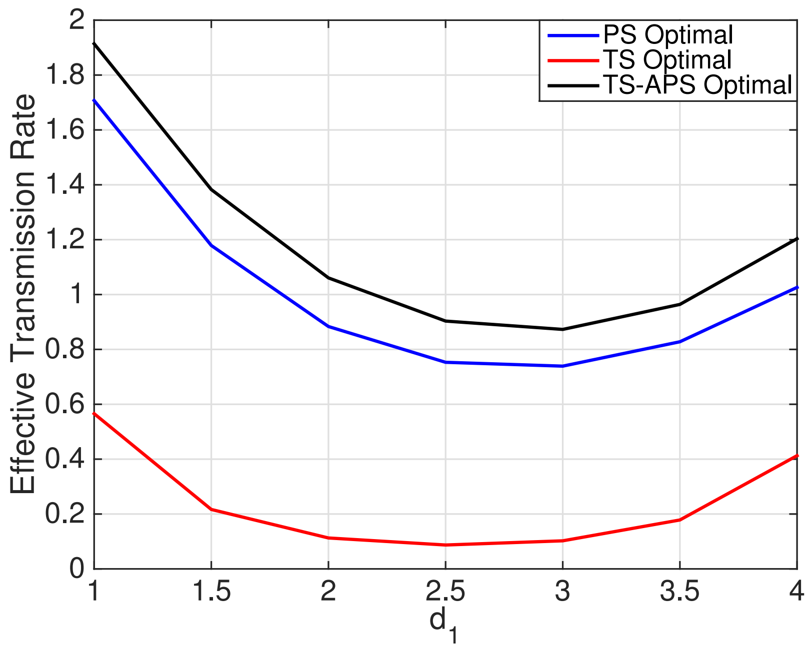



Figure 3.7: Effective transmission rate versus distance between $S \rightarrow R_k$. Parameters: R = 3, $\zeta = 1$, $\lambda_1 = \lambda_2 = 1$, $\sigma_D^2 = \sigma_R^2 = -20$ dBm, $P_0 = 20$ dBm, $L = 1000$, $P_C = \frac{P_0}{1000}$, and $N = 1$.

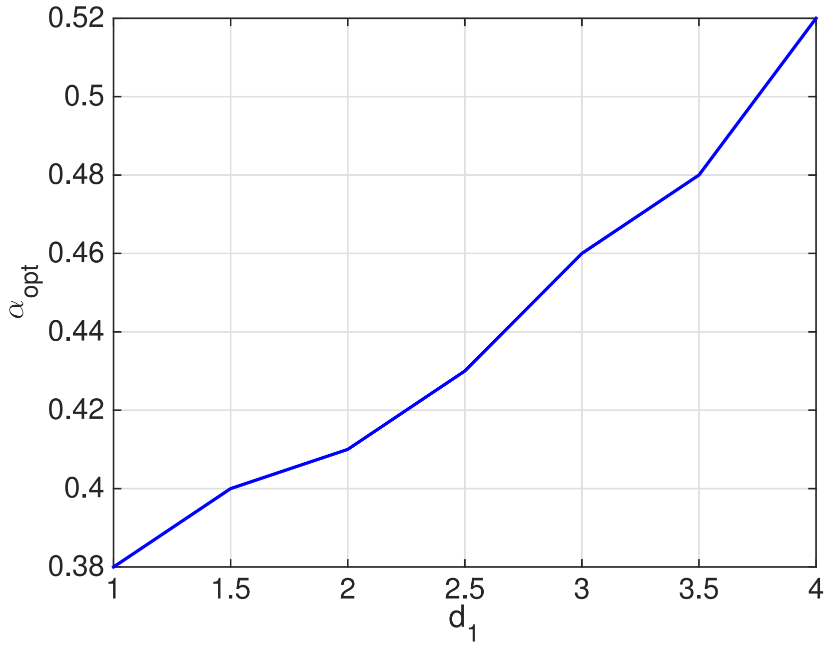



Figure 3.8: Optimal TS ratio versus distance between $S \rightarrow R_k$. Parameters: $\mathsf{R} = 3$, $\zeta = 1$, $\lambda_1 = \lambda_2 = 1$, $\sigma_D^2 = \sigma_R^2 = -20$ dBm, $P_0 = 20$ dBm, $L = 1000$, $P_C = \frac{P_0}{1000}$, and $N = 1$.

# CHAPTER 4

# Relaying Protocol for Distributed Sensor Networks with Energy Harvesting Relay Nodes

In the conventional energy-harvesting (EH) relaying protocols based on time switching (TS) and power splitting (PS), the system performance depends on the parameters such as TS and PS ratios. In order to achieve the optimum performance, these parameters need to be optimized. In the distributed cooperative networks, where relay operates independently, the optimization of PS and TS ratios becomes cumbersome and challenging. In this chapter, we overcome this issue by proposing two relaying protocols referred to as *adaptive time-switching* (ATS) and *adaptive time-switching adaptive power-splitting* (ATS-APS) protocols. In the proposed protocols, the relay can dynamically optimize their respective TS and PS ratios according to their local channel condition among relays, i.e., without any external help from the source or destination, which makes the proposed protocols promising for the distributed relaying network. Through rigorous numerical analysis, we show that the proposed protocols can outperform the conventional approach. We also derive mathematical expressions for the outage probability and the effective transmission rate in the framework of decode-and-forward (DF) relaying with partial relay selection (PRS) scheme based on various diversity combining techniques including maximum ratio combining (MRC), selection combining (SC), and selective relaying (SR). Through numerical analysis, we demonstrate that the proposed *adaptive SR* technique, where the source receives assistance from the relay only if the source-to-destination link is in deep fading, can achieve better performance than the other techniques compared here in terms of the achievable effective transmission rate. All the theoretical results developed are confirmed by numerical simulations.

## 4.1 Introduction

Wireless sensor networks are energy-constrained networks, which consist of a large number of small, inexpensive sensor nodes, often powered by batteries. In order to maintain such nodes, periodic replacement of the exhausted batteries is mandatory, which may not be feasible in certain circumstances; for example, the nodes may be deployed in hazardous areas or embedded inside inaccessible places such as building structures or human bodies. In such a scenario, energy harvesting (EH) from the environment can be a viable solution. In view of the fact that radio signal can carry information and energy at the same time, a fascinating new research direction, the so-called *simultaneous wireless information and power transfer* (SWIPT), has recently been pursued [7–9].

### 4.1.1 Review of Previous Work

The concept of SWIPT was first introduced in [9] and further explored in [10, 11]. The aforementioned papers base their analyses on the assumption that a receiver can decode information and harvest energy from the same signal. However, this may not be feasible given the current state-of-the-art of electronic circuits [8]. In [7], therefore, time-switching (TS) and power-splitting (PS) schemes were proposed as practical receiver designs for an EH system. In [12], a TS-based relaying (TS-R) and PS-based relaying (PS-R) protocols[1] were proposed to enable energy harvesting and information processing at the relay and the effective transmission rate and ergodic capacity were derived in the framework of amplify-and-forward (AF) relaying. Similarly in [13], these protocols were analyzed in the framework of decode-and-forward (DF) relaying. In [14, 15], an interference-aided EH scheme was proposed, where the relay harvests energy from the received information signal and co-channel interference signals. The mathematical expression for ergodic and outage capacities were derived in the framework of DF relaying. In [16], the analytical results for the optimum TS and PS ratios for TS-R and PS-R protocols were developed in the framework of DF relaying. Similarly, the optimum TS ratio of TS-R protocol in the framework of AF relaying was derived in [17]. In [18], a multi-relay assisted two-hop EH relay system with PS-R protocol was analyzed and the optimization problems of power splitting ratios at the relays were formulated for DF and AF relaying protocols and efficient algorithms were proposed to find the optimal solutions. In [19, 20], the outage behavior of *partial relay selection* (PRS) and *opportunist relay selection* (ORS) schemes, in the framework of the DF relaying and TS EH protocol, was analyzed and an analytical expression for the outage probability was developed. The performance of multi-hop relaying with EH relays was evaluated in [31] under the framework of TS-R and PS-R protocols. Through numerical simulations, it was reported that the TS-R protocol along with AF relaying is a better combination from the perspective of the network coverage extension. Similarly, in [67, 68] a clustering-based multi-hop relaying with PRS scheme was proposed and analyzed in the framework of DF relaying and it was reported that cluster-based scheme can improve the performance of EH multi-hop relaying networks.

In [21], a *time-power-switching based relaying* (TPS-R) was proposed in the framework of AF relaying, where in the first time slot (i.e., the slot dedicated for the source-to-relay transmission) the relay operates in PS mode to receive energy and information from the source, and in the second time slot the received signal is transmitted to the destination with the harvested energy. (We note that there is a basic difference of the term TS ratio used in the context of TS-R and TPS-R protocols in that *in TS-R it determines the portion of the block time allocated for EH, whereas in TPS-R it determines the portion of the block time dedicated for source-to-relay transmission*.) In [19, 22], the TPS-R approach was further studied and analyzed. For the AF relaying, the slot duration dedicated for the source-to-relay and relay-to-destination should be identical, which thus makes the TPS-R protocol proposed in [21] impractical for the scenario of AF relaying [23]. In order to overcome this issue, a hybrid protocol is proposed in [23], where the relay can operate in the three different modes, i.e., TS-R, PS-R, or both at a time, and the optimized TS and PS ratios were derived in the framework of DF and AF relaying. Through numerical analysis, it was shown that the hybrid approach can outperform both the TS-R and PS-R protocols if it is properly designed. A similar approach was also discussed in [24] in the case of AF relaying, and similar conclusions were drawn.

[1] We adopt unconventional nations such as TS-R and PS-R instead of TSR and PSR here in order to avoid confusion with the similar acronyms introduced later, e.g., PRS.

### 4.1.2 Motivation

The major issue of the aforementioned hybrid protocol is that the processing power required for the relaying circuitry is assumed to be negligible and hence ignored in the numerical analysis [19, 21–24]. If the circuit power of the relay node is also taken into account, the switching strategies and optimization techniques of hybrid relaying protocols proposed in [23] and [24] should be revised. Due to the causality principle of energy, i.e., by the fact that the energy cannot be used before it is harvested, simultaneous EH and information decoding (ID) with the same harvested energy may not be feasible in practice [21, 22], which makes the conventional PS-R protocol unfeasible for the EH relay networks that are powered only by the harvested energy, i.e., without any other embedded energy supply [21, 22]. Furthermore, the performance of the conventional TS-R and PS-R protocols as well as its hybrid version depends on the value of the PS and TS ratios, and in order to achieve the optimum performance, these parameters should be optimized [12, 13, 16, 17, 24]. Even though the analytical expressions for the optimum PS and TS ratios were derived in [16, 17], the results obtained for one particular channel realization may not work for other cases in general. Moreover, the optimization process generally requires the knowledge of the channel state of the entire network, and it cannot be performed by the relay that only has its own channel knowledge. However, this ideal assumption of channel knowledge may not be the case for the distributed relaying networks where the relay operates independently with minimal support and coordination (or in most cases no help at all) from the centralized processing unit.

In summary, practical protocols should deal with the necessity of energy consumed by the receiver circuit that processes information decoding as well as the availability of limited channel knowledge at the relay.

### 4.1.3 Contribution

Motivated by the practical limitations raised above, in this chapter we propose an *adaptive time-switching* (ATS) and *adaptive time-switching adaptive power-splitting* (ATS-APS) relaying protocols, where the relay first harvests the minimum required energy to power its circuit before any information processing takes place. The major advantage of the proposed schemes is that the relay can dynamically adjust its respective TS and PS ratios as per their local channel condition without any external help from the source or destination (i.e., the relay is required to have only the channel condition between the source and relay). Through rigorous numerical analysis we show that the proposed schemes can outperform the conventional schemes. Our contributions can be summarized as follows;

- We propose ATS and ATS-APS protocols where the relay can dynamically adjust its respective TS and PS ratios according to their local channel condition only, and we also show that they can outperform the conventional TS and PS schemes. We derive the mathematical expressions for their outage probability and effective transmission rate considering various diversity combining techniques, such as maximum ratio combining (MRC) and selection combining (SC) in the framework of DF relaying and partial relay selection (PRS) scheme.
- We also propose a selective relaying (SR) scheme where the source receives assistance from the relay only if the source-to-destination link is in deep fading,

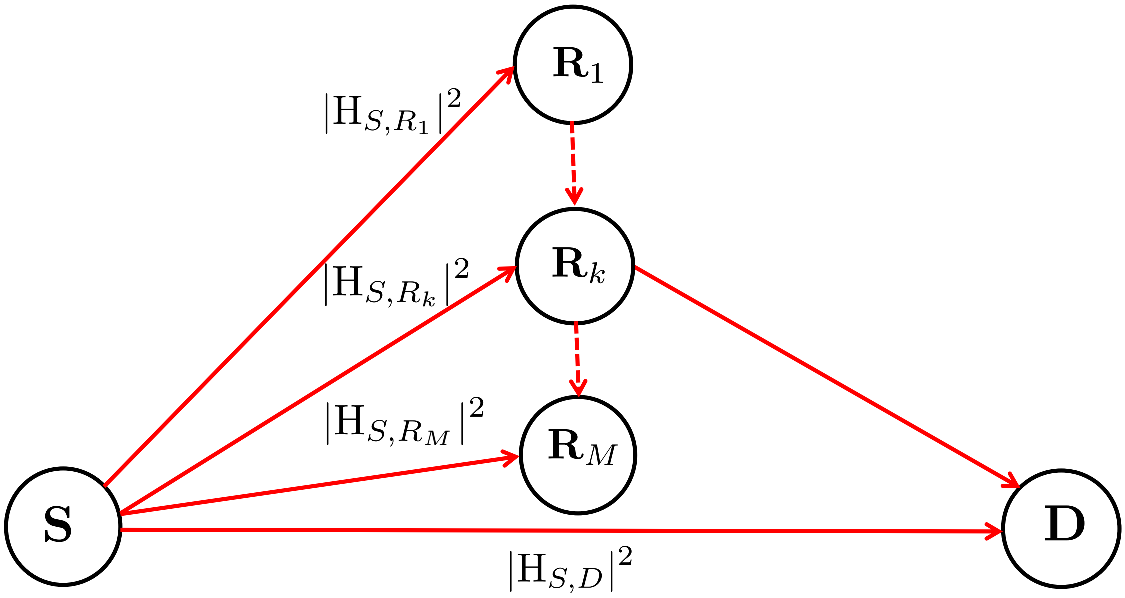



Figure 4.1: A relay network model.

and derive the mathematical expression for the outage probability and effective transmission rate. Numerical analysis demonstrates that the proposed *adaptive* SR scheme can achieve better performance compared to the conventional MRC and SC schemes in the framework of EH relay network.

We note that the scheme closely related to our ATS is proposed in [69]. The major difference is that in the proposed scheme EH time as well as information decoding (ID) time is adaptive, whereas in [69], the EH time is fixed.

## 4.2 Network Model

In this section, we briefly describe the EH relay network model considered throughout this chapter.

### 4.2.1 Relay Network Model

We consider a decode-and-forward (DF) relay network with one source ($S$), one destination ($D$), and $M$ EH relays denoted by $R_k$ with $k \in \{1,\ldots,M\}$. The corresponding network model is illustrated in Fig. 5.1, where each node is assumed to be equipped with a single antenna and half duplex [12, 13, 16, 17, 58, 61], i.e., it cannot transmit and receive at the same time, as is often the case with low-cost sensor networks [62]. The source is modeled as an energy unconstrained node and it transmits with a constant power $P_0$. For simplicity of our subsequent analyses, all the physical links between the nodes are assumed to be frequency flat block fading, where the fading coefficient remains constant during one entire time slot but changes independently from one slot to another. We also assume Rayleigh fading for each link. Therefore, the complex-valued fading coefficients follow statistically independent circularly symmetric complex Gaussian random variables with zero mean and variance $\sigma_{i,j}^2 = \mathbb{E}(|H_{i,j}|^2)$, where $\mathbb{E}(\cdot)$ is an expectation operation and $H_{i,j}$ denotes the fading coefficient of the channel from the node $i$ to node $j$ with $i \in \{S, R_k\}$ and $j \in \{R_k, D\}$, respectively. Note that the indices $i$ and

$j$ are reserved for transmitter side and receiver side, respectively, and $k \in \{1, \dots, M\}$ is consistently used as the index of the relay node in this chapter. Let $w_j$ be the additive white Gaussian noise (AWGN) observed at node $j$ with its variance $\sigma_j^2$, where $j \in \{R_k, D\}$. Furthermore, we assume for simplicity that the relay nodes have an identical noise level, i.e., $\sigma_{R_k}^2 = \sigma_R^2$ for any $k \in \{1, \dots, M\}$.

In order to further simplify the notation in our subsequent analyses, we define the path gains associated with fading between the different nodes, defined in Fig. 5.1, as $f \triangleq |H_{S,D}|^2$, $g_k \triangleq |H_{S,R_k}|^2$, and $h_k \triangleq |H_{R_k,D}|^2$. The path gains in flat Rayleigh fading channels follow exponential distribution [63] with its probability density function (pdf) expressed as $p(x) = \lambda \exp(-\lambda x)$, where the parameter $\lambda$ is given by $\lambda_{i,j} = 1/\sigma_{i,j}^2$. For simplicity, the statistical properties of the path gains from the source to any relay node and any relay node to the destination are assumed to be identical, i.e., $\lambda_{S,D} = \lambda_0$, $\lambda_{S,R_k} = \lambda_1$, and $\lambda_{R_k,D} = \lambda_2$ for all $k$. We note that by properly defining the path-loss model such that the difference of average power is suitably incorporated, we may normalize the path gains such that $\lambda_0 = \lambda_1 = \lambda_2 = 1$.

With respect to the geometrical property of the node locations, we consider the scenario where all the relay nodes are distributed in the same distance with respect to the source and destination. Specifically, let us denote $d_{S,D}$, $d_{S,R_k}$, and $d_{R_k,D}$ as the distances between $S$ and $D$, $S$ and $R_k$, and $R_k$ and $D$, respectively. We then assume that $d_{S,D} = d_0$, $d_{S,R_k} = d_1$, and $d_{R_k,D} = d_2$ for all $k$, since the relay nodes are often grouped in a cluster by clustering algorithm based on the geographical proximity of nodes [28, 64, 70]. Also, $R_k$ and $D$ are assumed to be located in the same direction from $S$ such that $d_{S,D} = d_{S,R_k} + d_{R_k,D}$ or in other words $d_0 = d_1 + d_2$.

For the resource constrained and low complexity sensor networks, maintaining the connectivity among all links could limit the network lifetime [51]. In such a scenario, the PRS approach where the relay is selected on the basis of single hop channel information is an attractive approach. In the PRS scheme, a relay that provides the best channel gain between the transmitter and the receiving cluster is selected from a set of $M$ relays [51]. For the relay selection propose, the distributed relay selection algorithm proposed in [50] may be used. In this chapter, we assume that the relay that has the best channel condition, i.e., the one with maximum $g_k$ can be uniquely identified through the ideal selection algorithm.

### 4.2.2 Battery and Energy Consumption Model

Throughout this chapter, it is assumed that the relay node is equipped with a discrete level energy battery of size $E_{\mathrm{B}}$ and that the battery can hold energy for an immediate use only due to leakage. Thus, all the harvested energy should be used in the same information block, and such system model is called as a *harvest-and-use (HU) architecture* [12, 13, 15–17, 31, 41, 54–56]. The battery level is discretized and expressed by $L$ threshold energy levels, i.e., $\epsilon^{(\ell)} \triangleq \ell E_B/L$ with $\ell \in \{1, \dots, L\}$. We define $L$ corresponding energy states, $s_\ell$, with $\ell \in \{1, \dots, L\}$, and thus the battery is said to be in the state $s_\ell$ when its stored energy is equal to $\epsilon^{(\ell)}$. Let $p_\ell$ denote the probability that the battery state is $s_\ell$, i.e., $p_\ell = \mathbb{P}\{s_\ell\}$. For sufficiently large energy levels, the discrete battery model can closely approximate a continuous battery model [58, 71, 72]. We also assume that the relay node needs $E_C$ amount of energy for the information decoding (ID) and re-encoding, which should be harvested at the start of transmission period, i.e., before any signal processing

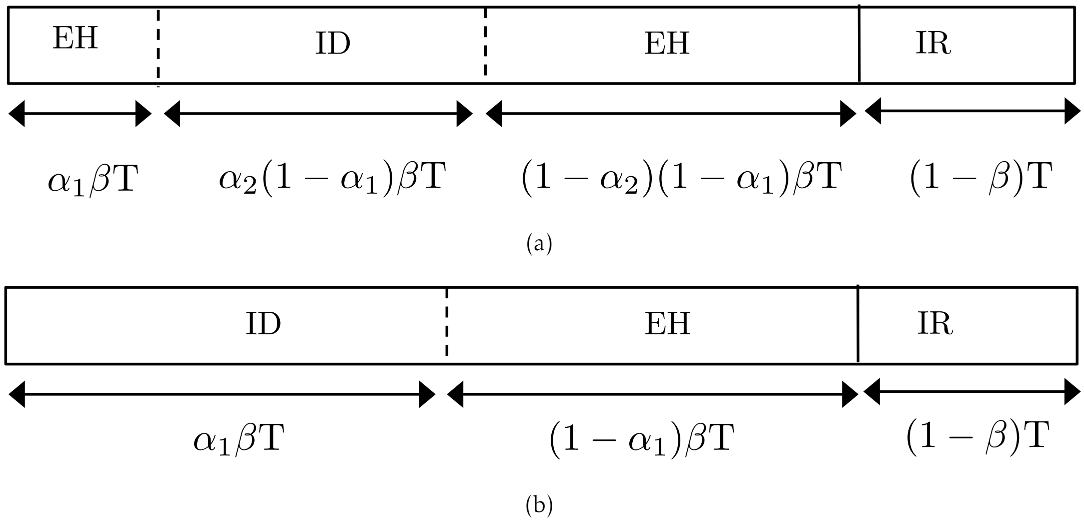



Figure 4.2: A block structure of the ATS protocol. (a) Original structure and (b) modified structure for analytical purpose.

takes place.

## 4.3 Adaptive Time Switching Relaying

In the conventional TS approach, in order to achieve the optimum throughput, the TS ratio needs to be optimized [12, 13, 16, 17, 23, 24]. Implementation of optimization process generally requires a centralized unit that determines the parameters based on the channel knowledge of the entire network. This optimization should be typically performed *offline*, which may not be suitable for the distributed relay networks. In this section, we propose an adaptive TS (ATS) relaying approach, where the relays can dynamically adjust their own TS ratios based on their local channel condition (i.e., channel between $S \to R_k$ link) only, irrespective of relay selection schemes, diversity combining techniques, or fading environments. We also theoretically analyze its performance.

### 4.3.1 ATS EH Relaying Protocol Model

We start from the conventional relaying framework where the entire block time $T$ dedicated for the source-to-destination transmission is divided into the two slots of duration $\beta T$ and $(1-\beta)T$, each for $S \to R_k$ transmission and $R_k \to D$ transmission, respectively. The block structure for the proposed ATS protocol is shown in Fig. 4.2(a), where the first slot of duration $\beta T$, dedicated for $S \to R_k$, is further divided into the three subslots as follows: In the first subslot of duration $\alpha_1\beta T$, the relay operates in the EH mode until it harvests sufficient amount of energy for circuit processing denoted by $E_C$, i.e., the energy required for the information decoding and re-encoding. Let us assume that any time is left after EH, and then the remaining first slot of $(1-\alpha_1)\beta T$ is further divided into the two subslots; In the subsequent subslot of duration $\alpha_2(1-\alpha_1)\beta T$, the relay tries to decode information. If any time is left after successful decoding, then in the third subslot of $(1-\alpha_2)(1-\alpha_1)\beta T$, it again switches back to the EH mode, and the energy harvested in this subslot is directly used to power the relay for transmission in the second slot, dedicated for $R_k \rightarrow D$.

For the sake of mathematical analysis, we reorder the block structure of the proposed protocol as shown in Fig. 4.2(b), where the two EH subslots are merged together into one without loss of generality. In the proposed protocol, the $S \rightarrow R_k$ link will be in outage in the case of the following two events; 1) if the relay cannot harvest $E_C$ amount of energy or, 2) it cannot decode the received signal. Thus, interchanging the order of these two events does not affect the mathematical analysis. For a given transmission rate $\mathsf{R}$ *per block time* $T$, the channel gain required to successfully decode the received signal can be expressed as

$$\alpha_1 \beta \log_2\left(1 + \frac{P_0 g_k}{\sigma_R^2 d_1^m}\right) \geq \mathsf{R} \tag{4.1}$$

where $\sigma_R^2$ is the variance of AWGN at $R_k$, $P_0$ is the transmission power of $S$, $g_k$ is the channel gain between $S$ and $R_k$, $d_1$ is the distance between $S$ and relay cluster (or any relay $R_k$), and $m$ is the path loss exponent. The ratio $\alpha_1$ required for successful decoding by $R_k$ is given by

$$\alpha_1 = \min\left(1, \frac{\mathsf{R}}{\beta \log_2\left(1 + g_k \frac{P_0}{\sigma_R^2 d_1^m}\right)}\right). \tag{4.2}$$

In practical systems, $\alpha_1$ should be also discrete. We therefore assume that $\alpha_1$ can take only discrete values and thus $\alpha_1$ can be expressed as

$$\delta_1 = \min_{n \in \{1,\ldots,N\}} \delta^{(n)} \quad \text{where} \quad \delta^{(n)} \geq \alpha_1, \tag{4.3}$$

where $\delta^{(n)} \triangleq n/N$ with $n \in \{1,\ldots,N\}$. We define $N$ corresponding time states $q_n$ with $n \in \{1,\ldots,N\}$, where $\delta_1$ is said to be in the state $q_n$ if $\delta_1 = \delta^{(n)}$. With the help of (4.2) and (4.3), the channel gain required to successfully decode the received signal, provided with $\delta_1 = \delta^{(n)}$, can be expressed as

$$\Gamma(n) = \left(2^{\mathsf{R}/\beta\delta^{(\mathsf{n})}} - 1\right) \frac{\sigma_R^2 d_1^m}{P_0}. \tag{4.4}$$

For a given $\delta_1$, the amount of energy harvested by $R_k$ in each block can be calculated as

$$E_k = (1 - \delta_1)\beta P_0 g_k \frac{\zeta}{d_1^m} \tag{4.5}$$

where $\zeta$ is the RF-to-DC conversion efficiency. By definition, the battery of all EH relay is discrete and finite, and therefore the energy of $R_k$ can be expressed as

$$\epsilon_k = \max_{\ell \in \{1,\ldots,L\}} \epsilon^{(\ell)} \quad \text{where} \quad \epsilon^{(\ell)} \leq E_k. \tag{4.6}$$

Due to leakage in the battery, relay cannot hold harvested energy for a long time. Therefore, it always transmits with all available energy and the transmission power of the relay node can be expressed as

$$P_{R_k} = \left(\frac{\epsilon_k - E_C}{1 - \beta}\right)^+ \tag{4.7}$$

where $(x)^+ = x$ if $x > 0$ and 0 otherwise.

### 4.3.2 Probability Expression for Harvested Energy

In the proposed ATS protocol, the EH time is dynamic, which depends on the time consumed by the relay for information decoding (ID). Thus, we are interested in the conditional probability of battery being in the state $s_\ell$ with $\ell \in \{1,\ldots,L\}$, provided that the state of $\delta_1$ is $q_n$ with $n \in \{1,\ldots,N\}$, i.e., the transition probability $p_{n,\ell} = \mathbb{P}\{s_\ell|q_n\}$. The channel gain required to harvest $\epsilon^{(\ell)} = \ell E_B/L$ units of energy for the information relaying, provided with $\delta_1 = \delta^{(n)}$, can be calculated as

$$\Gamma(\ell|n) = \frac{\left(\epsilon^{(\ell)} + E_C\right) d_1^m}{(1-\delta^{(n)})\beta\zeta P_0} \tag{4.8}$$

where $E_C$ and $\epsilon^{(\ell)}$ denote the amount of energy harvested for information processing (i.e., for information decoding and re-encoding) and that for re-transmission, respectively. For the ATS protocol, we shall calculate the transition probability $p_{n,\ell} = \mathbb{P}\{s_\ell|q_n\}$ by dividing the event into the following three cases.

▷ *Probability of battery being fully charged provided* $\delta_1 = \delta^{(n)}$ *with* $n = 1,\ldots,N$

When the amount of harvested energy at the relay is greater than or equal to $\epsilon^{(L)}$, the battery is said to be fully charged. The corresponding probability can be expressed as

$$\begin{aligned} p_{n,L} &= \mathbb{P}\left\{\left(\Gamma(n) \le \prod_{k=1}^{M} g_k < \Gamma(n-1)\right) \cap \left(\prod_{k=1}^{M} g_k \ge \Gamma(L|n)\right)\right\} \\ &= \begin{cases} F_{g_k}^M(\Gamma(n-1)) - F_{g_k}^M(\Gamma(L|n)), & \text{if } \Gamma(n) \le \Gamma(L|n) < \Gamma(n-1), \\ F_{g_k}^M(\Gamma(n-1)) - F_{g_k}^M(\Gamma(n)), & \text{if } \Gamma(n) \ge \Gamma(L|n), \\ 0, & \text{otherwise}, \end{cases} \end{aligned} \tag{4.9}$$

where $M$ is the number of relay nodes, $\delta^{(0)} = 0$, $\Gamma(n)$ and $\Gamma(L|n)$ are derived in (4.4) and (4.8), respectively, and $F_X = 1 - \exp(-x\lambda_X)$.

▷ *Probability of battery being partially charged provided* $\delta_1 = \delta^{(n)}$ *with* $j = 2,\ldots,N$

The battery is said to be partially charged if the harvested energy is greater than or equal to $\epsilon^{(1)}$ and less than $\epsilon^{(L)}$. For the given system model, the corresponding probability can be expressed as

$$\begin{aligned} p_{n,\ell} &= \mathbb{P}\left\{\left(\Gamma(n) \le \prod_{k=1}^{M} g_k < \Gamma(n-1)\right) \cap \left(\Gamma(\ell|n) \le \prod_{k=1}^{M} g_k < \Gamma(\ell+1|n)\right)\right\} \\ &= \begin{cases} F_{g_k}^M(\Gamma(n-1)) - F_{g_k}^M(\Gamma(\ell|n)), & \text{if } \Gamma(\ell|n) \ge \Gamma(n) \text{ and } \Gamma(n-1) \le \Gamma(\ell+1|n), \\ F_{g_k}^M(\Gamma(n-1)) - F_{g_k}^M(\Gamma(n)), & \text{if } \Gamma(n) \ge \Gamma(\ell|n) \text{ and } \Gamma(n-1) \le \Gamma(\ell+1|n), \\ F_{g_k}^M(\Gamma(\ell+1|n)) - F_{g_k}^M(\Gamma(n)), & \text{if } \Gamma(n) \ge \Gamma(\ell|n) \text{ and } \Gamma(\ell+1|n) \le \Gamma(n-1), \\ F_{g_k}^M(\Gamma(\ell+1|n)) - F_{g_k}^M(\Gamma(\ell|n)), & \text{if } \Gamma(\ell|n) \ge \Gamma(n) \text{ and } \Gamma(\ell+1|n) \le \Gamma(n-1), \\ 0, & \text{otherwise}. \end{cases} \end{aligned} \tag{4.10}$$

▷ *Probability of battery being partially charged provided $\delta_1 = \delta^{(1)}$ (minimum time required for ID)*

In this special case, the corresponding probability $p_{1,\ell}$ can be expressed as

$$p_{1,\ell} = \mathbb{P}\left\{\left(\prod_{k=1}^{M} g_k \geq \Gamma(1)\right) \cap \left(\Gamma(\ell|1) \leq \prod_{k=1}^{M} g_k < \Gamma(\ell+1|1)\right)\right\}$$
$$= \begin{cases} F_{g_k}^{M}(\Gamma(\ell+1|1)) - F_{g_k}^{M}(\Gamma(\ell|1)), & \text{if } \Gamma(\ell|1) \geq \Gamma(1), \\ F_{g_k}^{M}(\Gamma(\ell+1|1)) - F_{g_k}^{M}(\Gamma(1)), & \text{if } \Gamma(1) \geq \Gamma(\ell|1) \text{ and } \Gamma(1) < \Gamma(\ell+1|1), \\ 0, & \text{otherwise.} \end{cases} \tag{4.11}$$

### 4.3.3 Performance Analysis

The outage probability and effective transmission rate will be used to evaluate the system performance. We consider the following four different scenarios for the cooperative relaying; 1) $D$ ignores the transmission from $S$ as in [12, 13, 15, 17, 18, 23, 24, 31, 41, 54, 55, 58, 61] (which we refer to as *without direct path* in this chapter; 2) From the two received signals from $S$ and $R_k$, $D$ selects the signal with higher SNR and reject the other, i.e., selection combining (SC), [73, 74]; 3) $D$ combines the signal received from both $S$ and $R_k$ to maximize the SNR of the received signal, i.e., maximum ratio combining (MRC); and 4) $S$ receives assistance from $R_k$ only if the link between $S \to D$ is in deep fading and otherwise direct transmission from $S \to D$ only takes place.

▷ *Cooperative transmission without direct path*

In this scenario, whenever $S \to R_k$ or $R_k \to D$ link is in deep fading, the system will be in outage [46, 65]. If the energy harvested by transmitting relay node $R_k$ is $\epsilon_k = \epsilon^{(\ell)}$ with $\ell \in \{1, \ldots, L\}$, the channel capacity of $R_k \to D$ link can be expressed as

$$C_{R_k,D} = (1-\beta)\log_2\left(1 + \frac{\epsilon^{(\ell)} h_k}{d_2^m (1-\beta)\sigma_D^2}\right) \tag{4.12}$$

where $\sigma_D^2$ is the variance of AWGN at $D$. For the targeted data rate $\mathsf{R}$, the channel gain of $h_k$ required to successfully decode the signal received at $D$ can be expressed as

$$\Gamma^{RD}(\ell) = \left(2^{\mathsf{R}/(1-\beta)} - 1\right) \frac{\sigma_D^2 d_2^m (1-\beta)}{\epsilon^{(\ell)}}. \tag{4.13}$$

For the ATS relaying shown in Fig. 4.2(b), the outage occurs in the following events; 1) when the relay cannot decode the received signal successfully, i.e., $\alpha_1 \geq 1$; 2) when $\alpha_1 < 1$ but $\epsilon_k \leq E_C$; 3) when $\alpha_1 < 1$ and $\epsilon_k > E_C$ but $C_{R_k,D} < \mathsf{R}$. Therefore, the overall outage event can be expressed as

$$P_{\text{out}} = 1 - \mathbb{P}\left[\{(\epsilon_k > E_C) \cap (\alpha_1 < 1)\} \cap (C_{R_k,D} \geq \mathsf{R})\right]$$

which can be written as

$$P_{\text{out}} = 1 - \sum_{n=1}^{N-1} \sum_{\ell=1}^{L} p_{n,\ell}\left[1 - F_g^M(\Gamma^{RD}(\ell))\right] \tag{4.14}$$

where $p_{n,\ell}$ is derived in (4.9), (4.10), and (4.11), and $\Gamma^{RD}(\ell)$ is derived in (4.13). For the given transmission rate $\mathsf{R}$ and outage probability $P_{\text{out}}$, the effective transmission rate can be define as [55, 68]

$$\tau = \mathsf{R}(1 - P_{\text{out}}). \tag{4.15}$$

▷ *Cooperative transmission with direct path and SC*

In this scenario, we assume that $D$ can receive the signals transmitted by both $S$ and $R_k$, where it selects the signal with higher SNR for decoding (i.e. SC) [73, 74]. For the SC, the channel capacity at the destination can be expressed as [57, 75]

$$C_D = \max\left(C_{R_k D}, C_{SD}\right) \tag{4.16}$$

where $C_{R_k,D}$ is derived in (4.12) and $C_{SD}$, the channel capacity of $S \to D$ link, can be expressed as

$$C_{SD} = \beta \log_2\left(1 + \frac{f P_0}{\sigma_D^2 d_0^m}\right) \tag{4.17}$$

where $f = |H_{S,D}|^2$ and $d_0$ are the channel gain and distance for $S \to D$. The channel gain required to successfully decode the received signal at $D$ can be expressed as

$$\Gamma^{SD} = \left(2^{\mathsf{R}/\beta} - 1\right) \frac{\sigma_D^2 d_0^m}{P_0}. \tag{4.18}$$

With (4.17) and (4.18), the probability of $S \to D$ link being in outage can be expressed as

$$\begin{aligned} P_{\text{out}}^{SD} &= \mathbb{P}\left(f < \Gamma^{SD}\right) \\ &= 1 - \exp\left(-\lambda_f \Gamma^{SD}\right). \end{aligned} \tag{4.19}$$

In the SC scheme, the outage will occur if both the links, i.e., $R_k \to D$ and $S \to D$ are in outage. Using (4.14) and (4.19), the outage probability of SC scheme can be expressed as

$$P_{\text{out}}^{SC} = P_{\text{out}} P_{\text{out}}^{SD} \tag{4.20}$$

where the first and second probabilities represent the outage probabilities of $R_k \to D$ and $S \to D$ links, respectively.

▷ *Cooperative transmission with direct path and MRC*

In this scenario, we assume that $D$ can receive the signal transmitted by $S$ and $R_k$, where it linearly combines both the signals to increase the reliability and decoding probability (i.e., MRC) [73, 74]. In order to simplify the mathematical analysis, in this subsection the portion of block time dedicated for $S \to R_k$ transmission is assumed to be $\beta = 1/2$. Hence, the channel capacity at $D$, provided that the transmitting relay node has the harvested energy of $\epsilon^{(\ell)}$ unit with $\ell \in \{1, \ldots, L\}$, can be expressed as [45, 46, 76]

$$\begin{aligned} C_D^{MRC} &= \frac{1}{2} \log_2\left(1 + \frac{P_0 f}{d_0^m \sigma_D^2} + \frac{2\epsilon^{(\ell)} h_k}{d_2^m \sigma_D^2}\right) \\ &= \frac{1}{2} \log_2\left(1 + a + b^{(\ell)}\right) \end{aligned} \tag{4.21}$$

where $a = \frac{P_0 f}{d_0^m \sigma_D^2}$ and $b^{(\ell)} = \frac{2\epsilon^{(\ell)} g_k}{d_2^m \sigma_D^2}$ are also exponential random variables with parameters $\lambda_a = \frac{\lambda_0 \sigma_D^2 d_0^m}{P_0}$ and $\lambda_{b^{(\ell)}} = \frac{\lambda_2 \sigma_D^2 d_2^m}{2\epsilon^{(\ell)}}$, respectively [63]. For the targeted data rate of $\mathsf{R}$, the minimum SNR required to successfully decode the combined signal at $D$ can be expressed as

$$\Gamma = 2^{2\mathsf{R}} - 1. \tag{4.22}$$

Based on (4.21), the outage probability can be expressed as

$$\begin{aligned} P_{\text{out}}^{MRC} &= \mathbb{P}\left\{(a + b^{(\ell)}) < \Gamma\right\} \\ &= 1 - \sum_{n=1}^{N-1} \sum_{\ell=1}^{L} p_{n,\ell} \left( \frac{\lambda_a}{\lambda_a - \lambda_{b^{(\ell)}}} \exp(-\lambda_{b^{(\ell)}}\Gamma) + \frac{\lambda_{b^{(\ell)}}}{\lambda_{b^{(\ell)}} - \lambda_a} \exp(-\lambda_a \Gamma) \right), \end{aligned} \tag{4.23}$$

where $\Gamma$ is derived in (4.22). For brevity, the specific expression for the case when $\lambda_a = \lambda_{b^{(\ell)}}$ is omitted but can be found in, e.g., [45].

▷ *Cooperative communication with direct path and selective relaying (SR)*

In practical cooperative relaying networks, before any information transmission takes place, the source and destination should exchange Ready-to-Send (RTS) and Clear-to-Send (CTS) packets [50]. In our system model, we assume that with the help of CTS and reciprocity theorem [66], the source is able to estimate the instantaneous channel gain $f = |H_{S,D}|^2$. By knowing $f$, the source may determine whether successful communication can be achieved without the help of relay nodes (i.e., direct transmission) or not. For simplicity of analysis, we assume that when the relay is active in the transmission block, the destination only receives the signal transmitted from the relay. The channel capacity at the destination for the direct transmission can be expressed as

$$C_D = \log_2\left(1 + \frac{P_0 f}{d_0^2 \sigma_D^2}\right) \tag{4.24}$$

where $f$ is the channel gain for $S \to D$ link. The channel gain required to successfully decode the received signal at $D$ can be expressed as

$$\Gamma^D = \left(2^{\mathsf{R}} - 1\right) \frac{\sigma_D^2 d_0^m}{P_0}. \tag{4.25}$$

Note that comparing (4.25) and (4.18), we can observe that when the direct link is not in deep fading, employing the relay for assistance leads only to an increase of the required signal power due to the required transmission rate increased by the factor $1/\beta$. In this case, the outage at destination occurs if the signal transmitted by the source cannot be successfully decoded by destination, which can be expressed as

$$\begin{aligned} P_{\text{out}}^D &= \mathbb{P}\left(f < \Gamma^D\right) \\ &= 1 - \exp\left(-\lambda_f \Gamma^D\right). \end{aligned} \tag{4.26}$$

In the proposed selective relaying (SR), based on the simplified assumption described above the outage occurs if 1) both the $S \to D$ and $S \to R_k$ links are in deep fading; or 2) the $S \to R_k$ link is not in deep fading but both $S \to D$ and $R_k \to D$ links are in deep fading. The outage probability can be expressed as

$$P_{\text{out}}^{SR} = P_{\text{out}}^D P_{\text{out}}^{SD} \tag{4.27}$$

where $P_{\text{out}}^{SD}$ and $P_{\text{out}}^D$ are derived in (4.26) and (4.19), respectively.

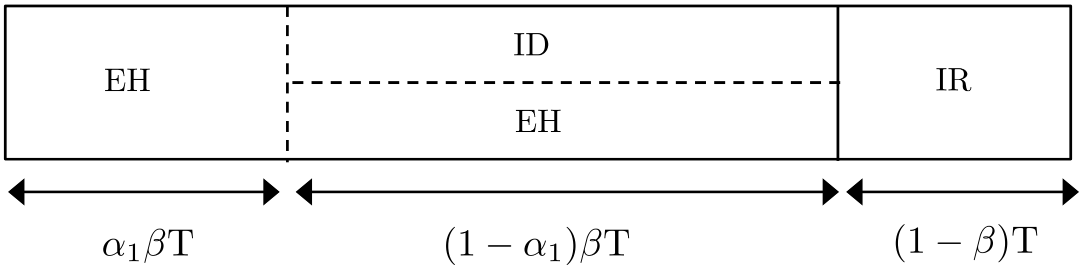



Figure 4.3: A block structure of the ATS-APS protocol.

## 4.4 Adaptive Time-Switching Adaptive Power-Splitting Scheme

From the theoretical viewpoint, PS EH relaying is known to achieve better performance than TS EH relaying. However, in the case of HU architecture, the implementation of PS EH relaying is challenging or even unfeasible. This is because for HU architecture the relay nodes are powered by the instantaneously harvested energy, whereas in PS relaying approach it is assumed that ID and EH can take place simultaneously [16]. In the literature, it is assumed that the processing power required for the relaying circuitry is negligible [12, 13, 15–17, 31, 41, 54–56]. Even if this assumption may be reasonable for the conventional relay nodes that are powered by the battery, it may not be the case for EH relay nodes, especially when they are operated with the HU architecture.

In order to make the PS feasible under the framework of the HU architecture, the relay should be allowed to harvest at least $E_C$ amount of energy (i.e., the energy required for information decoding and re-encoding) before it is switched to PS mode. In this section, we propose a hybrid *adaptive time-switching adaptive power-splitting* (ATS-APS) approach, where the relay first tries to harvest $E_C$ amount of energy before switching to PS mode. The approach is called *adaptive* since the relay independently attempts to adjust its TS and PS ratios according to its local channel condition (i.e., the channel condition of $S \to R_k$ link) without any external channel knowledge.

The block structure of the proposed ATS-APS protocol is shown in Fig. 4.3. Here, the block time $T$ dedicated for the $S \to D$ communication is divided into the two slots $\beta T$ and $(1-\beta)T$ for $S \to R_k$ link and $R_k \to D$ link, respectively. The block time $\beta T$ dedicated for $S \to R_k$ is further divided into the two subslots, i.e., $\alpha_1 \beta T$ and $(1-\alpha_1)\beta T$, where the first subslot is divided associated with ATS, whereas the APS is applied to the second subslot.

### 4.4.1 ATS Model

In the first time subslot, the relay is switched to the EH mode and remains in the same mode until it harvests $E_C$ amount of energy. Similar to (4.5), the energy harvested at the $k$th relay during the first subslot of each block can be expressed as

$$E_k = \alpha_1 \beta \zeta g_k P_0 \frac{1}{d_1^m}. \tag{4.28}$$

Therefore, the fraction of block time required to harvest $E_C$ amount of energy can be expressed as

$$\alpha_1 = \frac{E_C d_1^m}{(1-\beta)\zeta g_k P_0}. \tag{4.29}$$

Again, we assume that $\alpha_1$ can only take discrete values, and thus $\alpha_1$ will be replaced by

$$\delta_1 = \min_{n\in\{1,\dots,N\}} \quad \text{where} \quad \delta^{(n)} \geq \alpha_1. \tag{4.30}$$

The channel gain required to harvest $E_C$ amount of energy can be thus expressed as

$$\Gamma(n) = \frac{E_C d_1^m}{P_0 \zeta (1-\beta)\delta^{(n)}}. \tag{4.31}$$

### 4.4.2 APS Model

Once the relay harvests $E_C$ amount of energy, it will switch to the APS mode, where the observation flow is dynamically split into the two streams with power splitting ratio $\rho_k \in (0, 1)$; For a given received signal power $P$, $\rho_k P$ is used for ID and the remaining $(1-\rho_k)P$ is subject to EH [61, 67, 68]. In such a way, only the minimum required signal power (i.e., the portion required for successful decoding) should go to the ID unit and remaining power will be collected by the EH unit [68].

### 4.4.3 Analytical Expressions for ATS-APS Model

Based on the above ATS and APS models, for given $\delta_1 = \delta^{(n)}$, the data rate supported by the $S \to R_k$ link of the proposed ATS-APS protocol can be written as

$$C_{S,R_k} = (1-\delta^{(n)})\beta \log_2\left(1 + \rho_k \frac{P_0 g_k}{\sigma_R^2 d_1^m}\right) \tag{4.32}$$

where $n = 1, \dots, N$. Thus, the PS ratio $\rho_k$ can be calculated as

$$\rho_k = \min\left(1, \frac{2^{\mathsf{R}/\beta(1-\delta^{(n)})} - 1}{g_k \gamma_k}\right) \tag{4.33}$$

where $\mathsf{R}$ is the targeted data rate and

$$\gamma_k = \frac{P_0}{\sigma_R^2 d_1^m}. \tag{4.34}$$

Note that the selection of $\rho_k$ in the above equation is based on the strategy that a relay first tries to decode the information, and if there is any energy left, it then performs EH. From (4.29) and (4.33), it can be observed that whenever the link between $S \to R_k$ is in deep fading, i.e., $\alpha_1 \geq 1$ or $\rho_k \geq 1$, no energy will be harvested as it cannot store the harvested energy for the later use. Thus the channel gain required to harvest $\epsilon^{(\ell)}$ amount of energy (with $\ell \in \{1, \dots, L\}$), provided that the time fraction $\delta^{(n)}$ with $n \in \{1, \dots N\}$ required to harvest $E_C$ amount of energy in the first slot, can be expressed as

$$\Gamma(\ell|n) = \left(2^{\mathsf{R}/\beta(1-\delta^{(n)})} - 1\right)\frac{\sigma_R^2 d_1^m}{P_0} + \frac{\epsilon^{(\ell)} d_1^m}{\beta(1-\delta^{(n)})\zeta P_0} \tag{4.35}$$

where the first term represents the channel gain required to ensure the successful decoding, and the second term corresponds to the channel gain required to harvest $\epsilon^{(\ell)}$ amount of energy, provided that the time required to harvest $E_C$ amount of energy is $\delta^{(n)}$.

Let $p_{n,\ell}$ with $n \in \{1, \dots, N\}$ and $\ell \in \{1, \dots, L\}$ denote the probability that the battery state is $s_\ell$, provided that the state of the energy harvesting time is $q_n$, i.e., $p_{n,\ell} = \mathbb{P}\{s_\ell | q_n\}$. For the proposed ATS-APS protocol, this probability can be calculated by substituting (4.31) and (4.35) into (4.9), (4.10), and (4.11). Similarly, the outage probabilities of the ATS-APS protocol for the four different scenarios described in Section 4.3.3 can be obtained by substituting $p_{n,\ell}$ derived for the ATS-APS protocol into (4.14), (4.20), (4.23), and (4.27).

Table 4.1: Simulation parameters

| Parameter | Numerical value |
|---|---|
| Number of relay nodes | $M = \{1, 10\}$ |
| Distance between $S \to D$ | $d_0 = 5$ m |
| Distance between $S \to R_k$ | $d_1 = 1$ m |
| Distance between $R_k \to D$ | $d_2 = d_0 - d_1$ |
| Targeted data rate | R = 1 bit per channel use |
| Path loss exponent | $m = 3$ |
| RF-to-DC conversion efficiency | $\zeta = 0.8$ |
| Transmission power of the source | $P_0 = 10$ dBm |
| Required circuit power | $P_C = -18$ dBm |
| TS ratio | $\beta = 0.5$ |
| Noise power | $\sigma_i^2 = -10$ dBm with $i \in \{R_k, D\}$ |

## 4.5 Numerical Results

In this section, based on the theoretical analysis carried out in the previous sections, we present several numerical results and discuss the insights gained from them. The effective transmission rate is used as our performance measure. The accuracy of the derived analytical results are also validated by Monte Carlo simulations. Unless otherwise stated, the parameters listed in Table 4.1 are chosen for our subsequent numerical results. The other relevant parameters will be described separately.

### 4.5.1 Comparison of Theoretical and Simulation Results

In this subsection, the analytical results derived in the previous sections for the proposed ATS and ATS-APS protocols with the four combining schemes (i.e., without direct path, SC, MRC, and SR) are examined and verified through simulation results. Figures 4.4(a) and 4.4(b) compare the effective transmission rate based on both the theoretical analysis (indicated by the lines) and the corresponding simulation (circular marks) over Rayleigh fading channel with $M = 10$ and all the four representative combining cases. The transmission power of the source $P_0$ is chosen as our parameter. From the results, it can be observed that irrespective of combining schemes and EH protocols, the theoretically derived results are in excellent agreement with the simulation results for given source power $P_0$, which validates our theoretical analysis. For the remainder of this chapter, we only plot the numerical results based on the theoretical analysis.

### 4.5.2 Comparison with Existing Approach

Figure 4.5 shows the relationship between the effective transmission rate and TS/PS ratio for the TS and PS schemes, respectively. In this subsection, only the results obtained for the case without direct path are compared. In the proposed ATS and ATS-APS schemes, the TS ratio $\beta$ determines the portion of the block time dedicated for the $S \to R_k$ transmission, whereas in the conventional TS scheme, the TS ratio determines the portion of the block time dedicated for the EH. From the results it can be observed that the effective transmission rate achieved by the proposed ATS and ATS-APS protocols with $\beta = 0.5$, i.e., without any optimization (denoted by the cross mark) is higher than that of the conventional TS and PS scheme, irrespective of the selected TS/PS ratio. The results also show that by properly selecting $\beta$, the effective transmission rate of the proposed protocol can be further improved, which clearly demonstrates their effectiveness.

### 4.5.3 Performance Analysis of Various Combination Techniques

Figure 4.6 shows the effective transmission rate as a function of transmission power of the source $P_0$ for the four combining cases. The results are obtained for the proposed ATS-APS protocol. From the results it can be observed that for the given system parameter the proposed SR scheme outperforms the conventional MRC and SC schemes, irrespective of $P_0$. This is because, in the MRC ans SC schemes, the relay is always employed irrespective of the channel gain of $S \to D$ link, due to which the portion of block time dedicated for the $S \to D$ should always be divided into the links $S \to R_k$ and $R_k \to D$, i.e, by half-duplexing constraint. As a consequence, the system assisted by relay should always transmit with twice the rate as compared to the direct transmission which can be observe from (4.25) and (4.18). Unlike the conventional scheme, SR exploits the channel information between the $S \to D$ link and avoids the use of relay if unnecessary, thereby enhancing the achievable performance.

### 4.5.4 Effect of TS ratio

Figure 4.7 shows the effective transmission rate as a function of TS ratio $\beta$ for the four combining cases. The results are obtained for the proposed ATS-APS protocol. From the results, it can be observed that for given system parameters, the effective transmission rate obtained with $\beta = 0.5$ (i.e., without any optimization) combined with SR outperforms all the other combination techniques compared here. Furthermore, we can observe that the performance of SR can be further improved with properly selected $\beta$. Another interesting observation is that even SC can outperform MRC (with $\beta = 1/2$) (denoted by circle mark in Fig. 4.7) if the TS ratio $\beta$ is properly selected.

### 4.5.5 Effect of Number of Relay Nodes

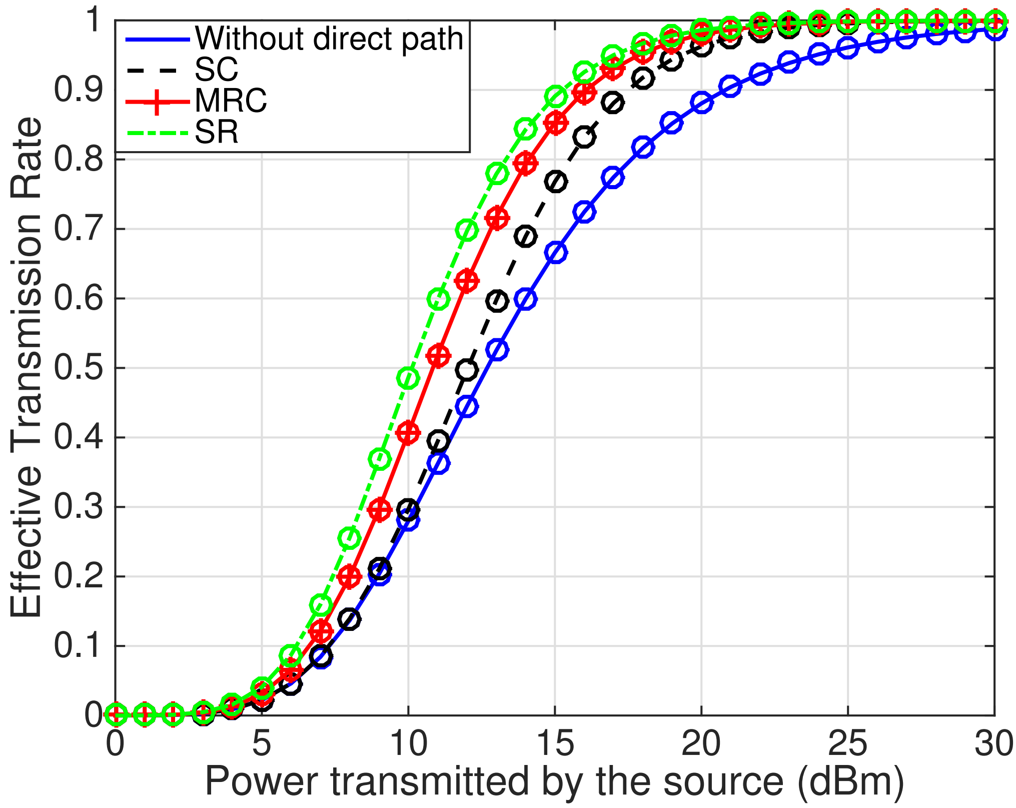
The relationship between the effective transmission rate of the proposed ATS-APS protocol with the various combination techniques and the number of relay nodes ($M$) is shown in Fig. 4.8. Note that the result corresponding to the direct transmission is obtained with (4.26). From the results, it can be observed that the proposed SR scheme can improve the system performance over the direct transmission case irrespective of the number of relay nodes, whereas the MRC and SC require more than 6 and 3 relay nodes, respectively. The reason for this behavior is the same as in the case of the result in the previous subsection. From the results, it can be concluded that with the proposed SR scheme, the effective transmission rate of the energy constrained sensor networks can be improved even with a very few relay nodes.

### 4.5.6 Effect of RF-to-DC Conversion Efficiency

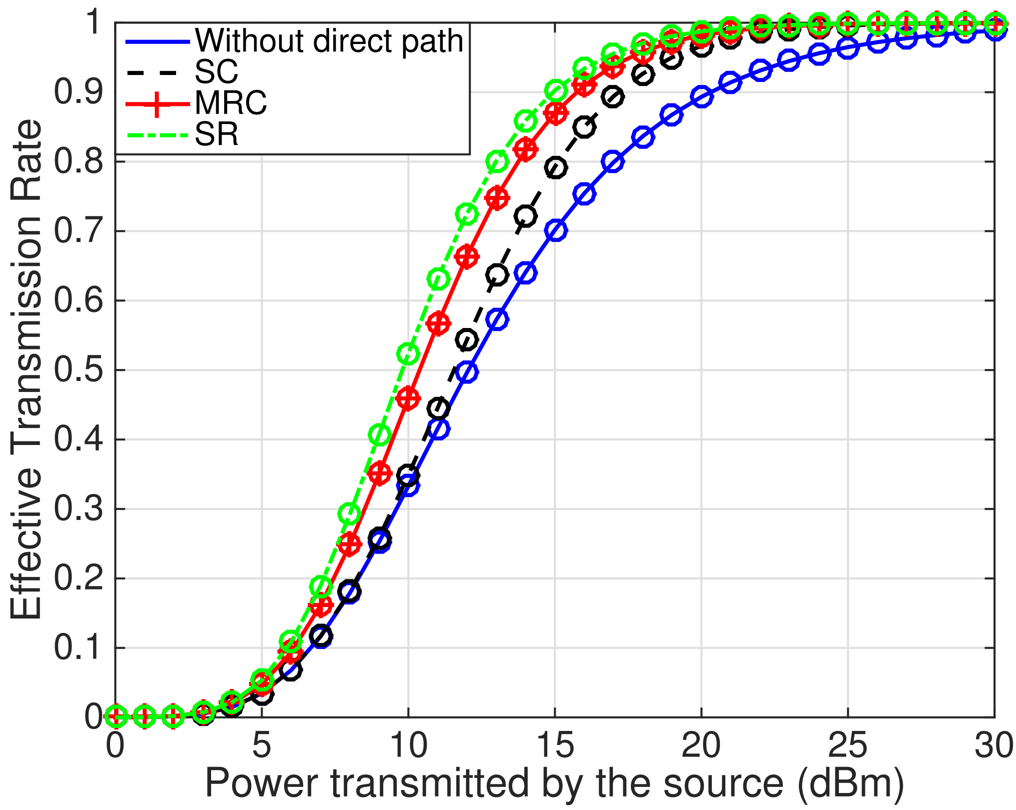
Finally, Fig. 4.9 compares the effective transmission rate of the ATS-APS protocol for various combining techniques as a function of RF-to-DC conversion efficiency $\zeta$. It can be observed that the proposed SR scheme can improve the system performance even with significantly low energy conversion efficiency compared to the other schemes. This stems from the fact that the SR scheme can exploit the knowledge of CSI between $S \to D$ link and employ the relay opportunistically to enhance the system performance. Therefore, the ATS-APS protocol combined with SR can be considered as a promising approach for practical EH sensor network scenarios operated with low energy conversion efficiency.

## 4.6 Conclusion

In this chapter, we have proposed the ATS and ATS-APS protocols that enable EH and information processing at the relay. We have derived the mathematical expressions for the outage probability and effective transmission rate for the proposed protocols in the framework of DF relaying and partial relay selection with various diversity combining techniques. Based on rigorous numerical analyses, we have demonstrated that the proposed ATS protocol can easily outperform the conventional TS protocol, and the proposed ATS-APS protocol can outperform all the existing protocols compared here under reasonable assumptions and conditions. We have also shown that for the EH relay networks, the proposed SR technique, where the source receives assistance from the relay only when the direct link between source and destination is in deep fading, should be the better option for improving the system performance, compared to the commonly studied MRC and SC approaches.




(a)




(b)

Figure 4.4: Effective transmission rate versus power transmitted by the source $P_0$, (a) ATS scheme (b) ATS-APS scheme. Parameters: R $= 1$, $\zeta = 0.8$, $P_C = -18$ dBm, $M = 10$, $\sigma_D = \sigma_R = -10$ dBm, $d_0 = 5$ m, $d_1 = 1$ m, $\beta = 0.5$, and $L = 1000$.

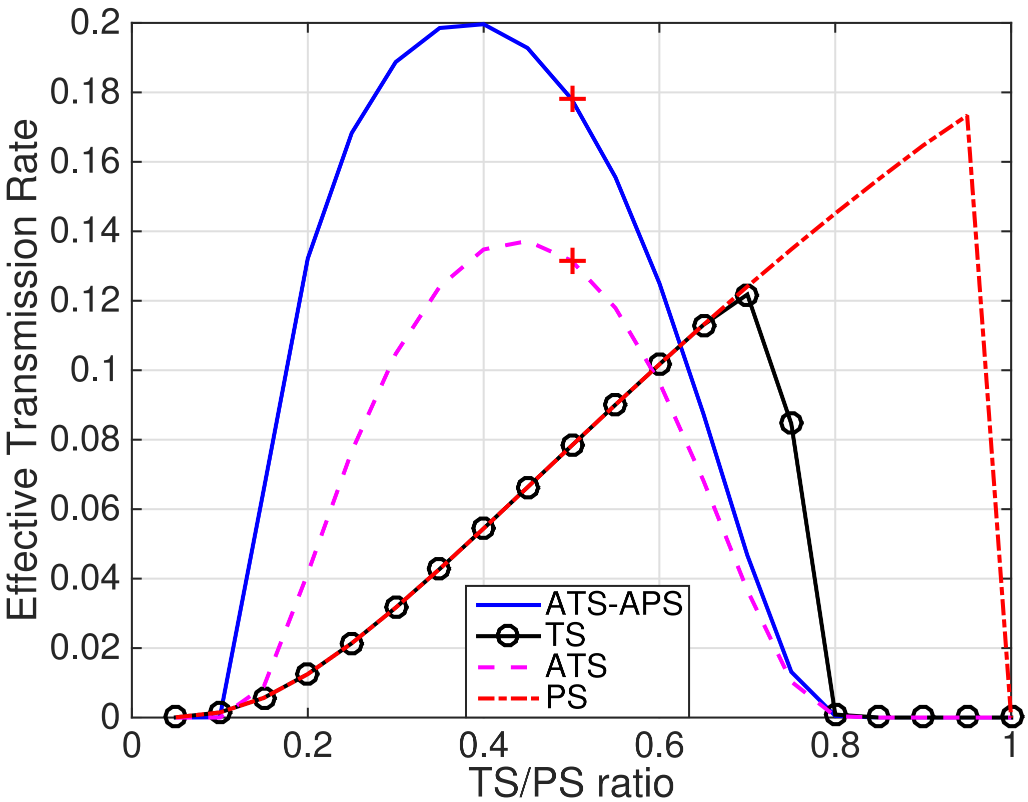



Figure 4.5: Effective transmission rate versus TS/PS ratio (cross mark:effective transmission rat for $\beta = 0.5$, i.e., without optimization). Parameters: R = 1, $\zeta = 0.8$, $P_C = -18$ dBm, $\sigma_D = \sigma_R = -10$ dBm, $d_0 = 5$ m, $d_1 = 1$ m, $M = 1$, $P_0 = 12$ dBm, and $L = 1000$.

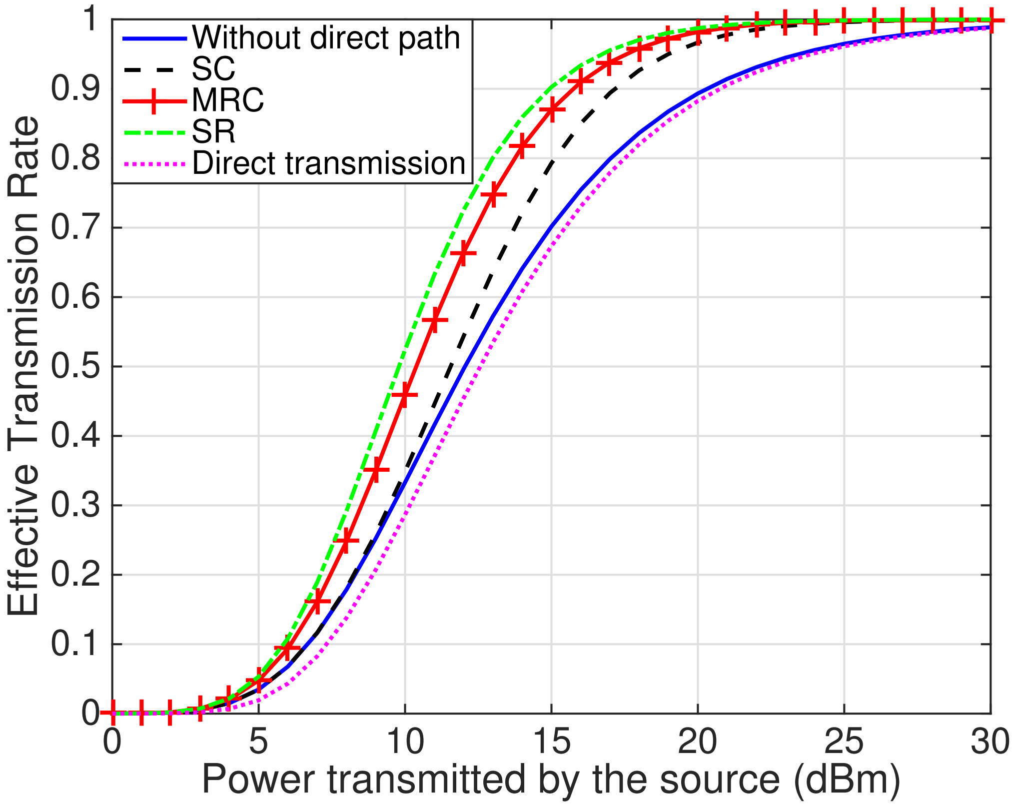



Figure 4.6: Effective transmission rate of the ATS-APS protocol with various diversity combining versus power transmitted by the source $P_0$. Parameters: R = 1, $\zeta = 0.8$, $P_C = -18$ dBm, $\sigma_D = \sigma_R = -10$ dBm, $d_0 = 5$ m, $d_1 = 1$ m, $M = 10$, $\beta = 0.5$, and $L = 1000$.

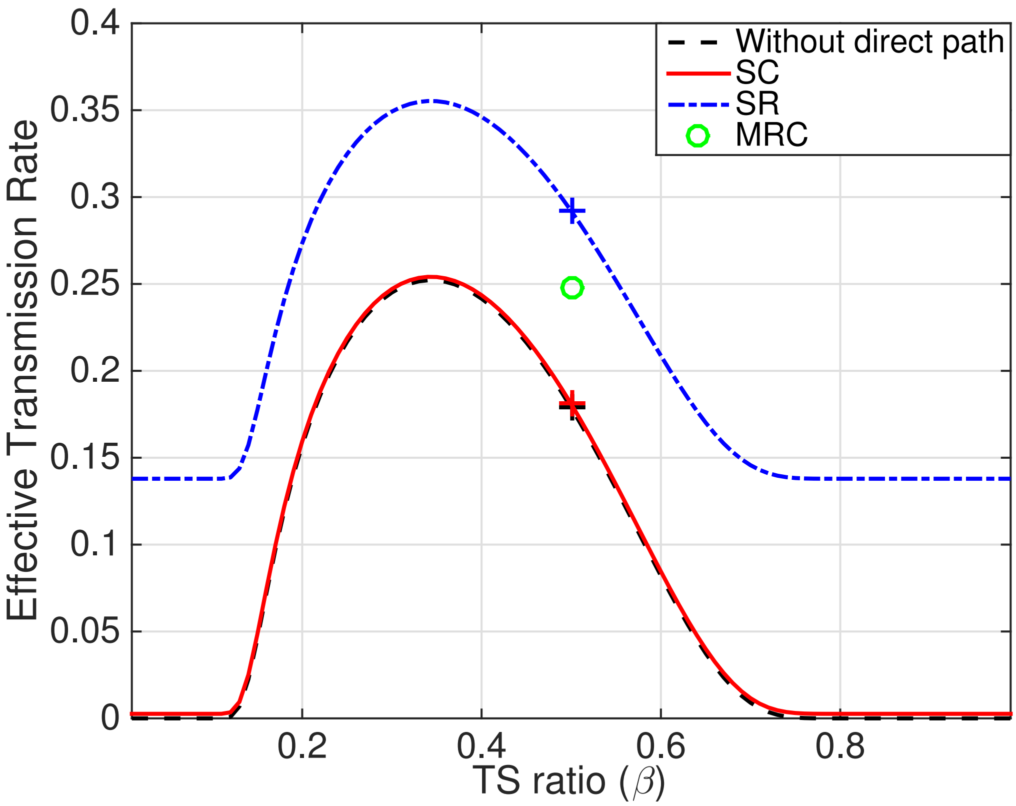



Figure 4.7: Effective transmission rate of the ATS-APS protocol with various diversity combining versus TS ratio $\beta$. Parameters: $\mathsf{R} = 1$, $\zeta = 0.8$, $P_C = -18$ dBm, $\sigma_D = \sigma_R = -10$ dBm, $d_0 = 5$ m, $d_1 = 1$ m, $M = 10$, $P_0 = 8$ dBm, and $L = 1000$.

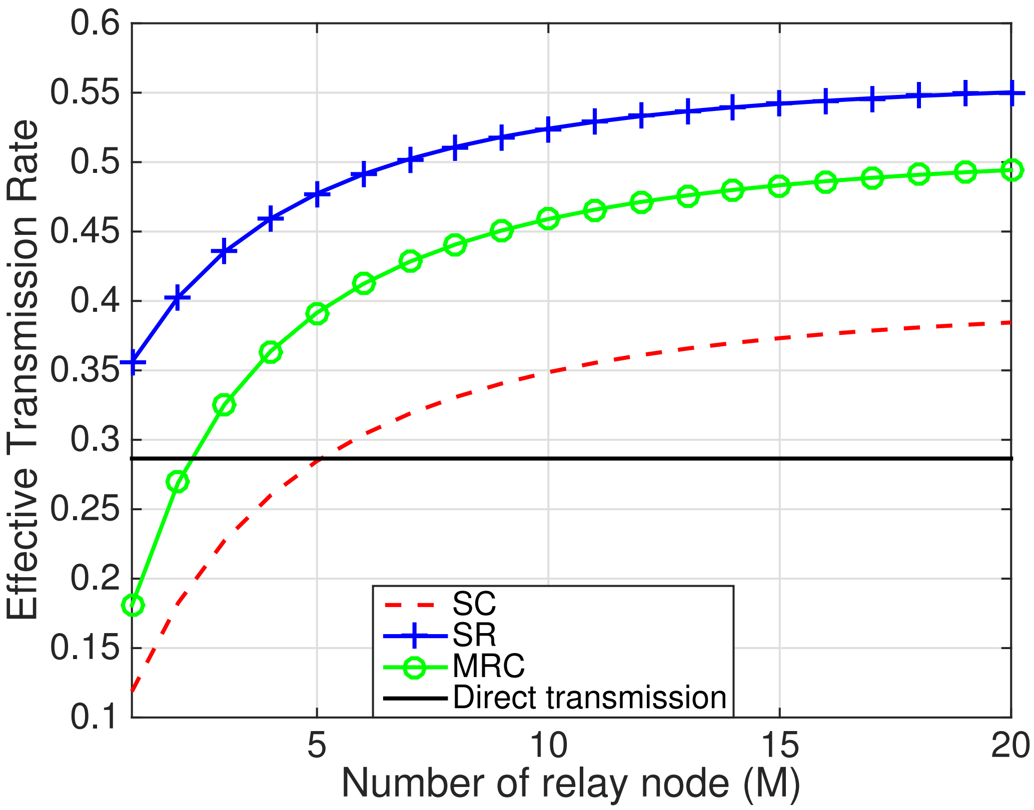



Figure 4.8: Effective transmission rate versus the number of relay nodes $M$. Parameters: R $= 1$, $\zeta = 0.8$, $P_C = -18$ dBm, $\sigma_D = \sigma_R = -10$ dBm, $d_0 = 5$ m, $d_1 = 1$ m, $P_0 = 10$ dBm, $\lambda_i = 1$ with $i = \{0, 1, 2\}$, $\beta = 0.5$, and $L = 1000$.

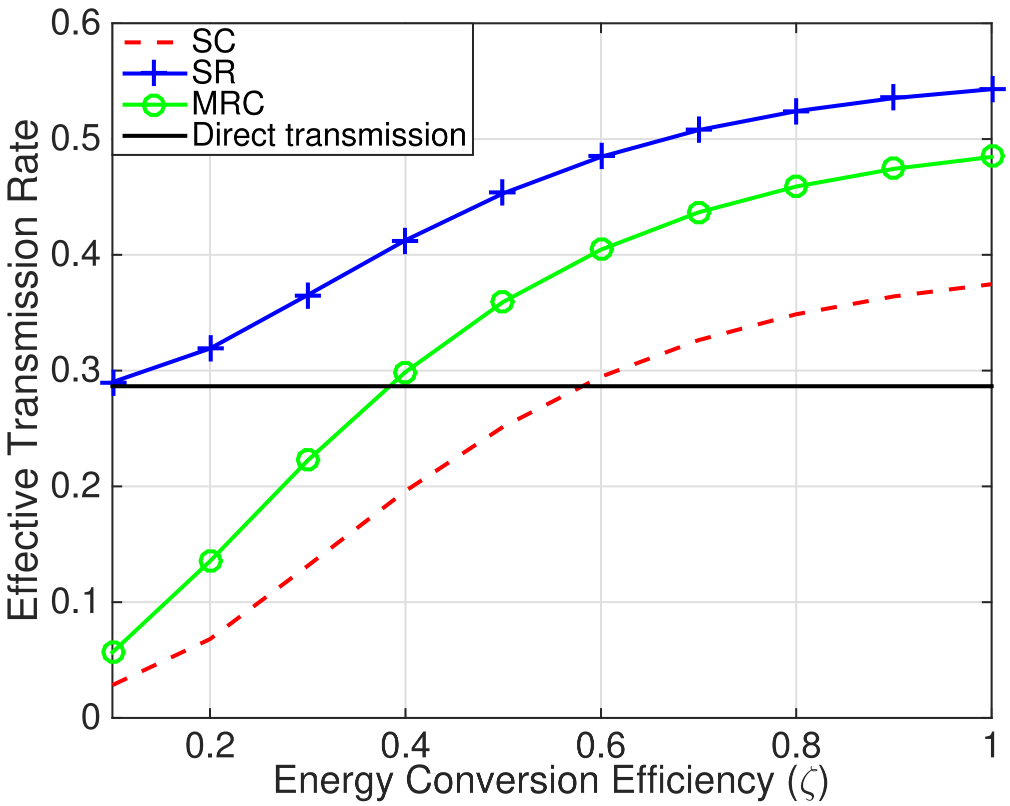



Figure 4.9: Effective transmission rate versus RF to DC conversion efficiency $\zeta$ Parameters: R = 1, $P_C = -18$ dBm, $\sigma_D = \sigma_R = -10$ dBm, $d_0 = 5$ m, $d_1 = 1$ m, $M = 10$, $P_0 = 10$ dBm, $\beta = 0.5$, and $L = 1000$.

# CHAPTER 5

# A Clustering-Based Multihop Relaying Approach for Energy Harvesting Sensor Networks

In this work, we propose a clustering-based multihop relaying with the partial relay selection (PRS) scheme for an energy harvesting (EH) relaying network and analyze the performance in the framework of the decode-and-forward (DF) relaying and adaptive power splitting (APS) protocol over symmetric and asymmetric fading channel models. In particular, we analyze the system performance in terms of the outage probability, effective transmission rate, and throughput. Through extensive numerical analysis, we show that the proposed scheme can substantially outperform the conventional multihop relaying without clustering as well as direct transmission, which suggests that the proposed scheme can be used to extend the network coverage without any extra energy from the network. We also demonstrate that the proposed scheme can compensate for the performance loss due to poor RF-to-DC conversion efficiency as well as path loss by exploiting the gain associated with multihop relaying as well as the diversity gain achieved through the PRS scheme. Moreover, we investigate the relationship between the total number of relay nodes in the network as well as the number of hops, and show that there is an optimal number of hops that can maximize the throughput for a given transmission power of the source. The effect of the asymmetric channels in our clustering-based multihop relaying is also investigated and it is revealed that the existence of Rician fading will help improve the throughput at the destination side, rather than the source side, as opposed to the conventional multihop relaying scenarios without clustering.

## 5.1 Introduction

For severely energy constrained wireless networks such as mobile *ad hoc* wireless networks and wireless sensor networks, multihop transmission is a viable option to overcome wireless impairments and efficiently enhance network coverage. In the multihop relaying, the communication between the source and destination is established with the help of intermediate nodes that relay the information of the source to the destination [77]. For the energy constrained relay nodes, relaying the information of the source could be subject to severe energy limitation, which may considerably affect the lifetime of their own network. A radio-frequency (RF) energy harvesting (EH) technique can be a viable option to prolong the lifetime of such energy-constrained wireless networks [3]; the relay can harvest energy from the information source to assist the source transmission as discussed in [7, 8]. Such a relaying scheme, where the intermediate nodes take part in relaying while exploiting the energy harvested from the signal transmitted by the same source, is analyzed in [12, 13, 58].

In [58], a classical three-node cooperative network with an EH relay node is studied and analyzed in terms of the outage probability for a battery model with dicretized levels and finite capacity. The outage probability and the ergodic capacity for the time switching (TS) EH and power splitting (PS) EH protocols in the framework of amplify-and-forward (AF) and decode-and-forward (DF) protocols are derived in [12] and [13], respectively. In [61], the application of wireless information and power transfer (WIPT) to the cooperative networks with randomly located relays is investigated for the DF framework. In [16], the outage probability expressions for the PS relaying and TS relaying protocols with given PS and TS ratios are derived in the framework of DF relaying and the optimal ratios that maximize the transmission rate are determined. In [17], closed-form expressions for the average SNR, outage probability, and throughput are derived for the TS EH protocol in the framework of DF relaying, and an expression for the optimal TS ratio is obtained. The results are also extended to an opportunistic relay selection (ORS) scheme. In [78], closed form expressions for the outage probability and the network throughput are derived in the framework of adaptive and non adaptive power allocation schemes. Furthermore, a closed-form expression for the optimal relay position which can achieve the minimum outage probability is derived. Reader interested in the conventional two-hop energy harvesting network can find further details in [15, 54, 56] and references therein.

All the above-mentioned studies, however, deal with the dual-hop relaying, which may not be necessarily practical for low-power wireless sensor networks where the communication link between the source and destination may not be supported by a single relay due to severe path loss, shadowing, and fading. For the conventional multihop relaying networks without EH (i.e., the networks with fully powered relays), extensive work has been done, which can be found in [25–30] and references therein. On the other hand, the studies on multihop relaying with WIPT are rather scarce; the performance of multihop relaying with EH relays is evaluated in [31] under the framework of TS and PS EH protocols. Through numerical simulations, it is shown that in order to extend the network coverage, the TS along with AF relaying is a better combination. However, it does not provide any analytical expression for the outage probability or the achievable throughput. Apart from that, the above reference [31] deals with multihop relaying as a wireless network of a cascaded point-to-point links and, as a consequence, the average throughput diminishes as the number of nodes increases toward infinity [32].

Motivated by the above observation, in this work we propose a clustering-based multihop relaying with the partial relay selection (PRS) scheme for the EH relay networks, which can improve the performance of the multihop relaying with WIPT, by combining the benefits of the multihop relaying (i.e., gain achieved by the path loss reduction) and relay selection (i.e., diversity gain) [27, 28, 33]. The main contributions of this work are summarized as follows:

- We derive the closed-form expression for the outage probability, effective transmission rate, and throughput for the proposed scheme in the framework of the DF relaying and adaptive power splitting (APS) protocol, considering both *symmetric* and *asymmetric channel models*. Here, the symmetric channel model refers to the case where all the wireless links are subject to the same fading statistics (e.g., all the links are Rayleigh fading), whereas the asymmetric channel model refers to the case where the different wireless links are subject to different fading (e.g., mixed

Rician-Rayleigh or Rayleigh-Rician fading).

- Based on our analytical results, we compare the effective transmission rate of the proposed scheme and the conventional multihop relaying approach without clustering [31] and show that the proposed scheme can substantially outperform the conventional approach.
- Furthermore, we demonstrate that the proposed scheme can compensate for the performance loss due to poor RF-to-DC conversion efficiency, and could be used to extend the network coverage without any extra energy from the network.
- We study the relationship between the number of the total relay nodes in the network and the number of hops, and reveal that there is an optimal number of hops that can maximize the throughput for a given transmission power of the source.
- We compare the throughput performance of the proposed scheme over various asymmetric fading channels and reveal that the conventional observation that the multihop relaying networks over asymmetric fading channels can achieve maximum throughput in Rician/Rayleigh fading environment [79, 80] (i.e., the links closer to the source are subject to Rician fading and those closer to the destination are subject to Rayleigh fading) does not necessarily hold true in the case of the proposed scheme with relay node clustering.

To the best of our knowledge, an analysis in terms of the outage probability, effective transmission rate, and the throughput of the *clustering-based* multihop relaying with EH relays *under the scenario of WIPT* has not been reported in the literature. A closely related system model is studied in [33], where the throughput of a wireless sensor network with EH nodes in the framework of clustering-based DF relaying is analyzed under the assumption that the EH nodes can harvest energy from the surrounding environment, whereas in this work, EH nodes can harvest energy only through the signal transmitted by the information source.

The remainder of the chapter is organized as follows; In Section 5.2, we describe the system and channel models considered throughout the chapter. In Section 5.3, the closed-form expressions for the outage probability, effective transmission rate, and the throughput for the clustering-based multihop relaying network over symmetric and asymmetric fading environment are derived. In Section 5.4, the numerical results under various scenarios of multihop relaying are presented and the insights gained from them are discussed. Finally, conclusions are given in Section 5.5.

## 5.2 System and Channel Models

### 5.2.1 Multi hop Wireless Sensor Networks

As illustrated in Fig. 5.1, we consider a clustering-based multihop wireless EH sensor network where a single source node $S_0$ and a single destination node $S_K$ are connected through $K-1$ clusters of relays (i.e., $K$-hop relay channel). In each cluster $k \in \{1, 2, \cdots, K-1\}$, the relay nodes are denoted by $S_{k,m}$, where $m \in \{1, 2, \cdots, M_k\}$ represents the node index for each cluster and $M_k$ is the number of the relay nodes in the $k$th cluster. Therefore, the

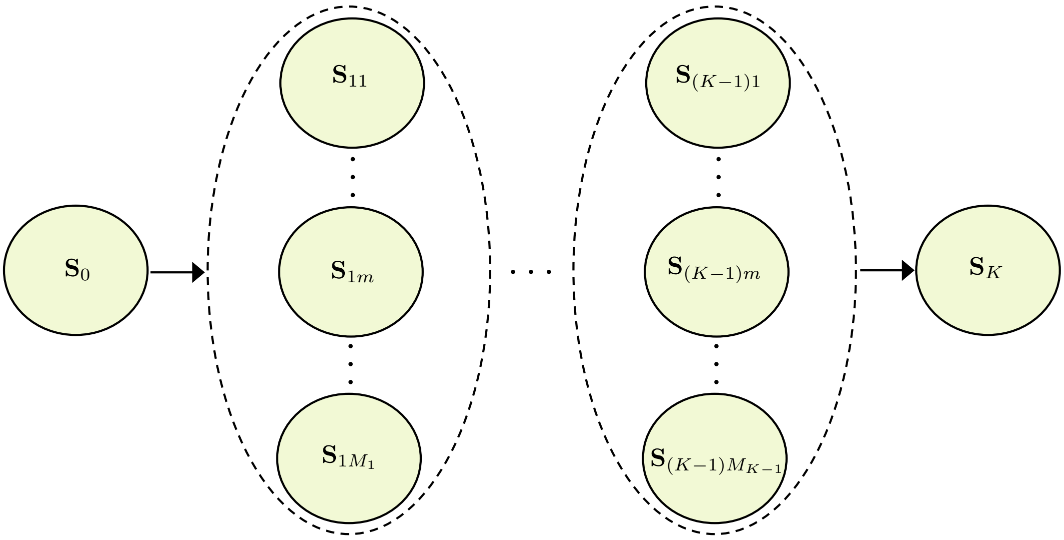



Figure 5.1: Clustering-based multihop relaying network.

total number of relay nodes is given by

$$N = \sum_{k=1}^{K-1} M_k. \tag{5.1}$$

It is assumed that there is no direct link between the source and destination. Therefore, the source communicates with the destination through $K$-hop relaying channel. We assume that the relays are grouped into clusters on the basis of their geographical proximity (or equivalently average SNR) as discussed in [27, 28, 64, 70]. By this assumption, the nodes in the $k$th hop and those in the $k$th cluster become equivalent. We thus use the terms the *kth hop* and the *kth cluster* interchangeably in what follows. However, it should be noted that if the number of hops is $K$, then that of the clusters is $K-1$.

It is considered that there is no cluster head and thus all the relays in a cluster are treated equally [27, 28]. Note that when $M_1 = \cdots = M_{K-1} = 1$, the proposed model is equivalent to the conventional multihop relaying without clustering where the message is sent over a predetermined route [31, 77].

### 5.2.2 Channel and Access Models

We consider that each hop takes $T$ seconds to transmit the signal as in [31] and all the physical links between the nodes are frequency flat block fading, where the fading coefficient remains constant during one block time, i.e., for $T$ seconds, but changes independently to the next. If a link experiences Rayleigh fading, then the channel gain $h_{k,m} \in \mathbb{R}$ experienced by the $m$th relay in the $k$th cluster, follows a random variable (RV) with exponential distribution [63]. The corresponding probability density function (pdf) of $h = h_{k,m}$ is expressed as

$$p_h(x) = \frac{1}{\lambda_{k,m}} \exp\left(-\frac{x}{\lambda_{k,m}}\right) \tag{5.2}$$

where $\lambda_{k,m} = \mathbb{E}(h_{k,m})$, with $\mathbb{E}(\cdot)$ representing an expectation operation. Since the clustering algorithm based on the geographical proximity of nodes is employed [64, 70], this system model ensures that all the links in one hop have the same average channel power. As a result, we have $\lambda_{k,m} = \lambda_k$ for $\forall m \in \{1,\ldots,M_k\}$. If a link experiences Rician fading, then the pdf of $h = h_{k,m}$ can be expressed as

$$p_h(x) = \frac{2(V+1)e^{-V}x}{\lambda_{k,m}} e^{-\frac{(V+1)x^2}{\lambda_{k,m}}} I_0\left(2x\sqrt{\frac{V(V+1)}{\lambda_{k,m}}}\right) \tag{5.3}$$

where $V$ is the Rician factor defined as the ratio of the powers of the line-of-sight (LoS) component to the scattered components, and $I_0(\cdot)$ is the zeroth order modified Bessel function of the first kind [79].

Furthermore, we assume that the noise level of the additive white Gaussian noise (AWGN) observed by all the relay nodes in the $k$th cluster is identical with its average power $\sigma_k^2$.

Finally, all the nodes are assumed to be half duplex and equipped with only a single antenna as in [12, 13, 16, 17, 58, 61, 78]. In order to avoid the inter-relay interference and to ensure the orthogonality among transmitting nodes, a time-division multiple-access (TDMA) scheme with $K$ time slots, each consisting of $T$ seconds, is considered for simplicity.

### 5.2.3 Relay Selection Scheme

For the relay selection within each cluster $k$, we consider the partial relay selection (PRS) scheme where a relay that provides the best channel gain between the transmitter and the receiving cluster is selected from a set of $M_k$ relays [51]. With the distributed relay selection algorithm proposed in [50], selection can be done locally, i.e., in a distributive fashion. The channel gain of the relay selected at the $k$th cluster can be found as

$$h_k^* \triangleq \max_{m\in\{1,\ldots,M_k\}} h_{k,m}. \tag{5.4}$$

Throughout this work, we assume that only the receiver side has full channel state information (CSI), which can be obtained through the pilot symbols [81].

### 5.2.4 Battery Model

We assume that the relay node is equipped with a discrete-level energy battery of size $E_\mathrm{B}$, which is capable of holding energy for an immediate use only, due to leakage. Thus, all the harvested energy should be used in the same information block, and such a system model is also known as a *harvest-and-use (HU) architecture* [12, 13, 15–17, 31, 41, 54–56]. We also assume that the battery is discretized into $L$ energy levels as $\epsilon^{(\ell)} \triangleq \ell E_\mathrm{B}/L$ with $\ell \in \{1,\ldots,L\}$, and the battery is said to be in the state $s_\ell$ when its stored energy is equal to $\epsilon^{(\ell)}$. Apparently, for sufficiently large energy levels, the discrete battery model can closely approximate a continuous battery model [58, 71, 72].

### 5.2.5 APS Protocol

For the information relaying with EH, the adaptive power splitting (APS) protocol proposed in [61, 82] is employed, where the selected EH relay at the $k$th cluster will dynamically split the received signal into the two streams with power splitting ratio $\alpha_k$ and $(1-\alpha_k)$ for information decoding and EH, respectively. For a given $\alpha_k$, the energy harvested by the selected relay in the $k$th cluster can be expressed as

$$E_k = \frac{\zeta(1-\alpha_k)P_{k-1}h_k^*}{d_k^\eta} \tag{5.5}$$

where $P_{k-1}$ is the transmission power of the transmitting node in the previous cluster, $d_k$ is the distance between the $(k-1)$th and $k$th clusters, $\eta$ is the path loss exponent, $\zeta \in (0,1]$ is the RF-to-DC conversion efficiency, and $h_k^*$ is the channel gain of the selected relay in the $k$th cluster defined in (5.4). Note that $P_0$ corresponds to the transmission power of the source.

By definition, the battery energy harvested by each relay is discrete and finite. Therefore, the energy of the selected relay can be expressed as

$$\epsilon_k = \max_{\ell \in \{1,\ldots,L\}} \epsilon^{(\ell)} \quad \text{where} \quad \epsilon^{(\ell)} \leq E_k. \tag{5.6}$$

The transmission power of the relay selected in the $k$th cluster can be expressed as

$$P_k = \max\left(0, \frac{\epsilon_k - E_\mathrm{C}}{T}\right) \tag{5.7}$$

where $E_\mathrm{C}$ is the required energy that should be consumed by the receiver circuit of the selected relay for information decoding and re-encoding. For the APS scheme, the channel capacity corresponding to the $k$th hop, i.e., the link from the $(k-1)$th cluster to the $k$th cluster, can be expressed as [31]

$$C_k = \log_2\left(1 + \alpha_k \frac{P_{k-1}h_k^*}{\sigma_k^2 d_k^\eta}\right)\mathbf{1}_{\epsilon_k > E_\mathrm{C}} \tag{5.8}$$

where $\sigma_k^2$ is the average power of the corresponding AWGN and $\mathbf{1}_\mathsf{E}$ is the indicator function that returns 1 when the event $\mathsf{E}$ occurs and returns 0 otherwise [76]. The indicator function in (5.8) represents the circuit power constraint on the $k$th relay for its information decoding. Note that $C_K$ is the capacity observed by the destination node $S_K$. Since we consider the DF relaying scheme for information relaying, the relay needs to successfully decode the received signal before further processing. Hence, the power splitting ratio $\alpha_k$ for a given transmission rate $\mathsf{R}$ can be calculated as

$$\alpha_k = \min\left(1, \frac{2^\mathsf{R} - 1}{h_k^* \gamma_k}\right), \tag{5.9}$$

where

$$\gamma_k = \frac{P_{k-1}}{\sigma_k^2 d_k^\eta}. \tag{5.10}$$

### 5.2.6 Outage Probability

From (5.5) and (5.9), it can be observed that when the selected relay cannot decode the received signal successfully (i.e., $\alpha_k \geq 1$), it will not harvest any energy due to the assumption of the HU architecture that it cannot retain the harvested energy for the later use. When $\alpha_k < 1$, then the relay first feeds the $(1-\alpha_k)$ portion of the received signal to the EH unit, and if the harvested energy satisfies $\epsilon_k > E_\mathrm{C}$ (i.e., the harvested energy is higher than that required for the information decoding), then the information decoding unit utilizes the harvested energy to decode the received signal. Therefore, the outage at the destination will be caused by either of the following events: 1) any of the previous hop is in outage, i.e., $\epsilon_k < E_\mathrm{C}$ with $\forall k \in \{1, \ldots, K-1\}$, or 2) none of the previous hops is in outage but the destination is in outage. Therefore, the outage event can be expressed as

$$P_\mathrm{out} = 1 - \Pr\left\{\left(\cap_{k=1}^{K-1} (\epsilon_k > E_\mathrm{C})\right) \cap (C_K \geq \mathsf{R})\right\}. \tag{5.11}$$

From (5.11), it can be observed that the outage at the destination depends on all the previous hops and this generally leads to difficulty in precise mathematical analysis. However, the discrete-level battery model introduced in Section 5.2.4 would make the subsequent analysis mathematically tractable. For the APS protocol, the channel gain required to harvest $\epsilon^{(\ell)} = \ell E_\mathrm{B}/L$ units of energy for the information relaying at the relay in the $k$th cluster, or equivalently, the channel gain to reach the state $s_\ell$ in the $k$th hop, can be given by

$$\Gamma_k(\ell) = \left(2^\mathsf{R} - 1\right)\frac{\sigma_k^2 d_k^\eta}{P_{k-1}} + \frac{(\epsilon^{(\ell)} + E_\mathrm{C}) d_k^\eta}{\zeta P_{k-1}}, \tag{5.12}$$

where the first term represents the amount of channel gain required to ensure the successful decoding of the received signal at the relay in the $k$th hop, and the second term denotes the amount of channel gain required to harvest $\epsilon^{(\ell)} + E_\mathrm{C}$ units of energy by the relay, with $\epsilon^{(\ell)}$ representing the amount of the harvested energy left after information decoding, i.e., the amount of energy that will be used for the information relaying to the $(k+1)$th cluster.

### 5.2.7 Effective Transmission Rate and Throughput

For a fixed transmission rate $\mathsf{R}$ and outage probability $P_\mathrm{out}$, the effective transmission rate can be defined as [55]

$$\Psi = \mathsf{R}\{1 - P_\mathrm{out}\}. \tag{5.13}$$

The network throughput indicates the bandwidth efficiency of the network which is one of the important performance metrics of the multihop relaying networks [28], which can be defined in the TDMA framework as [83]

$$\tau = \frac{\Psi}{K}. \tag{5.14}$$

### 5.2.8 Remark

Based on the above system, network, and channel models, we are particularly interested in the following aspects:

- The performance of the network (in terms of effective transmission rate and throughput) should depend on the number of relays as well as the number of clusters. Then, for a given number of total relay nodes $N$ in the network, how we should allocate them among different clusters?

- Increasing the number of hops $K$ should help reducing path loss, but it also reduces the bandwidth efficiency due to the assumption of TDMA. Thus, is it reasonable to increase $K$ from the viewpoint of network throughput?

These issues will be investigated in Section 5.4 through numerical analysis.

## 5.3 Performance Analysis

We analyze the performance of the proposed system over various fading models. We start with the most general scenario in our framework, i.e., all the links follow Rician fading. The results for other channel settings can be obtained directly from this result.

We consider that all the relay nodes are EH nodes and take part in the relaying with harvested energy. The corresponding channel gains are modeled as random variables as described in Section 5.2.2. For simplicity of our subsequent analysis, we assume that $\{h_{k,m}\}$ are independent and identically distributed (iid) with its pdf given by (5.3). Consequently, we have $\lambda_{k,m} = \mathbb{E}(h_{k,m}) = \lambda$ for all $k \in \{1, \ldots, K\}$ and $m \in \{1, 2, \cdots, M_k\}$.

### 5.3.1 Probability Expressions for Harvested Energy

We are interested in the probability that the battery of the relay selected in the $k$th cluster reaches the energy level of $\ell \in \{1, 2, \cdots, L\}$ after information decoding and re-encoding (i.e., the amount of energy left for information transmission to the next cluster) and we denote this by $q_k(\ell)$. In our system model, the only node that always transmits with constant power $P_0$ is the source, i.e., the first link in the multihop relay channel. The transmission power of the relay nodes in the subsequent clusters is modeled as a random variable by nature. Upon derivation of a theoretical expression for $q_k(\ell)$, these two cases, i.e., whether the information is transmitted by the source ($k = 1$) or relay ($1 < k < K$), will be separately dealt with in what follows.

▷ *Energy Harvested at the First Hop:*

Based on the PRS scheme where the relay with the best channel condition from the source is chosen according to (5.4), the probability of harvesting $\epsilon^{(\ell)}$ units of energy for information relaying (i.e., the amount of harvested energy left after the information decoding) with $\ell \in \{1, \ldots, L\}$ can be calculated by the following two steps.

▷ *Case 1: Battery being partially charged:*

When the energy harvested at the relay is greater than or equal to $\epsilon^{(1)}$ and less than $\epsilon^{(L)}$, the battery is said to be *partially charged*. The corresponding probability $q_k(\ell)$ in the first hop ($k = 1$) can be expressed as

$$\begin{aligned} q_1(\ell) &= \Pr\{\Gamma_1(\ell) \le h_1^* < \Gamma_1(\ell+1)\} \\ &= \prod_{m=1}^{M_1} F_{h_{1,m}}(\Gamma_1(\ell+1)) - \prod_{m=1}^{M_1} F_{h_{1,m}}(\Gamma_1(\ell)) \\ &= F_h^{M_1}(\Gamma_1(\ell+1)) - F_h^{M_1}(\Gamma_1(\ell)) \end{aligned} \tag{5.15}$$

where $M_1$ is the number of rely nodes in the first cluster, $\Gamma_1(\ell)$ is the required channel gain derived in (5.12), and the expression $F_X(x_0) = \Pr(X < x_0)$ is the cumulative distribution function (cdf) of the RV $X$. Since $\{h_{k,m}\}$ are iid with its pdf given by (5.3), for $h = h_{k,m}$ we have

$$F_h(x) = 1 - Q\left(\sqrt{2V}, \sqrt{(V+1)\frac{2x}{\lambda}}\right), \tag{5.16}$$

where $V$ is the Rician factor and $Q(\cdot,\cdot)$ is the generalized first order Marcum-$Q$ function [63].

▷ *Case 2: Battery being fully charged:*

When the energy harvested by the relay node is greater than or equal to $\epsilon^{(L)}$, the battery is considered to be *fully charged*. The corresponding probability can be expressed as

$$\begin{aligned} q_1(L) &= \Pr\{h_1^* \geq \Gamma_1(L)\} \\ &= 1 - F_h^{M_1}(\Gamma_1(L)). \end{aligned} \tag{5.17}$$

▷ *Energy Harvested at the $k$th Hop ($1 < k < K$):*

Except for the relay in the first hop, all the other relays harvest energy through the signal transmitted by the preceding EH relay with its own discrete-level battery. Hence, the channel gain required to harvest $\epsilon^{(\ell)}$ units of energy for the information relaying of the selected node in the $k$th cluster, provided that the transmitting node in the previous hop (i.e., $(k-1)$th hop) has the harvested energy of $\epsilon^{(j)}$ units with $j \in \{1, \ldots, L\}$, can be calculated as

$$\Gamma_k(\ell \mid j) = \left(2^{\mathsf{R}} - 1\right) \frac{\sigma_k^2 d_k^\eta T}{\epsilon^{(j)}} + \frac{(\epsilon^{(\ell)} + E_{\mathrm{C}}) d_k^\eta T}{\zeta \epsilon^{(j)}}. \tag{5.18}$$

Similar to the case of $k = 1$, we derive $q_k(\ell)$, i.e., the probability that the energy $\epsilon^{(\ell)}$ is left for the selected relay in the $k$th cluster, in the following two steps.

▷ *Case 1: Battery being partially charged:*

When the energy harvested at the relay is greater than or equal to $\epsilon^{(1)}$ and less than $\epsilon^{(L)}$ (partially charged), the corresponding probability $q_k(\ell)$ can be written as

$$\begin{aligned} q_k(\ell) = \sum_{j=1}^{L} & q_{k-1}(j) \\ & \times \left[F_h^{M_k}(\Gamma_k(\ell+1 \mid j)) - F_h^{M_k}(\Gamma_k(\ell \mid j))\right]. \end{aligned} \tag{5.19}$$

▷ *Case 2: Battery being fully charged:*

When the energy harvested by the relay is greater than or equal to $\epsilon^{(L)}$ (fully charged), the corresponding probability can be expressed as

$$q_k(L) = \sum_{j=1}^{L} q_{k-1}(j) \left[1 - F_h^{M_k}(\Gamma_k(L \mid j))\right]. \tag{5.20}$$

### 5.3.2 Outage Probability Expressions

Whenever the destination fails to receive or decode the signal transmitted by the source, the system is said to be in outage [65]. The channel gain required to successfully decode the signal at the $k$th hop, provided that the power of the $(k-1)$th hop is given by $P_{k-1} = \frac{\epsilon^{(\ell)}}{T}$ with $\ell \in \{1, \ldots, L\}$, is

$$\Gamma_K(\ell) = \left(2^{\mathsf{R}} - 1\right) \frac{\sigma_K^2 d_K^\eta T}{\epsilon^{(\ell)}}. \tag{5.21}$$

With the help of (5.11), the outage probability for the proposed scheme with transmission rate R can be expressed as

$$\begin{aligned} P_{\text{out}} &= 1 - \sum_{\ell=1}^{L} q_{K-1}(\ell)\{1 - F_h(\Gamma_K(\ell))\} \\ &= 1 - \sum_{\ell=1}^{L} q_{K-1}(\ell) Q\left(\sqrt{2V}, \sqrt{(V+1)\frac{2}{\lambda}\Gamma_K(\ell)}\right), \end{aligned} \tag{5.22}$$

where $q_k(\ell)$ is derived in (5.15) and (5.17) for $k = 1$ and in (5.19), and (5.20) for $k > 1$.

The effective transmission rate and throughput can be obtained from (5.13) and (5.14), respectively, based on the outage probability expression developed above.

### 5.3.3 Other Fading Scenarios

▷ *Rayleigh Fading:*

If all the wireless links experience Rayleigh fading, from (5.2) and (5.3), it can be readily observed that the results are obtained by substituting $V = 0$ for the Rician cases, i.e., with $F_h(x)$ of (5.16) replaced by

$$F_h(x) = 1 - \exp\left(-\frac{x}{\lambda}\right). \tag{5.23}$$

The corresponding outage probability is given by

$$P_{\text{out}} = 1 - \sum_{\ell=1}^{L} q_{K-1}(\ell) \exp\left(-\frac{1}{\lambda}\Gamma_K(\ell)\right). \tag{5.24}$$

Note that $q_k(\ell)$ can be found in the same manner as that of the Rician case again with $F_h(x)$ of (5.16) replaced by (5.23).

▷ *Asymmetric Fading Channels:*

The previous results can be extended to the cases where the channel is composed of mixture of Rayleigh and Rician fading with slight modification by adopting $F_h(x)$ of (5.16) when the channel is Rician and that of (5.23) when the channel is Rayleigh.

For example, if the first $K'$ hops (with $K' < K$) are subject to Rayleigh fading and the remaining $K - K'$ hops are subject to the Rician fading, then since the last hop to destination is Rician, the outage probability can be expressed as (5.22) with $\Gamma_K(\ell)$ given in (5.21), but $q_k(\ell)$ should be calculated according to the fading statistic of each link $F_h(x)$:

$$F_h(x) = \begin{cases} 1 - \exp(-x/\lambda), \\ \qquad \text{for } \ k \in \{1, 2, \cdots, K'\}, \\ 1 - Q\left(\sqrt{2V}, \sqrt{(V+1)\frac{2x}{\lambda}}\right), \\ \qquad \text{for } \ k \in \{K'+1, 2, \cdots, K\}. \end{cases} \tag{5.25}$$

## 5.4 Numerical Results

In this section, based on the theoretical analysis carried out in the previous section, we present several numerical results and discuss the insights gained from them. The outage probability, effective transmission rate, and throughput are used as our performance

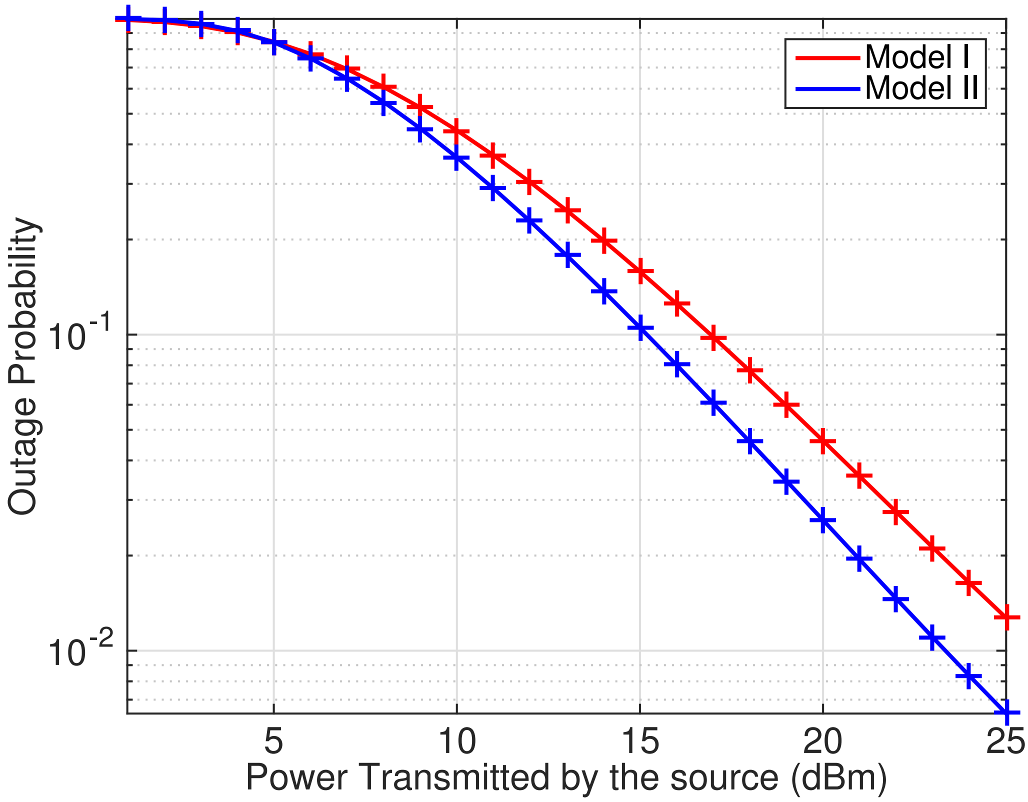



Figure 5.2: Outage probability versus power transmitted by the source $P_0$ (solid lines: theoretical analysis, discrete points: simulation). Parameters: $\mathsf{R} = 1$, $\zeta = 0.8$, $P_C = \frac{P_0}{100}$, $\sigma_k^2 = -10$ dBm, $\lambda_k = 1$, $d_{SD} = 5$ m, $d_k = \frac{d_{SD}}{K}$, $K = 5$, $M = 2$, $V = 10$, and $L = 1000$.

measures. The accuracy of the developed analytical results are also verified by Monte-Carlo simulations.

We initially consider a homogeneous network case consisting of $(K-1)$ clusters, each of which has the same number of nodes denoted by $M$, i.e., $M = M_1 = M_2 = \cdots = M_{K-1} = N/(K-1)$. Also, unless otherwise stated, the following parameters are chosen as our baseline example scenario: The distance between source to distance is $d_{SD} = 5$ m [61] and the clusters are located with equal distance, i.e., $d_k = d_{SD}/K$ for $\forall k \in \{1, 2, \cdots, K\}$. Furthermore, we normalize the fading coefficient such that $\lambda = 1$, the path-loss exponent is $\eta = 3$, and in the case of Rician fading, Rician factor is chosen as $V = 10$. The transmission power of the source is $P_0$ dBm, the circuit power is $P_C = \frac{P_0}{100}$ (i.e., 1% of the transmission power of the source), the noise power is $\sigma_k^2 = -10$ dBm for $\forall k \in \{1, 2, \cdots, K\}$, and the RF-to-DC conversion efficiency is $\zeta = 0.8$. The transmission rate is $\mathsf{R} = 1$ and the number of the battery levels is $L = 1000$.

We also consider the following four models for fading:

- **Model I:** All the wireless links are subject to Rayleigh fading.
- **Model II:** Only the first link, i.e., $S_0 \to S_1$, is subject to Rician fading and the remaining links are subject to Rayleigh fading.
- **Model III:** The first two links, i.e., $S_i \to S_j$ with $(i, j) \in \{(0, 1), (1, 2)\}$ are subject to

Rician fading and the remaining links are subject to Rayleigh fading.

- **Model IV:** Only the last link, i.e., $S_{K-1} \rightarrow S_K$ is subject to the Rician fading and the rest of the links are subject to Rayleigh fading.

In most part of this section, we assume that all the channels are subject to Rayleigh fading (i.e., model I) as an example of the severe environment. The mixed fading cases are explored only in Section 5.4.7 (except for comparison of theoretical and simulation results in the next subsection).

### 5.4.1 Comparison of Theoretical and Simulation Results

We first compare our theoretical derivation with the simulation results. Fig. 5.2 compares the outage probability based on both the theoretical analysis (indicated by the solid lines) and the corresponding simulation (discrete points) over channel models I and II, with two relay node case ($M = 2$) and $K = 5$ hops. The transmission power of the source $P_0$ is chosen as our parameter. From the results, it can be observed that the theoretically derived outage probabilities are in excellent agreement with the simulation results, irrespective of the source power $P_0$ and channel model, validating our theoretical analysis. For the rest of this section, we only plot the numerical results based on the theoretical analysis.

### 5.4.2 Conventional versus Proposed Schemes

Fig. 5.3 shows the relationship between the effective transmission rate and the number of hops $K$ for various cases in terms of the number of relay nodes per cluster $M$. These results are obtained over Rayleigh fading environment (model I). The case with $M = 1$ represents the effective transmission rate of the conventional approach (i.e., without clustering). From the results, it can be observed that the proposed approach outperforms the conventional one irrespective of the number of hops $K$. We can also observe that due to the attenuation of channel associated with path loss, the system performance with multihop relaying improves as the number of hops increases (i.e., gain in terms of path loss). Furthermore, we can also observe that as the number of relay nodes in each cluster increases, the performance of the proposed scheme also improves since the proposed clustering scheme can exploit the spatial diversity gain as well with the help of PRS scheme.

### 5.4.3 Effect of RF-to-DC Conversion Efficiency

The relationship between the effective transmission rate and the RF-to-DC conversion efficiency $\zeta$ is shown in Fig. 5.4 for various cases in terms of the number of relay nodes per cluster, where the number of hops is chosen as $K = 5$. These results are obtained over Rayleigh fading environment (model I). It can be observed that while the effective transmission rate of the conventional network is very sensitive to the value of $\zeta$, the proposed scheme can cope with the effects of poor $\zeta$ by the diversity gain, which makes the proposed scheme very attractive for practical multihop sensor network scenarios operated with low energy conversion efficiency.

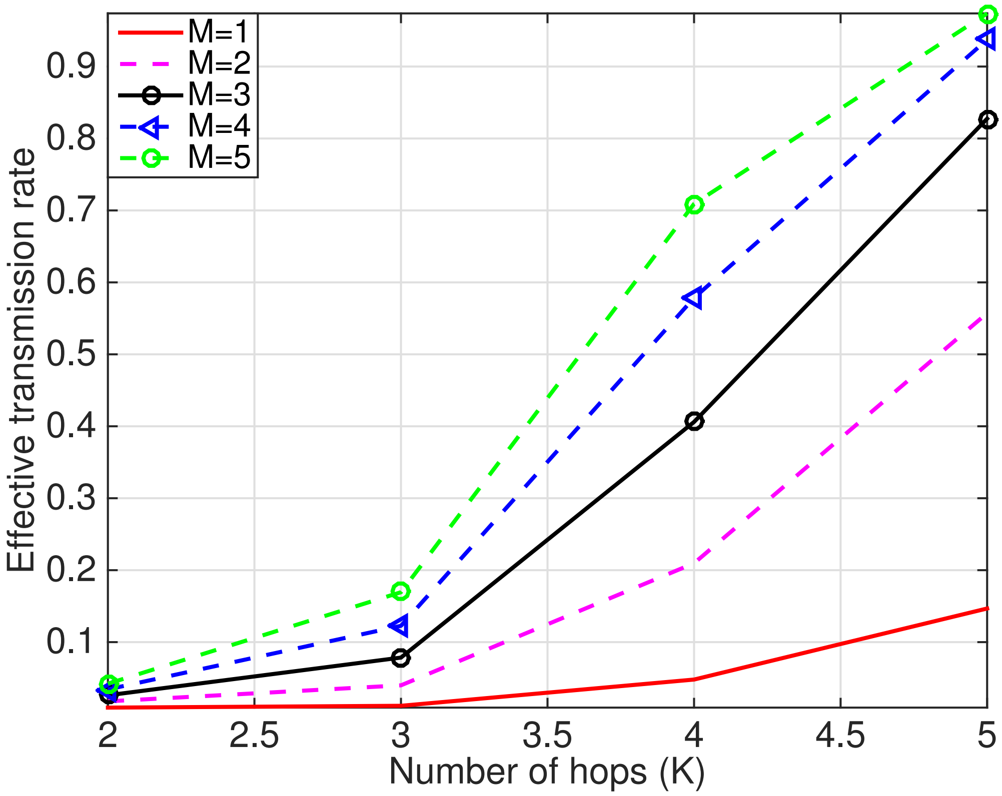



Figure 5.3: Effective transmission rate versus the number of hops with several cases of relay nodes per cluster $M$. Parameters: R = 1, $\zeta = 0.8$, $P_0 = 10$ dBm, $P_C = \frac{P_0}{100}$, $\sigma_k^2 = -10$ dBm, $\lambda_k = 1$, $d_{SD} = 5$ m, $d_k = \frac{d_{SD}}{K}$, and $L = 1000$.

### 5.4.4 Resource Allocation

From the above analysis, we can conclude that the performance of the proposed scheme is dominated by the number of relays present in each cluster, which gives rise to the following issue stated in Section 5.2.8: For a given number of total relay nodes $N$ in the network, what is the best strategy to distribute them among different clusters?

In order to investigate this issue, in Fig. 5.5 the effective transmission rate of the network is compared for the four different kinds of topologies listed in Table 5.1, where $N = 8$ relays are distributed among four different clusters with distinctive patterns. These results are obtained over Rayleigh fading environment (model I).

We observe from Fig. 5.5 that the effective transmission rate achieved with topology 1 is maximum among the four topologies compared, followed by 2, 4, and 3. From these

Table 5.1: Network topologies investigated ($K = 5$).

| Network ID | Network Topologies $[M_1\, M_2\, M_3\, M_4]$ |
|---|---|
| 1 | [2 2 2 2] |
| 2 | [3 2 2 1] |
| 3 | [1 2 2 3] |
| 4 | [3 3 1 1] |

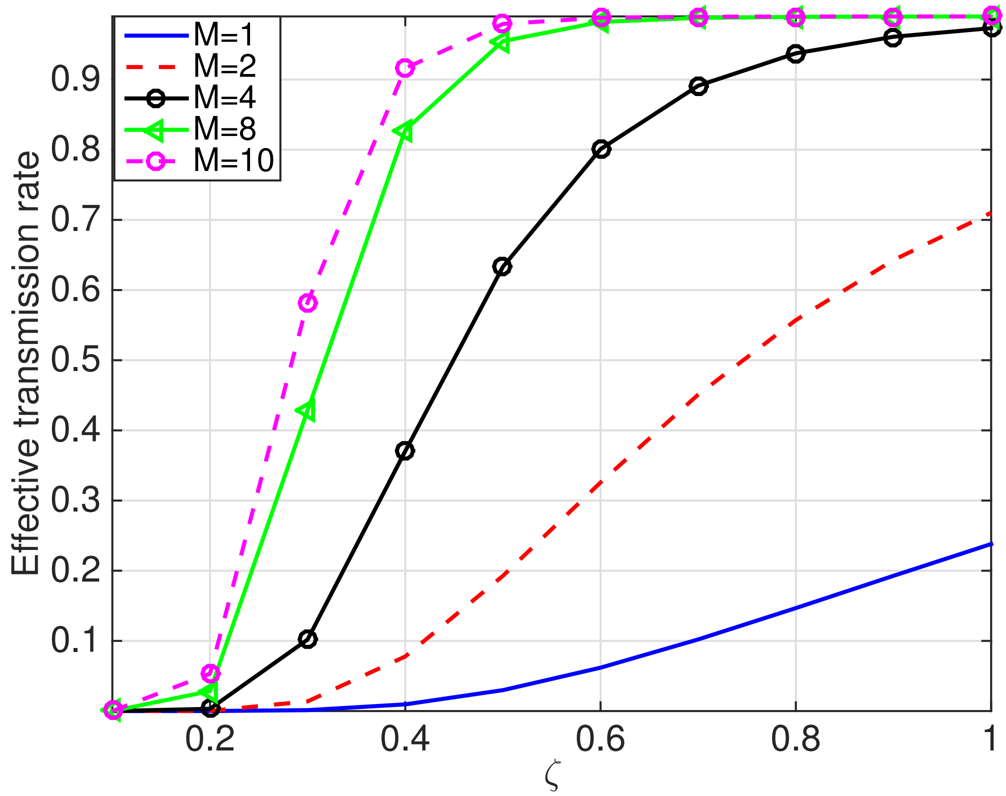



Figure 5.4: Effective transmission rate versus RF to DC conversion efficiency. Parameters: R = 1, $P_0 = 10$ dBm, $P_C = \frac{P_0}{100}$, $\zeta = 0.8$, $\sigma_k^2 = -10$ dBm, $\lambda_k = 1$, $d_{SD} = 5$ m, $K = 5$, $d_k = \frac{d_{SD}}{K}$, and $L = 1000$.

results, it can be concluded that in the energy harvesting multihop networks, the best performance can be achieved when all the clusters enjoy the same level of diversity (i.e, the result for network 1, where each cluster has the equal number of relay nodes).

Furthermore, if it would not be possible to assign the relay nodes equally to each cluster, the cluster closer to the source should be provided with a larger number of relay nodes instead of those closer to the destination. This stems from the fact that in the proposed energy harvesting network, the receiver performance strongly depends on the transmission power, and the transmit power of the source node is only the energy source that can be used for forwarding the information toward the destination through multiple relays.

### 5.4.5 Throughput Improvement by Path Loss Reduction

From the numerical results analyzed so far, it is obvious that by increasing the number of hops, gain due to the reduction of path loss in each hop can be achieved, but at the same time the bandwidth efficiency is reduced by a factor of $1/K$ as indicated by (5.14). Thus, as stated in Section 5.2.8, it may be interesting to investigate if the use of multihop relaying can be justified from the perspective of bandwidth efficiency.

Fig. 5.6 shows the throughput as a function of the transmission power of the source $P_0$ under the assumption of the homogeneous network of $M = 10$ but with various numbers of hops $K$. These results are obtained over Rayleigh fading environment (model

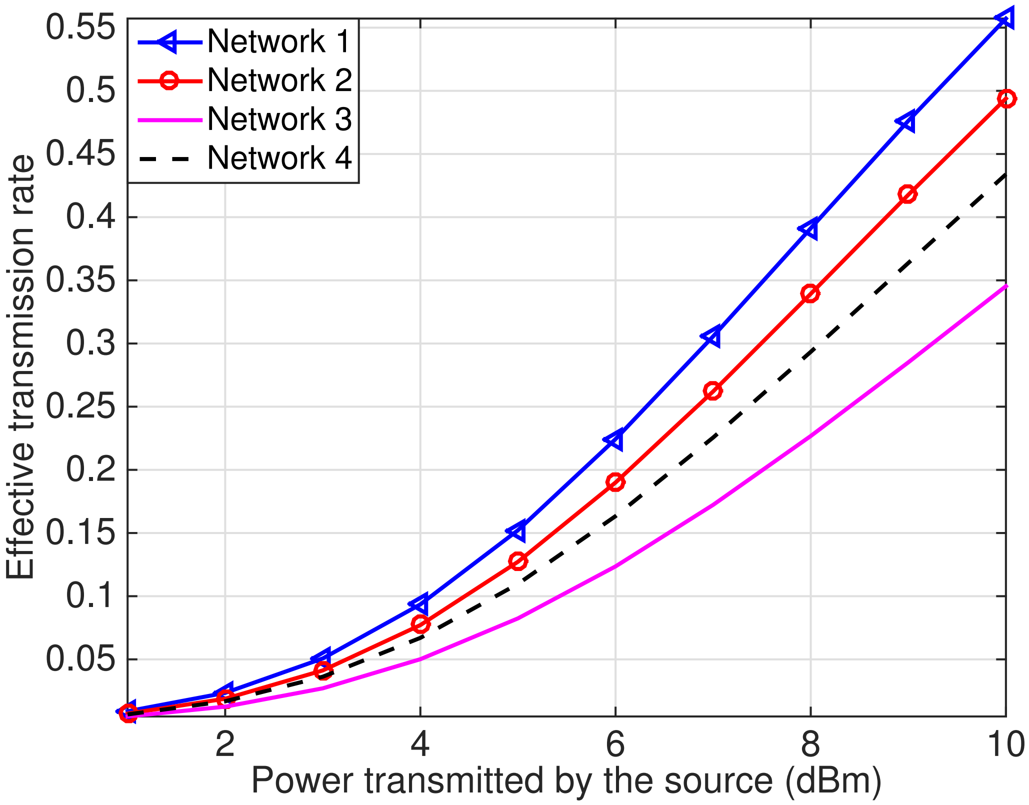



Figure 5.5: Effective transmission rate versus power transmitted by the source with the four different network topologies. Parameters: R = 1, $\zeta = 0.8$, $P_0 = 10$ dBm, $P_C = \frac{P_0}{100}$, $K = 5$, $\sigma_k^2 = -10$ dBm, $\lambda_k = 1$, $d_{SD} = 5$ m, $d_k = \frac{d_{SD}}{K}$, and $L = 1000$.

I). From the results, it can be observed that the number of hops that can achieve the maximum throughput differs depending on the transmission power, and in the case of low $P_0$, larger number of $K$ results in better throughput. However, since the achievable throughput in this case is reduced by a factor of $1/K$, the direct transmission (i.e., $K = 1$) eventually outperforms the others as $P_0$ increases under the considered parameter setting. Nevertheless, it can be concluded that when the transmission power is limited, which is the case with typical sensor networks, larger gain due to the path loss reduction achieved by multihop can effectively increase the throughput.

### 5.4.6 Throughput Improvement versus Total Number of Relay Nodes

In Section 5.4.4, we have observed that for a given number of the total relay nodes $N$, the effective transmission rate can be improved if the nodes are distributed equally for a given number of clusters $K - 1$. In what follows, we investigate how the throughput can be improved by increasing $N$ for a different number of hops $K$. To this end, for a given pair of $N$ and $K$, we equally allocate the relay nodes among all the clusters (i.e., the homogeneous case) whenever possible. For a fair comparison, if any relay nodes are left after this equal allocation process, the remaining relay nodes are assigned to the first cluster following the observation in Section 5.4.4.

Fig. 5.7 shows the relationship between the throughput and the number of relays in the cluster for various number of hops. These results are obtained over Rayleigh fading

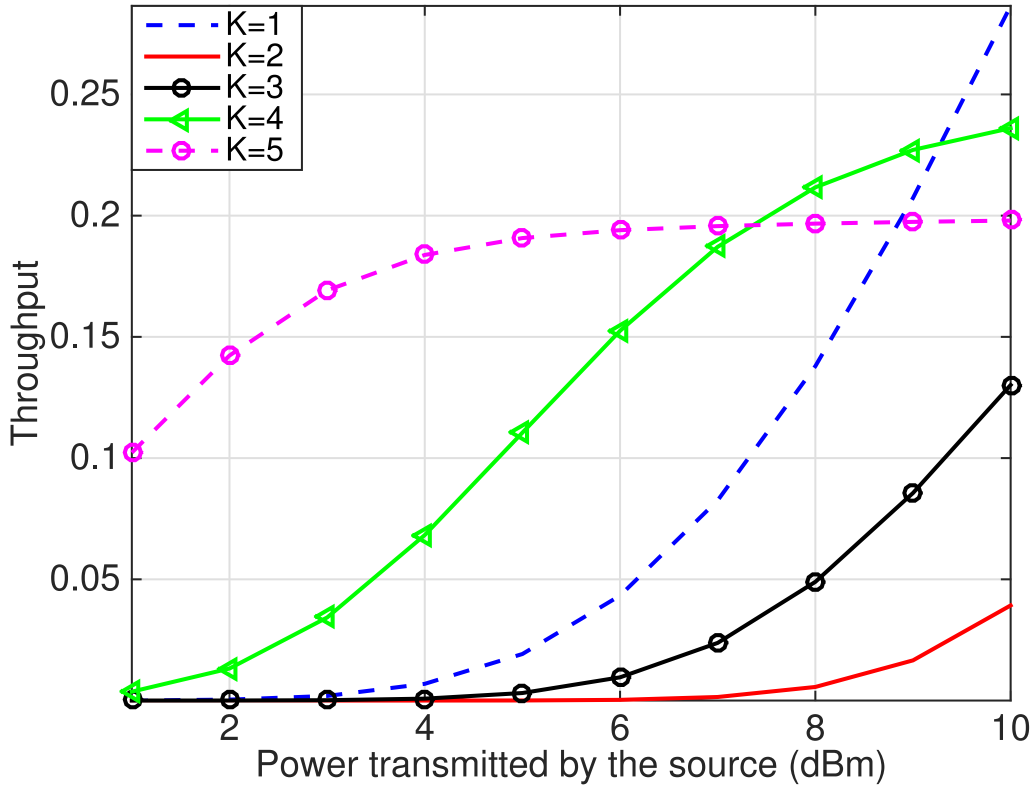



Figure 5.6: Throughput versus power transmitted by the source. Parameters: $\mathsf{R} = 1$, $\zeta = 0.8$, $\sigma_k^2 = -10$ dBm, $\lambda_k = 1$, $M = 10$, $d_{SD} = 5$ m, $d_k = \frac{d_{SD}}{K}$, $P_C = \frac{P_0}{100}$, $\eta = 3$, and $L = 1000$.

environment (model I). It can be observed that for a given number of total relay nodes $N$, the number of the hops $K$ that maximizes the throughput may be different. When $N$ is small, increasing $K$ would result in better throughput, but as $N$ increases, the resulting throughput soon reaches its upper limit, and thus reducing $K$ will eventually improve the throughput.

The above result also suggests that when there are not sufficient relay nodes in terms of achievable diversity in the network, the system performance can be improved with the help of the gain associated with path loss reduction achieved by increasing the number of hops. If there are a number of the relay nodes in the network that can guarantee sufficient diversity, it would be better to reduce the number of hops $K$ such that the throughput limit (which is a factor of $1/K$) can be enhanced.

### 5.4.7 Effect of Asymmetric Channel

Finally, we investigate the effect of asymmetric channel model where different hop may experience different fading phenomena. The four models described at the beginning of this section are evaluated in what follows.

Fig. 5.8 shows the relationship between the throughput and the number of relay nodes per cluster in various fading environments with transmission rate $\mathsf{R} = 2$. When the number of relays per cluster is small, the system achieves the maximum throughput with channel model III, due to the fact that the end-to-end performance of the DF

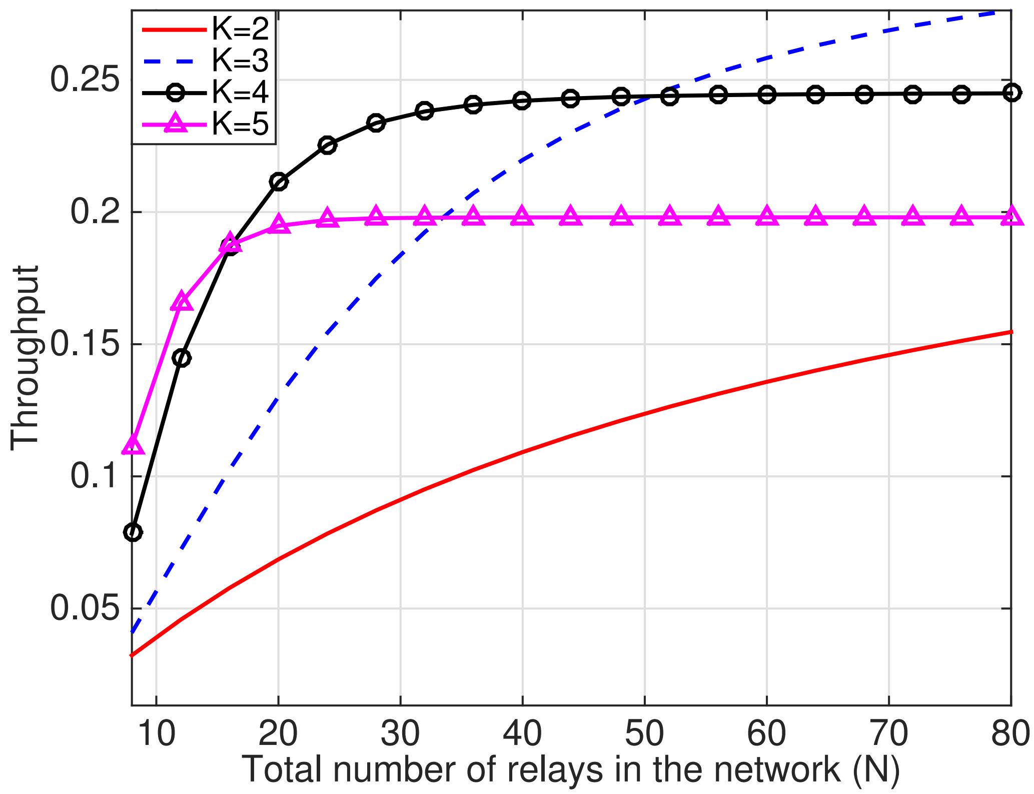



Figure 5.7: Throughput versus the number of total relay nodes with different number of hops. Parameters: R = 1, $\zeta = 0.8$, $P_0 = 10$ dBm, $P_C = \frac{P_0}{100}$, $\sigma_k^2 = -10$ dBm, $\lambda_k = 1$, $d_{SD} = 5$ m, $d_k = \frac{d_{SD}}{K}$, $\eta = 3$, and $L = 1000$.

relaying with EH relay node is dominated by the channel gains of the hops closer to the source, which is in line with the results observed in [79, 80]. On the other hand, as the number of the relay nodes in each cluster increases, the throughput achieved with model IV becomes maximum, whereas the throughput values achieved with the other three channel models become identical.

The reason for this contrast is that in the proposed scheme, all the hops enjoy the diversity gain due to the PRS scheme except for the last hop that consists of only one node (i.e., destination). As a consequence, the relays in the intermediate hops can compensate for the absence of the LoS channel by exploiting the spatial diversity. In the case of model IV, each cluster can enjoy the diversity gain in the intermediate hops due to the PRS scheme, and the last hop can also enjoy the LoS channel, which makes it the best channel model. This observation could be useful for engineers to design the routing protocol of the EH sensor networks that enable relay node clustering.

## 5.5 Conclusion

We have proposed a clustering-based multihop relaying with the PRS scheme for an EH relaying network, which can improve the system performance by exploiting the gain due to the path loss reduction as a result of multihop relaying and the gain due to the spatial diversity based on the PRS scheme. The results suggest that with the help of gain in path loss reduction as well as diversity gain, the proposed scheme can compensate for

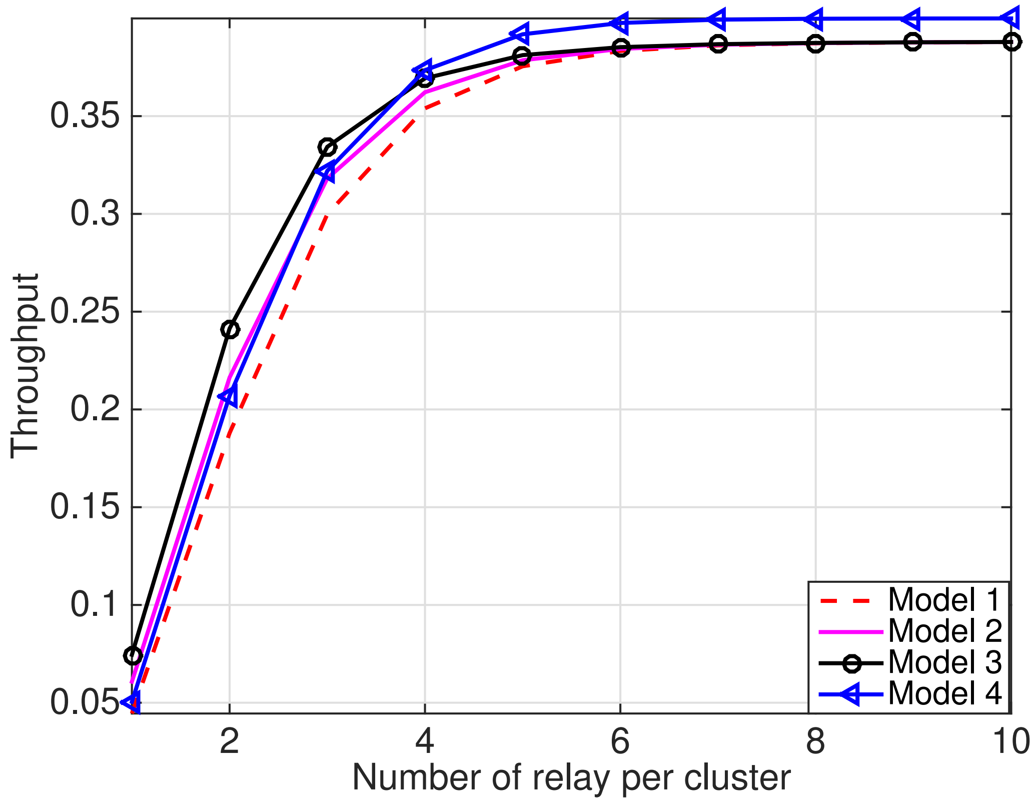



Figure 5.8: Throughput versus the number of relay nodes in each cluster with the four different fading models. Parameters: R = 2, $\zeta = 0.8$, $P_0 = 10$ dBm, $\sigma_k^2 = -10$ dBm, $\lambda_k = 1$, $d_{SD} = 5$ m, $K = 5$, $d_k = \frac{d_{SD}}{K}$, $V = 10$, $P_C = \frac{P_0}{100}$, and $L = 1000$.

possible performance degradation associated with poor RF-to-DC conversion efficiency, which makes the proposed scheme attractive for the practical multihop sensor network scenarios operated with low energy conversion efficiency and low power.

We have also compared the performance of the proposed scheme with the conventional multihop relaying scheme without clustering as well as the direct transmission, and numerically outlined the benefit of the clustering approach; it may enhance the network coverage without consuming any extra power, suitable for lifetime improvement of energy constrained sensor networks. The performance has been also investigated under the constraint of the total number of relay nodes with different number of hops, and it has been shown that there is an optimal number of hops that can maximize the throughput for a given transmission power of the source. The effect of the asymmetric channels has been also investigated. It has been revealed that in the case of the proposed clustering, compared to the environment where all the links are subject to Rayleigh fading, the existence of Rician fading will help improve the throughput more effectively at the destination side, rather than the source side, as opposed to the conventional multihop relaying scenarios without clustering.

CHAPTER 6

# Conclusion

In order to improve the network throughput and spectral efficiency of the energy harvesting cooperative networks, in this thesis, we have proposed various relaying protocols and strategies.

In Chapter 1, we have reviewed the literatures related to the wireless EH schemes and emphasized on the importance and need of wireless EH to enhance the system performance and network coverage of the energy constrained wireless networks, such as wireless sensor networks and ad-hoc networks. We have also discussed that the performance gain achieved with EH sensor networks, strongly depend on the kind of energy harvesting protocol is used by the relay nodes, which motivates this work.

In Chapter 2, we have provided general overview of the traditional as well as energy harvesting cooperative networks including relaying protocols, relay selection schemes and energy harvesting techniques.

In Chapter 3, We have proposed a TS-APS protocol for EH relay networks, where the relays are powered by the RF signal of the source. We have also derived the analytical expressions for the outage probability and effective transmission rate, in the framework of DF relaying, considering random and opportunistic relay selection schemes. Based on the numerical comparison in terms of theoretical analysis and simulations, we have shown that the proposed TS-APS approach with properly optimized TS ratio can achieve better effective transmission rate than the traditional TS and PS schemes.

In Chapter 4, we have proposed the ATS and ATS-APS protocols that enable EH and information processing at the relay. We have derived the mathematical expressions for the outage probability and effective transmission rate for the proposed protocols in the framework of DF relaying and partial relay selection with various diversity combining techniques. Based on rigorous numerical analyses, we have demonstrated that the proposed ATS protocol can easily outperform the conventional TS protocol, and the proposed ATS-APS protocol can outperform all the existing protocols compared here under reasonable assumptions and conditions. We have also shown that for the EH relay networks, the proposed SR technique, where the source receives assistance from the relay only when the direct link between source and destination is in deep fading, should be the better option for improving the system performance, compared to the commonly studied MRC and SC approaches.

In Chapter 5, we have proposed a cluster-based multi hop relaying with the partial relay selection (PRS) scheme for the EH relay networks, and derived the mathematical expression for the outage probability and network throughput. Through numerical analysis we have shown that by combining the benefits of the multihop relaying (i.e., gain achieved by the path loss reduction) and relay selection (i.e., diversity gain), the proposed scheme can out perform the traditional multihop relaying scheme, i.e., one with out clustering.

In all of the relaying schemes and protocols proposed in this work are designed such that only local CSI (i.e., CSI between transmitter and receiver) is required at the relay for the parameters optimization, which makes them very attractive and suitable for the distributed relay networks, like wireless sensor networks and ad-hoc networks, where the individual node needs to operate independently with limited help and information from other nodes. In this work we have solely focused on the *harvest use* (HA) architecture where relay cannot hold the harvested energy for long time, in the future work these schemes can be extended to the *harvest and store* (HS) architecture, apart from them verifying the proposed protocol in the real environment by hardware implementation, would be interesting option for the future work.

# Bibliography

[1] M. Uysal, *Cooperative Communication for Improved Wireless Network Transmission*. New York: Information Science Reference, 2010.

[2] Z. Sheng, K. Leung, and Z. Ding, "Cooperative wireless networks: From radio to network protocol designs," *IEEE Communications Magazine*, vol. 49, no. 5, pp. 64–69, May 2011.

[3] X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, "Wireless networks with RF energy harvesting: A contemporary survey," *IEEE Communications Surveys and Tutorials*, vol. 17, no. 2, pp. 757–789, Nov 2015.

[4] "Battery solutions for wearable devices," *TDK Techno Magazine*, May 2017.

[5] Powercast, "PCT200 data sheet," Jun 2017, rev. 3.

[6] ——, "PCT200 data sheet," Jun 2017, rev. 1.

[7] R. Zhang and C. K. Ho, "MIMO broadcasting for simultaneous wireless information and power transfer," *IEEE Transactions on Wireless Communications*, vol. 12, no. 5, pp. 1989–2001, May 2013.

[8] L. Liu, R. Zhang, and K.-C. Chua, "Wireless information transfer with opportunistic energy harvesting," *IEEE Transactions on Wireless Communications*, vol. 12, no. 1, pp. 288–300, Jan 2013.

[9] L. R. Varshney, "Transporting information and energy simultaneously," in *IEEE International Symposium on Information Theory*, Toronto, ON, Jul 2008, pp. 1612–1616.

[10] P. Grover and A. Sahai, "Shannon meets tesla: Wireless information and power transfer," in *IEEE International Symposium on Information Theory*, Austin, Tx, Jun 2010, pp. 2363–2367.

[11] A. M. Fouladgar and O. Simeone, "On the transfer of information and energy in multi-user systems," *IEEE Communications Letters*, vol. 16, no. 11, pp. 1733–1736, Nov 2012.

[12] A. A. Nasir, X. Zhou, S. Durrani, and R. A. Kennedy, "Relaying protocols for wireless energy-harvesting and information processing," *IEEE Trans. Inf. Theory*, vol. 12, no. 7, pp. 3622–3636, Jul 2013.

[13] ——, "Throughput and ergodic capacity of wireless energy harvesting based DF relaying network," in *2014 IEEE International Conference on Communications, ICC 2014*, Sydney, Jun 2014, pp. 4066–4071.

[14] Y. Gu and A. Sonia, "Interference aided energy harvesting in decode-and-forward relaying systems," in *2014 IEEE International Conference on Communications (ICC)*, Sydney, NSW, 2014, pp. 5389–5393.

[15] Y. Gu, A. Sonia, and S. Aïssa, "RF-based energy harvesting in decode-and-forward relaying systems: Ergodic and outage capacities," *IEEE Transactions on Wireless Communications*, vol. 14, no. 11, pp. 6425–6434, Nov 2015.

[16] M. Ju, K. M. Kang, K. S. Hwang, and C. Jeong, "Maximum transmission rate of PSR/TSR protocols in wireless energy harvesting DF-based relay networks," *IEEE Journal on Selected Areas in Communications*, vol. 33, no. 12, pp. 2701–2717, Dec 2015.

[17] S. Atapattu, H. Jiang, J. Evans, and C. Tellambura, "Time-switching energy harvesting in relay networks," in *2015 IEEE International Conference on Communications (ICC)*, London, Jun 2015, pp. 5416 – 5421.

[18] Y. Liu, "Wireless information and power transfer for multirelay-assisted cooperative communication," *IEEE Communications Letters*, vol. 20, no. 4, pp. 784–787, Apr 2016.

[19] D. T. Do, "Optimal throughput under time power switching based relaying protocol in energy harvesting cooperative networks," *Wireless Personal Communications*, vol. 2015, no. 769286, pp. 1–8, 2015.

[20] N. T. Do, V. N. Q. Bao, and B. An, "Outage performance analysis of relay selection schemes in wireless energy harvesting cooperative networks over non-identical Rayleigh fading channels," *Sensors*, vol. 16, no. 3, p. 295, Feb 2016.

[21] D. T. Do, "Optimal throughput under time power switching based relaying protocol in energy harvesting cooperative networks," *Mobile Information System*, vol. 2015, no. 769286, p. 8, 2015.

[22] T. P. Huynh, D. T. Do, H. S. Nguyen, and T. D. Nguyen, "Design of energy harvesting protocol for relay mobile node in WLAN," in *2015 17th International Conference on Advanced Communication Technology (ICACT)*, Seoul, Jul 2015, pp. 304–308.

[23] S. Atapattu and J. Evans, "Optimal energy harvesting protocols for wireless relay networks," *IEEE Transactions on Wireless Communications*, vol. 15, no. 8, pp. 5789–5803, May 2016.

[24] R. Tao, A. Salem, and K. Hamdi, "Adaptive relaying protocol for wireless power transfer and information processing," *IEEE Communications Letters*, vol. 20, no. 10, pp. 2027 – 2030, Oct 2016.

[25] J. Boyer, D. D. Falconer, and H. Yanikomeroglu, "Multihop diversity in wireless relaying channels," *IEEE Transactions on Communications*, vol. 52, no. 10, pp. 1820–1830, Oct 2004.

[26] A. Ribeiro, X. Cai, and G. B. Giannakis, "Symbol error probabilities for general cooperative links," *IEEE Transactions on Wireless Communications*, vol. 4, no. 3, pp. 1264–1273, May 2005.

[27] B. Zhao and M. C. Valenti, "Practical relay networks: A generalization of hybrid-ARQ," *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 1, pp. 7–18, Jan 2005.

[28] V. Nguyen, Q. Bao, and H. Y. Kong, "Performance analysis of decode-and-forward relaying with partial relay selection for multihop transmission," *Journal of Communication and Networks*, vol. 12, no. 5, pp. 433–441, Dec 2010.

[29] Z. Li and B. Li, "Improving throughput in multihop wireless networks," *IEEE Transactions on Vehicular Technology*, vol. 55, no. 3, pp. 762–773, Jun 2006.

[30] G. K. Karagiannidis, "Performance bounds of multihop wireless communications with blind relays over generalized fading channels," *IEEE Transactions on Wireless Communications*, vol. 5, no. 2, pp. 498–503, Mar 2006.

[31] M. Mao, N. Cao, Y. Chen, and Y. Zhou, "Multi-hop relaying using energy harvesting," *IEEE Wireless Communications Letters*, vol. 4, no. 5, pp. 565–568, Oct 2015.

[32] P. Gupta and P. R. Kumar, "The capacity of wireless networks," *IEEE Trans. Inf. Theory*, vol. 46, no. 2, pp. 388 – 404, Mar 2000.

[33] V.-d. Nguyen, C. T. Nguyen, and O.-s. Shin, "Energy harvesting for throughput enhancement of cooperative wireless sensor networks," *International Journal of Distributed Sensor Networks*, vol. 12, no. 7, pp. 1–7, Jul 2016.

[34] X. Tao, X. X, and Q. Cui, "An overview of cooperative communications," *IEEE Communications Magazine*, vol. 50, no. 6, pp. 65–67, Jun 2012.

[35] H. Ju, E. Oh, and D. Hong, "Improving efficiency of resource usage in two-hop full duplex relay systems based on resource sharing and interference cancellation," *IEEE Transactions on Wireless Communications*, vol. 8, no. 8, pp. 3933–3938, Aug 2009.

[36] H. Alves, G. Fraidenraich, R. D. Souza, M. Bennis, and M. Latva-Aho, "Performance analysis of full duplex and selective and incremental half duplex relaying schemes," in *IEEE Wireless Communications and Networking Conference, WCNC*, Shanghai, Apr 2012, pp. 771–775.

[37] I. Krikidis, H. A. Suraweera, and C. Yuen, "Amplify-and-forward with full-duplex relay selection," in *2012 IEEE International Conference on Communications (ICC)*, Ottawa ON, 2012, pp. 3532–3537.

[38] H. A. Suraweera, I. Krikidis, G. Zheng, C. Yuen, and P. J. Smith, "Low-complexity end-to-end performance optimization in MIMO full-duplex relay systems," *IEEE Transactions on Wireless Communications*, vol. 13, no. 2, pp. 913–927, 2014.

[39] L. Song, Y. Li, and Z. Han, "Resource allocation in full-duplex communications for future wireless networks," *IEEE Wireless Communications*, vol. 22, no. 4, pp. 88–96, Aug 2015.

[40] Y. Zeng and R. Zhang, "Full-duplex wireless-powered relay with self-energy recycling," *IEEE Wireless Communications Letters*, vol. 4, no. 2, pp. 201–204, Apr 2015.

[41] M. Mohammadi, B. K. Chalise, H. A. Suraweera, C. Zhong, G. Zheng, and I. Krikidis, "Throughput analysis and optimization of wireless-powered multiple antenna full-duplex relay systems," *IEEE Transactions on Communications*, vol. 64, no. 4, pp. 1769–1785, Apr 2016.

[42] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity-part i: system description," *IEEE Transactions on Communications*, vol. 51, no. 11, pp. 1927–1938, Nov 2003.

[43] a. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity-part ii: implementation aspects and performance analysis," *IEEE Transactions on Communications*, vol. 51, no. 11, pp. 1939–1948, Nov 2003.

[44] K. Azarian, H. E. Gamal, and P. Schniter, "On the achievable diversity multiplexing tradeoff in half-duplex cooperative channel," *IEEE Trans. Inf. Theory*, vol. 51, no. 12, pp. 4152–4172, Dec 2005.

[45] J. N. Laneman, D. N. C. Tse, G. W. Wornell, and W. G. W., "Cooperative diversity in wireless networks: efficient protocols and outage behavior," *IEEE Transactions on Information Theory*, vol. 50, no. 12, pp. 3062–3080, Dec 2004.

[46] R. Nabar, H. Bolcskei, and F. Kneubuhler, "Fading relay channels: Performance limits and space-time signal design," *IEEE Journal on Selected Areas in Communications*, vol. 22, no. 6, pp. 1099–1109, Aug 2004.

[47] A. S. Ibrahim, A. K. Sadek, W. Su, and K. J. R. Liu, "Cooperative communications with relay selection: When to cooperate and whom to cooperate with?" *IEEE transcations on Wireless Communications*, vol. 7, no. 7, pp. 2814–2827, Jul 2008.

[48] J. N. Laneman, D. N. C. Tse, W. G. W., G. Wornell, and D. N. C. Tse, "An efficient protocol for realizing cooperative diversity in wireless networks," in *Proceedings. 2001 IEEE International Symposium on Information Theory*, Washington, DC, 2001.

[49] J. N. Laneman and G. W. Wornell, "Distributed spacetime-coded protocols for exploiting cooperative diversity in wireless networks," *IEEE Transactions on Information Theory*, vol. 49, no. 10, pp. 2415–2425, Oct 2003.

[50] A. Bletsas, A. Khisti, D. P. Reed, and A. Lippman, "A simple cooperative diversity method based on network path selection," *IEEE Journal on Selected Areas of Communications (JSAC), Special Issue on 4G Wireless Systems*, vol. 24, no. 3, pp. 659–672, Mar 2006.

[51] I. Krikidis, J. Thompson, S. Mclaughlin, and N. Goertz, "Amplify-and-forward with partial relay selection," *IEEE Communications Letters*, vol. 12, no. 4, pp. 235–237, Apr 2008.

[52] B. Medepally and N. B. Mehta, "Voluntary energy harvesting relays and selection in cooperative wireless networks," *IEEE Transactions on Wireless Communications*, vol. 9, no. 11, pp. 3543–3553, Nov 2010.

[53] P. T. Venkata, S. N. A. U. Nambi, R. V. Prasad, and I. Niemegeers, "Bond graph modeling for energy harvesting wireless sensor networks," *IEEE Computer Society*, vol. 45, no. 9, pp. 31–38, Sep 2012.

[54] C. Zhong, H. A. Suraweera, G. Zheng, I. Krikidis, and Z. Zhang, "Wireless information and power transfer with full duplex relaying," *IEEE Transactions on Communications*, vol. 62, no. 10, pp. 3447–3461, Oct 2014.

[55] H. Chen, Y. Li, J. L. Rebelatto, B. F. Uchôa-filho, and B. Vucetic, "Harvest-then-cooperate : Wireless-powered cooperative communications," *IEEE Transactions on Signal Processing*, vol. 63, no. 7, pp. 1700–1711, Apr 2015.

[56] I. Krikidis, G. Zheng, and B. Ottersten, "Harvest-use cooperative networks with half/full-duplex relaying," in *IEEE Wireless Communications and Networking Conference, WCNC*, Shanghai, Apr 2013, pp. 4256–4260.

[57] I. Krikidis, S. Sasaki, S. Timotheou, and Z. Ding, "A low complexity antenna switching for joint wireless information and energy transfer in MIMO relay channels," *IEEE Transactions on Communications*, vol. 62, no. 5, pp. 1577–1587, May 2014.

[58] I. Krikidis, S. Timotheou, and S. Sasaki, "RF energy transfer for cooperative networks: Data relaying or energy harvesting?" *IEEE Communications Letters*, vol. 16, no. 11, pp. 1772–1775, 2012.

[59] N. T. Do, V. N. Q. Bao, and B. An, "A relay selection protocol for wireless energy harvesting relay networks," in *2015 IEEE International Conference on Advanced Technologies for Communications (ATC)*, no. January 2016, Ho Chi Minh, Oct 2015, pp. 243–247.

[60] C. Zhang, L. Hu, and Z. Ding, "Dynamic power splitting policies for AF relay networks with wireless energy harvesting," in *2015 IEEE International Conference on Communication Workshop (ICCW)*, London, Jun 2015, pp. 2035–2039.

[61] Z. Ding, I. Krikidis, B. Sharif, and H. V. Poor, "Wireless information and power transfer in cooperative networks with spatially random relays," *IEEE Transactions on Wireless Communications*, vol. 13, no. 8, pp. 4440–4453, Aug 2014.

[62] V. Raghunathan, S. Ganeriwal, M. Srivastava, G. S, M. Srivastava, S. Ganeriwal, and M. Srivastava, "Emerging techniques for long lived," *IEEE Communications Magazine*, vol. 44, no. 4, pp. 108–114, May 2006.

[63] J. G. Proakis and M. Salehi, *Digital Communications*, 5th ed. New York: McGrawhill, 2008.

[64] E.-R. Belding, "Multi-level hierarchies for scalable ad hoc routing," *Wireless Networks*, vol. 9, no. 5, pp. 461–478, Sep 2003.

[65] T. David and Viswanath Pramod, *Fundamentals of Wireless Communication*. Cambridge: Cambridge University Press, 2005.

[66] T. Rappaport, *Wireless Communications: Principles and Practice*. Upper Saddle River, NJ: Prentice Hall, 1996.

[67] V. Singh and H. Ochiai, "Throughput improvement by cluster-based multihop wireless networks with energy harvesting relays," in *IEEE Topical Conference on Wireless Sensors and Sensor Networks (WiSNet)*, Phoenix, AZ, Jan 2017, pp. 61–64.

[68] ——, "Performance analysis of the clustering-based multihop wireless energy harvesting sensor networks over symmetric and asymmetric fading channels," *International Journal of Distributed Sensor NetworksInternational Journal of Distributed Sensor Networks*, vol. 13, no. 2, p. 12, 2017.

[69] K. Ishibashi, "Dynamic harvest-and-forward: New cooperative diversity with RF energy harvesting," in *2014 6th International Conference on Wireless Communications and Signal Processing, WCSP 2014*, Hefei, Dec 2014.

[70] E. Belding-Royer, "Hierarchical routing in ad hoc mobile networks," *Wireless Communication & Mobile Computing special issue on Ad hoc Networking*, vol. 2, no. 5, pp. 515–532, Aug 2002.

[71] Z. Zhou, M. Peng, Z. Zhao, W. Wang, and R. S. Blum, "Wireless-powered cooperative communications: Power-splitting relaying with energy accumulation," *IEEE Journal on Selected Areas of Communications , Special Issue on 4G Wireless Systems*, vol. 34, no. 4, pp. 969–982, Jan 2016.

[72] W. J. Huang, Y. W. Peter Hong, and C. C. Jay Kuo, "Lifetime maximization for amplify-and-forward cooperative networks," *IEEE Transactions on Wireless Communications*, vol. 7, no. 5, pp. 1800–1805, May 2008.

[73] T. Eng, N. Kong, and L. B. Milstein, "Comparison of diversity combining techniques for Rayleigh-fading channels," *IEEE Transactions on Communications*, vol. 44, no. 9, pp. 1117–1129, Sep 1996.

[74] Z. Chen, J. Yuan, and B. Vucetic, "Analysis of transmit antenna selection/maximal-ratio combining in Rayleigh fading channels," *IEEE Transactions on Vehicular Technology*, vol. 54, no. 4, pp. 1312–1321, Jul 2005.

[75] H. Wang, S. Ma, T. S. Ng, and H. V. Poor, "A general analytical approach for opportunistic cooperative systems with spatially random relays," *IEEE Transactions on Wireless Communications*, vol. 10, no. 12, pp. 4122–4129, Dec 2011.

[76] K. Huang and E. Larsson, "Simultaneous information and power transfer for broadband wireless systems," *IEEE Transactions on Signal Processing*, vol. 61, no. 23, pp. 5972 – 5986, Dec 2013.

[77] J. Boyer, D. Falconer, and H. Yanikomeroglu, "A theoretical characterization of the multihop wireless communications channel with diversity," in *GLOBECOM'01. IEEE Global Telecommunications Conference*, vol. 2, San Antonio, TX,, Nov 2001, pp. 841–845.

[78] M. Haghifam, B. Makki, M. Nasiri-Kenari, and T. Svensson, "On wireless energy and information transfer in relay networks," *submitted for publication*, 2016.

[79] H. A. Suraweera, G. K. Karagiannidis, and P. J. Smith, "Performance analysis of the dual-hop asymmetric fading channel," *IEEE Transactions on Wireless Communications*, vol. 8, no. 6, pp. 2783–2788, Jun 2009.

[80] H. Ding, D. B. da Costa, X. Wang, U. Dias, R. de Sousa, and J. Ge, "On the effects of LOS path and opportunistic scheduling in energy harvesting relay systems," *IEEE Transactions on Wireless Communications*, vol. 15, no. 12, pp. 8506 – 8524, Dec 2016. [Online]. Available: http://ieeexplore.ieee.org/document/7586130/

[81] M. M. Butt, I. Krikidis, and N. Marchetti, "Minimizing outage probability by exploiting CSI in wireless powered cooperative networks," in *Global Communications Conference (GLOBECOM), 2016 IEEE*, Washington, DC, Dec 2016, pp. 1–7.

[82] Z. Ding and H. V. Poor, "Energy harvesting cooperative networks: Is the Max-Min criterion still diversity-optimal?" *IEEE Transactions on Wireless Communications*, vol. 15, no. 1, pp. 553–567, Sep 2014.

[83] A. A. Nasir, X. Zhou, S. Durrani, S. Member, and R. A. Kennedy, "Wireless-powered relays in cooperative communications : Time-switching relaying protocols and throughput analysis," *IEEE Transactions on Communications*, vol. 63, no. 5, pp. 1607–1622, Mar 2015.

# Publications

## Journal Papers

[J-1] V. Singh and H. Ochiai, "Performance Analysis of the Clustering-Based Multi-hop Wireless Energy Harvesting Sensor NetworksOver Symmetric and Asymmetric Fading Channels," *Int. J. Distrib. Sens. Networks*, vol. 12, no. 2, 2017.

[J-2] V. Singh and H. Ochiai, "Adaptive Time-Switching and Power-Splitting Protocols for Energy Harvesting Sensor Networks with Multiple Relays," (submitted to IEEE Transactions on Wireless Communication)

## International Conference Papers

[I-1] V. Singh and H. Ochiai, "Throughput Improvement by Cluster-Based Multihop Wireless Networks with Energy Harvesting Relays," *2017 IEEE Topical Conference on Wireless Sensors and Sensor Networks (WiSNet)* , Phoenix, AZ, Jan 2017.

[I-2] V. Singh and H. Ochiai, "An Efficient Time Switching Protocol with Adaptive Power Splitting for Wireless Energy Harvesting Relay Networks," in *Proceedings of the IEEE Vehicular Technology Conference (VTC 2017 Spring)*, Sydney, Australia, June 2017. (Selected for IEEE VTS Tokyo Chapter 2017 Student Paper Award)