Improving Lifetime in Wireless Selective Relay Networks

by

Seyed Ali Mousavifar

B.A.Sc., The University of British Columbia, 2006

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF APPLIED SCIENCE

in

The Faculty of Graduate Studies

(Electrical and Computer Engineering)

THE UNIVERSITY OF BRITISH COLUMBIA

(Vancouver)

September 2009

© Seyed Ali Mousavifar 2009

Abstract

Two novel algorithms based on imposing a soft limit on transmit power are proposed for improving the lifetimes of Amplify and Forward (AF) wireless relay networks. The impact of the algorithms on the network lifetime of four selective relay strategies, Minimum Transmission Power (MPT), Minimum Outage Probability (MOP), Maximum Energy Index (MEI), and Maximal Residual Energy (MRE) are studied. The network lifetime is defined as the number of successfully received messages at the destination while ensuring the system outage probability requirement is met.

In the first system model, there are N number of parallel relay paths with only one relay in each path between the source and the destination. The proposed algorithm uses the system outage probability derived in previous studies and a fixed transmit power threshold at the relays. The algorithm increases the lifetime drastically when the number of relays is larger than 3 [1].

In the second system model, the destination uses N number of parallel paths with only one relay in each path and the source-destination link to receive messages. A diversity scheme is proposed in which the destination uses the source-destination link to obtain the signal broadcast to the relays by the source. The destination then informs the relays of the SNR deficiency which needs to be made up by the selected relay. The system outage probability is derived for the diversity scheme. The proposed algorithm deploys a dynamic transmit power threshold with the diversity scheme and improves the lifetime drastically [2].

The proposed algorithms are shown to improve the lifetime while ensuring that a target system outage probability is met. However, their features also increase the delay that a message may experience. To address this problem, we propose a delay reduction scheme, which disables the soft transmit power limit, if message delay exceeds a certain threshold. The delay reduction scheme is shown to significantly lower the message delay without much decrease in the lifetime.

Table of Contents

Appendices

List of Tables

List of Figures

List of Abbreviations

Acronyms

ADF	Amplify-decode and Forward
AF	Amplify and Forward
BER	Bit Error Rate
CRS	Cooperative Relay Strategy
CSI	Channel State Information
DF	Decode and Forward
DSTBC	Distributed Space Time Block Coding
ECG	Equal Gain Combining
EG-CRS	Equal Gain Cooperative Relay Strategy
MEI	Maximum Energy Index
MOP	Minimum Outage Probability
MRC	Maximal Ratio Combining
MRE	Maximum Residual Energy
MTP	Minimum Transmission Power
O-CRS	Opportunistic Cooperative Relay Strategy
PP-CRS	Proportion to the Path-SNR Cooperative Relay Strategy

Acknowledgments

I would like to express my deep-felt gratitude to my advisor, Prof. Cyril Leung of the Electrical Engineering Department at The University of British Columbia, for his advice, encouragement, enduring patience, and constant support. Although I pursued my research remotely from UBC, he made himself available by means of telephone and internet at home or at the university to give me advice and feedback. His response to my verbal thanks was a very modest, “It’s my job.” I wish all students have the honor and opportunity to work under his supervision. I would like to thank him for his effort in reviewing this work and providing helpful feedbacks.

I also wish to thank my co-supervisor, Dr. Tamer Khattab assistant professor at Qatar University for his advice and supports throughout my stay in Qatar. I would like to thank him for his effort in providing helpful comments and technical advice. This research work was funded by Qatar National Research Fund (QNRF) under the National Priorities Research Program (NPRP) grant number NPRP-1-7-7-3.

I also wish to thank my siblings, Reza, Elham, and Mehdi for their support. And finally, I like to thank my partner in life, Irene Sattarzadeh, for her loving support while I completed this research.

Dedication

Dedicated to my parents:

Shahla Golbakhsh & Seyed Mohammadali Mousavifar

Chapter 1

Introduction

Cooperative relay networking is an emerging technology which allows wireless networks to improve their performance. Traditionally, the fixed base stations at the two ends of a communication link have to mitigate the effects of fading. By using intermediate relays between the source and destination, significant energy saving can be obtained due to the decrease in the effects of path loss and shadowing. More recently, the use of intermediate relays in parallel paths between the source and destination to mitigate the effects of Rayleigh fading and shadowing has allowed an increase in system capacity and coverage through diversity. The use of cooperative relays in cellular, ad-hoc, and hybrid networks increases their capacity and coverage. The implementation of relay stations is economically feasible since their costs are low compared to base stations. This makes cooperative relay networks economically attractive.

1.1 Motivation

A wireless relay network consists of a source, destination, and intermediate relays as shown in Fig 1.1. In many applications, relays are placed in remote areas where battery energy is at a premium. For a given initial energy level, we wish to determine the

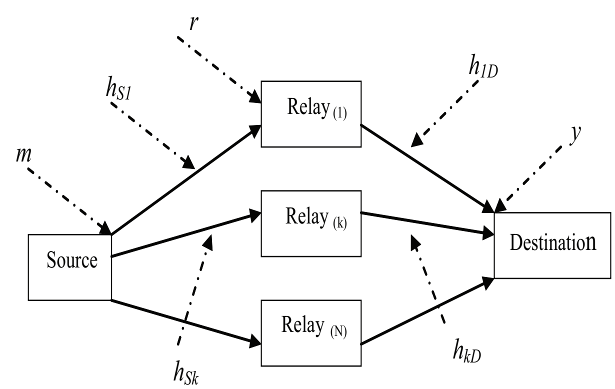

Figure 1.1: System Model ©[2009] IEEE

lifetime of the system, i.e. the time period during which messages can be reliably communicated from the source to the destination subject to certain quality of service (QoS) requirements. Beyond this period, the network may be able to successfully receive in a few instances in which the direct source-destination or source-relay-destination links are exceptionally good. However, the overall average probability of outage may be unacceptably high. Hence, for reliable communications with QoS requirements, the goal is to improve the system lifetime by designing simple, low-signalling overhead transmission algorithms and relay selection strategies.

1.2 Background

In this section, a number of terms and concepts which will be used in the thesis are introduced.

1.2.1 Relaying Methods

Relaying methods are concerned with the way in which messages are forwarded to the next relay or the destination. They include decode and forward (DF), amplify and forward (AF), and a hybrid of the two. For certain applications in [4,5] amplify-decode and forward (ADF) have been proposed.

DF The packet received from the previous node is first decoded. The decoded message which could be erroneous, is then encoded into a packet and transmitted to the next node.

AF The relay receives the signal and simply amplifies and forwards the signal to the next node or destination without decoding it. At the destination, the receiver demodulates the signal and makes a decision on the transmitted message. We assume AF relaying in our work in the following chapters. AF has the following advantages and disadvantages:

1. In [6] it was shown that the bit error rate (BER) performance of the non-regenerative (AF) and regenerative (DF) methods are alike at high signal to noise ratio (SNR) and the latter outperforms at low SNR.
2. AF is simpler to implement.

Time Index	Phase I	Phase II
Protocol I	S–to–R	R–to–D
Protocol II	S–to–(R,D)	R–to–D
Protocol III	S–to–R	(S,R)–to–D
Protocol IV	S–to–(R,D)	(S,R)–to–D

Table 1.1: Transmission Protocols

3. AF relay in [3], the gain at the relay is approximately inversely proportional to the channel gain and the received noise. If received signal at the relay suffer from poor channel gain and high noise power, the relay gain uses its maximum allowable energy to mitigate the noise.
4. The difficulty of obtaining closed-form expressions for the probability distribution of the SNR and outage probability for AF increases with the number of relays [7, 8].

1.2.2 Transmission Protocols in Wireless Relay Networking

A transmission protocol defines the signal transmission time for each node, i.e. certain time or frequencies slots are allocated to certain nodes to reduce the interference.

Table 1.1 shows different protocols for transmitting signals to the destination over two time slots, Phase I and Phase II, in a time division fashion. S, R, and D represent source, relay, and destination, respectively. These protocols are defined for a system of multiple paths and one relay per path. The nature of the source signal in Phase I is broadcast and thus all nodes are intended to receive the same message. During phase II one or more selected relays forward the packet to the next hub.

Protocol I

Protocol I [3,8–14] is designed for systems with poor channel conditions between source and destination. A direct communication path from source to destination not available. In Phase I, the source broadcasts to the relays and in Phase II, the relay(s) forwards its received signal to the destination. Diversity methods can be used if there are multiple relays.

Protocol II

In Protocol II [7,11,12,15–27], the relays and destination listen to the source broadcast during Phase I. In Phase II, one or more relays can forward the signal received in the broadcast phase to the destination. At the end of phase II, the destination selects or combines the signal it received in Phase I with copies from Phase II to decode the transmitted message.

Protocol II is applicable when the source-destination channel is not always poor. This protocol allows relays to save energy. However, special circuitry and buffering are required at the destination to store the signal in Phase I and to perform maximal ratio combining (MRC), selective combining (SC), or equal gain combining (ECG) in Phase II.

Protocol III

Protocol III [15, 19, 28, 29] is similar to protocol I, expect that during Phase II the source retransmits the signal to the destination. In Phase II, the destination receives a signal directly from the source as well as signal from the relays. One drawback of the Protocol III is that the source has to transmit the message twice compared to Protocol II. However if source has a less resrticted energy supply, Protocol III could allow the system to take advantage of the diversity when the source-destination channel gain is increased significantly in Phase II.

Protocol IV

Protocol IV [11] is similar to Protocols II, except that in Phase II the source and relay transmit to the destination using Distributed Space Time Block Coding (DSTBC). Using DSTC Phase II, in addition to the direct transmission of the message in Phase I allows Protocol IV to outperform Protocol II and III in BER [11]. Protocol IV, similar to Protocol III requires retransmission of the source in Phase II. Thus, source should have a less restriction in in power supply.

Moreover, some relay networks have transmission protocol which adopts to channel conditions [12], i.e. interchanges among Protocol I, II, or III.

1.2.3 Channel Gain Information and Residual Energy Information

Knowledge of the Channel State Information (CSI) and relay Residual Energy Information (REI) play an important role in the lifetime maximization of the wireless relay networks.

CSI

CSI allows relays to transmit signals with enough energy to satisfy the system requirements. For example, if the gain of the source-relay and relay-destination links are known to the relay, the relay will only use as much energy as is sufficient to satisfy the required SNR at the destination. If this information is not available, the relay may use a fixed gain [30]. If the relay gain is too high, some energy will be wasted. If the relay gain is too low, QoS requirements are not satisfied and retransmission may be required.

CSI may be estimated by the destination, relay, and/or source. For example, a pilot tone from the source allows the relay to estimate the source-relay link gain [3, 31] and a pilot tone from the destination allows the relay to estimate the relay-destination link (assuming reciprocity for relay-destination link). In [10], the destination keeps track of all the relay-destination link gains and it feeds them back to the relays. The level of CSI in the wireless relay networks is categorized into three groups:

1. CSI: The instantaneous channel gains is present at all or some of the nodes [3, 9, 10, 18–20, 30, 31], i.e source-relay and relay-destination channel gains are present at the source, destination, or/and relays.
2. Partial CSI: The statistics of the channel such as the variance of the channel gain is available at all or some nodes [18, 19, 30].
3. No CSI: the source, relays, or destination have no information about the channel gain or statistics of the channel gain. [30]

The acquisition of CSI involves special circuitry, RF overhead signalling, and energy consumptions at the receivers and transmitters. For example, when the destination feeds back the CSI to the relays, the control messages exchanged between the destination and relays are referred to as RF overhead signalling cost [10]. The BER performances of a two-hop wireless relay network with CSI, partial CSI, and no CSI are studied in [30].

REI

After each transmission a relay may forwards this information regarding its REI to a central node which selects the relay to be used. If REI and CSI are available at a central node in the relay network, the central node decides on the optimum relay which has a combination of the best channel gain and residual energy to transmits.

1.2.4 Power Allocation and Relay Selection: Distributed or Central

Relay selection and transmit power allocation can be done in either centralized or distributed fashion. In the centralized method, a master node is responsible for selecting the relay and the transmitted power to be used based on CSI and REI. As the number of relays increases, more relays have to communicate with the master node regarding the CSI and REI in the network and more RF signalling among them will be exchanged.

Distributed relay selection and power allocation are studies in [3, 9, 24, 25]. In some cases, one pilot tone from the source enables all the relays to compute the source-relay channel gain in a distributed manner without the need for exchange of messages between a central node and relays. A distributed method is proposed in [31] for relay selection and power allocation using a timer at each relay. Each timer is initialized with a value that is a function of the CSI and/or REI of the corresponding relay and all timers at all relays are activated at the same time. The relay with the first expired timer transmits and all other relays listening to transmission channel will stay idle. The timers get activated by receiving a pilot from the destination which is also used for CSI estimation. For example, if the objective of the wireless relay network is to select the relay with the best channel gain, the timers at the relays are initialized with a value which is inversely proportional to CSI of the channels, i.e. The relay which has the best channel condition will have the smallest initialized value for the timer and it will expire first. This distributed power allocation and relay selection method is used in [3, 9].

1.2.5 Cooperating Relay Strategy (CRS)

Each relay in the network may cooperate with other relays in different ways to transmit to the destination. Three CRSs are studied in [9]:

- Proportion to path SNR (PP-CRS): the power each relay contributes is proportional to its path SNR. The path SNR is defined as the equivalent SNR each relay can achieve at the destination if the relay uses all its available power.
- Equal gain (EG-CRS): all the relays have a fixed gain. Any relay which can satisfy the threshold SNR at the destination, denoted by γ_{th}, with the fixed gain can transmit.
- Opportunistic assignment (O-CRS): Only the relay that can satisfy γ_{th} using the least amount of energy transmits.

One extreme scenario is when all the relays satisfying γ_{th}. In [3], several CRSs are studied in which only one relay, based on its CSI and/or REI, is selected to transmit. They are referred to as Selective Cooperating Relay Strategies (S-CRS):

1. Minimum Transmission Power (MTP): Let P_k denote the minimum transmission energy needed by relay k to satisfy γ_{th}. In MPT, the relay k^* with the smallest P_k is selected, i.e. $k^* = \underset{k}{\operatorname{argmin}}\{P_k\}$.

2. Maximum Residual Energy (MRE): Let E_{0k} denote the residual energy of relay k. In MRE, the selected relay k^* satisfies: $k^* = \underset{k}{\operatorname{argmax}}\{E_{0k} - P_k\}$.

3. Maximum Residual-Energy Index (MEI): The selected relay k^* satisfies: $k^* = \underset{k}{\operatorname{argmax}}\{E_{0k}/P_k\}$.

4. Minimum Outage Probability (MOP): The selected relay k^* satisfies: $k^* = \underset{k}{\operatorname{argmin}}\{P_{outage}(\boldsymbol{E_0} - P_k\mathbf{1_k})\}$. where $\boldsymbol{E_0}$ is an $N \times 1$ vector denoting the residual energy of N relays and $\mathbf{1_k}$ is an $N \times 1$ vector which is equal to one only at the kth element and zero at any other row.

   In MOP, we aim to choose a relay which would minimize the system outage probability at the beginning of each transmission. The MOP mathematical representation shows that the system probability of outage is calculated as if the kth relay among the N relay has transmitted. The relay which minimizes the system outage probability is chosen in each transmission.

1.3 Related Works

The network lifetime is defined as the time span (or the number of successfully received messages) from the instant of the first transmission in the network to the instant at which the relays cannot satisfy the system requirements [32]. The system outage probability, P_{outage}, must not exceed the maximum allowable system outage probability, η, in [3]. Hence, the lifetime is defined as the number of successfully received messages while ensuring $P_{\text{outage}} < \eta$ in [3].

Early research on the lifetimes of the networks concentrates on routing algorithms [33] and positioning of the relays [34]. More recently, [35] show that CRS in the network can also combat the effects of fading and shadowing in wireless relay networks efficiently.

The average relay lifetimes of three CRSs are studied in [9]. The results show that the O-CRS has a better lifetime than EG-CRS and PP-CRS. In contrast to EG-CRS and PP-CRS, O-CRS causes the battery of some relays to deplete faster than others.

The discrete power allocation methods during the lifetime of AF relays for Three S-CRSs (MTP, MOP, and MEI) are proposed in [36]. The discrete power level enables a low cost implementation and a close integration with high speed digital circuits. The results show the lifetime of MOP and MEI are similar and larger than the lifetime of MTP when channel gain statistics are the same for all the relays, i.e all the links connecting the relays to the source and destination have the same channel gain variances. When the links have different channel variances, the lifetime of MOP is larger than those of MEI and MTP.

In [3], the lifetime of MOP, MRE, MEI, and MTP are analyzed and simulated for a system model shown in Figure 1.1 using a continuous and discrete power level amplifiers. The results show that MOP has a longer lifetime and better system outage probability than MTP, MRE, and MEI. When the number of relays increases, MRE lifetime performance decrease significantly compare to MOP, MTP, and MEI.

1.4 Thesis Organization

In Chapter 2, we propose an algorithm based on a transmit power threshold at the relays to improve the lifetime of the network subject to maintaining the system outage probability below η in all S-CRSs. In Chapter 3, we propose a diversity scheme which exploits the source-destination link during the phase in which source broadcasts to the relays. Then, we define a dynamic transmit power threshold for the proposed diversity scheme for all S-CRSs. In Chapter 4, we investigate the effects of the proposed algorithms on the maximum delay that a message may experience during the lifetime and introduce a delay reduction scheme to improve the delay. In addition, the effects of the number of relays, channel gain variances, and noise power on the performances of the algorithms in the network are discussed in Chapter 5. Recommendations and areas for future studies are highlighted in Chapter 6.

Chapter 2

Transmit Power Threshold Scheme

Wireless relays are used to reduce the transmit power and increase the performance of the wireless networks. They have been studied in many aspects such as power allocation [15] [7], capacity [16]- [18], outage probability [6] [19], and lifetime [3] [35] [36]. For the system model in [3], the lifetime is defined as the number of received messages satisfying a desired SNR at the destination under probability of outage constraints. In [3], the lifetimes of four S-CRSs (MOP, MTP, MRE, and MEI) are studied assuming each relay acquires CSI about its own links.

Our investigation shows that the strategies in [3] satisfy η but they do not utilize it efficiently. In other words, there is a gap between what the network satisfies and η. We propose a dynamic transmit power threshold at the relays which exploits the gap between η and the average fraction, $\overline{P_{\text{outage}}}$, of time slots which experience outage during the lifetime.

The proposed method improves the lifetime when the number of relays is larger than three. When the number of relay paths is less than three, the proposed method improves the lifetime mainly for high initial relay energy levels.

In Sections 2.1, 2.2, 2.3, we describe the system model, our proposed transmit power threshold algorithm and the simulation results, respectively.

2.1 System Model

Consider N parallel cooperative relay paths, each containing a single AF relay as shown in Figure 1.1. Assuming each relay has CSI about its own links, it can forward a message to the destination using enough power to achieve γ_{th}. The source broadcasts and the relays receive the signal in Phase I. One relay amplifies and forwards the signal and the destination receives it in Phase II. Assuming that the relay-destination links are reciprocal, the CSI for the source-relay and relay-destination can be acquired by pilot signal from the source and destination at the beginning of Phases I and II, respectively. The network must satisfy γ_{th} and ensure that $P_{\text{outage}} < \eta$.

2.1.1 Channel and Noise

The channel gains are assumed to be independent, circularly symmetric complex Gaussian random variables with unit variances and zero means, i.e. $\mathcal{CN}(0, 1)$. We denote the channel gain from the source to the k^{th} relay by h_{Sk} and the channel gain from the k^{th} relay to the destination by h_{kD}, as shown in Figure 1.1. Additive white Gaussian noise (AWGN) with unit variances and zero means are assumed at the relays and destination. We denote the noise at the k^{th} relay by w_k and the noise at the destination by w_D. The signals received at the relay and destination in Phases I and II are [3]:

$$r_k = \sqrt{P_S} h_{Sk} m + w_k \ , \tag{2.1}$$

and

$$\begin{aligned} y = & \quad G_k r_k + w_D \\ = & \sqrt{\frac{P_k}{P_S |h_{Sk}|^2 + 1}} \sqrt{P_S} h_{Sk} h_{kD} m \\ + & \sqrt{\frac{P_k}{P_S |h_{Sk}|^2 + 1}} h_{kD} w_k + w_D \ . \end{aligned} \tag{2.2}$$

In (2.1) and (2.2), m is the unit energy signal corresponding to the source messages, r_k is the received signal at the kth relay in Phase I, and y is the signal received at the destination in Phase II. P_S and P_k are the transmit powers of the source and the kth relay, respectively. The time index has been omitted for notational simplicity. The gain, G_k, at the kth relay is $\sqrt{\frac{P_k}{P_S |h_{Sk}|^2 + 1}}$.

2.1.2 Laws-of-Physics Restriction and Proposed Transmit Power Threshold

We assume that $P_{\max}$ is the physical power limit of a relay. In our proposed algorithm, we introduce a transmit power threshold, P_{soft}, to allow relay nodes to defer transmission in an effort to conserve energy, based on channel conditions. This provides the system with an extra degree of freedom which allows a trade-off between outage probability and energy consumption.

2.1.3 End-to-end Signal to Noise Ratio and $P_{\mathbf{outage}}$

Assuming $N_0 = 1$ at the relays and destination, the equivalent SNR, γ_{eq}, at the destination for a path passing through a non-regenerative relay is derived in [6]:

$$\gamma_{eq} = \frac{\gamma_r \gamma_D}{\gamma_r + \gamma_D + 1} \ , \tag{2.3}$$

where $\gamma_r = P_S |h_{Sk}|^2$ and $\gamma_D = P_k |h_{kD}|^2$. We rewrite (2.3) as:

$$\gamma_{eq} = \frac{P_S |h_{Sk}|^2 P_k |h_{kD}|^2}{P_S |h_{Sk}|^2 + P_k |h_{kD}|^2 + 1} \ . \tag{2.4}$$

Assuming each relay can obtain the CSI about its own links, each relay can compute minimum required power, P_k, to satisfy γ_{th} using (2.4). A system outage occurs if none of the relays can deliver the message with γ_{th} given the restriction on their transmission powers, i.e. $0 < P_k \leq min\{P_{\max}, E_{0k}\}$. Assuming that the messages are transmitted in one unit time, we can use the terms power or energy interchangeably to refer to $P_{\max}$ and E_{0k}. If system outage occurs due to adverse channel conditions the network waits for better channel conditions in subsequent time slots. If outage occurs as a result of low residual energy of the relays, the system is said to be inoperable. The destination investigates which kind of outage will occur in the next time slot given it has the REI information of all the relays.

We denote the maximum allowable transmission power of the kth relay by P_k', i.e. $P_k' = min\{P_{\max}, E_{0k}\}$. The outage probability of a single path consisting an AF relay as a function of P_k', is [6]:

$$P_{out}(P'_k) = 1 - [e^{-(\frac{\gamma_{th}}{P_S\sigma^2_{Sk}} + \frac{\gamma_{th}}{P'_k\sigma^2_{kD}})}\sqrt{\beta}K_1(\sqrt{\beta})] \ , \quad (2.5)$$

where $K_1(.)$ is the modified Bessel function of the second kind of order 1 and $\beta \triangleq \frac{4(\gamma^2_{th}+\gamma_{th})}{P_S P'_k \sigma^2_{kD}\sigma^2_{Sk}}$. The variance of the channel gain from the source to kth relay and from the kth relay to the destination are denoted by σ^2_{Sk} and σ^2_{kD}, respectively.

The system outage probability, P_{outage}, is given by the product of the outage probabilities of all relay paths:

$$P_{\text{outage}} = \prod_k P_{\text{out}}(P'_k) \ . \quad (2.6)$$

When outage occurs, the destination uses (2.6) to compare the system outage probability in the next time slot with η. $P_{\text{outage}} \geq \eta$ indicates that the low residual energy will cause future outages and violation of the system requirements in the subsequent time slots, i.e system is considered inoperable. $P_{\text{outage}} < \eta$ indicates that adverse channel condition was the result of previous outage and that the relay network continues to transmit in the subsequent time slots. The lifetime improvement strategy aims to increase the number of successfully received messages before the system becomes inoperable. The strategy works under the constraint that $\gamma_{eq} \geq \gamma_{th}$ and $P_{\text{outage}} < \eta$.

2.1.4 Relay Selection Strategies

MPT, MOP, MRE, and MEI are studied in conjunction with our proposed transmit power threshold algorithm. In step 1, all relays will compute the minimum power re-

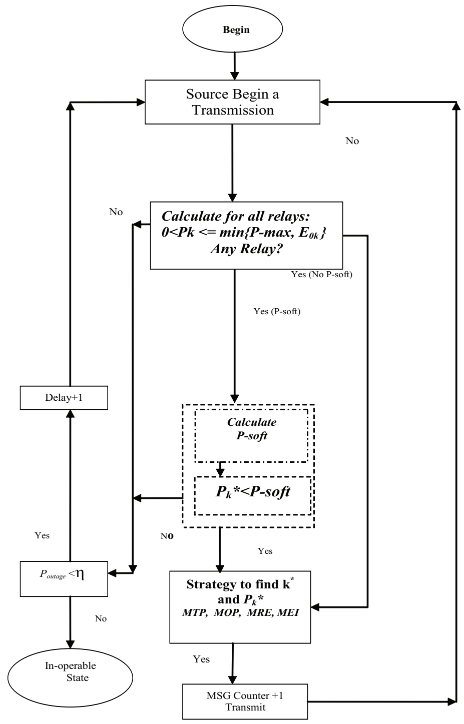

Figure 2.1: Flowchart of the transmit power threshold scheme ©[2009] IEEE

quired to satisfy γ_{th} and $0 < P_k \leq min\{P_{\max}, E_{0k}\}$. If there exist at least one relay satisfying the conditions, MPT, MOP, MRE, and MEI select one relay for the transmission. Otherwise, an outage has occurred and the relay network has to determine whether the network is operable or not using (2.6). The S-CRSs are discussed in Chapter 1. We briefly refer to them below:

Minimum Power Transmission (MPT)

In MPT, the selected relay k^* satisfies: $k^* = \underset{k}{\operatorname{argmin}}\{P_k\}$.

Maximum Residual Energy (MRE)

In MRE, the selected relay k^* satisfies: $k^* = \underset{k}{\operatorname{argmax}}\{E_{0k} - P_k\}$.

Maximum Energy-Efficiency Index (MEI)

In MEI, the selected relay k^* satisfies: $k^* = \underset{k}{\operatorname{argmax}}\{E_{0k}/P_k\}$.

Minimum Outage Probability (MOP)

In MEI, the selected relay k^* satisfies: $k^* = \underset{k}{\operatorname{argmin}}\{P_{outage}(\boldsymbol{E_0} - P_k\boldsymbol{1_k})\}$.
where $\boldsymbol{E_0}$ is an $N \times 1$ vector denoting the residual energy of N relays and $\boldsymbol{1_k}$ is an $N \times 1$ vector which is equal to one only at the kth element and zero at any other row.

Each selective strategy selects the appropriate relay, denoted by k^*, and its corresponding transmission power, denoted by P_k^*, to satisfy γ_{th}. At this stage, the network has successfully received a message to the destination under the given the constraints and the amount of transmission energy will be subtracted from the k^* relay. This procedure is illustrated in the flow chart diagram in Figure 2.1. The dashed box refers to the proposed algorithm in conjunction with the S-CRSs and it will be discussed next.

2.2 Proposed Transmit Scheme

We define $\overline{P_{\text{outage}}}$ as the average fraction of time slots which experience outage during a lifetime:

$$\overline{P_{\text{outage}}} \triangleq \frac{\sum_{i=1}^{MC} N_{\text{out}}[i]}{\sum_{i=1}^{MC} N_{\text{out}}[i] + \sum_{i=1}^{MC} N_{\text{rx}}[i]}, \tag{2.7}$$

where $N_{\text{out}}[i]$ is the number of time slots in outages during the ith lifetime and $N_{\text{rx}}[i]$ is the number of time slots in which a message is successfully received during the ith lifetime, and MC is the number of points in *Monte Carlo* simulation.

It is important to note that in our simulations N_{out} does not include the last outage

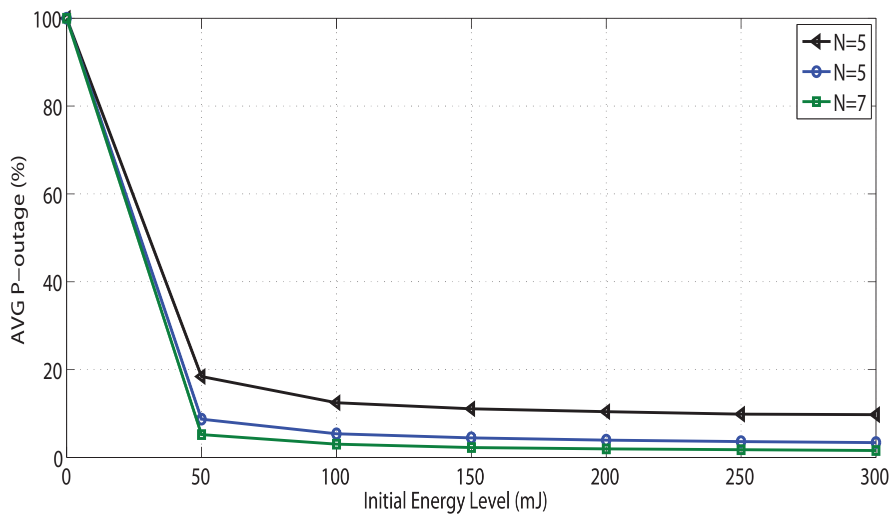

Figure 2.2: The average lifetime and $\overline{P_{\text{outage}}}$ ("Avg. P_{outage}") in MOP and $N = 3, 5, 7$: N_{out} includes the last outage

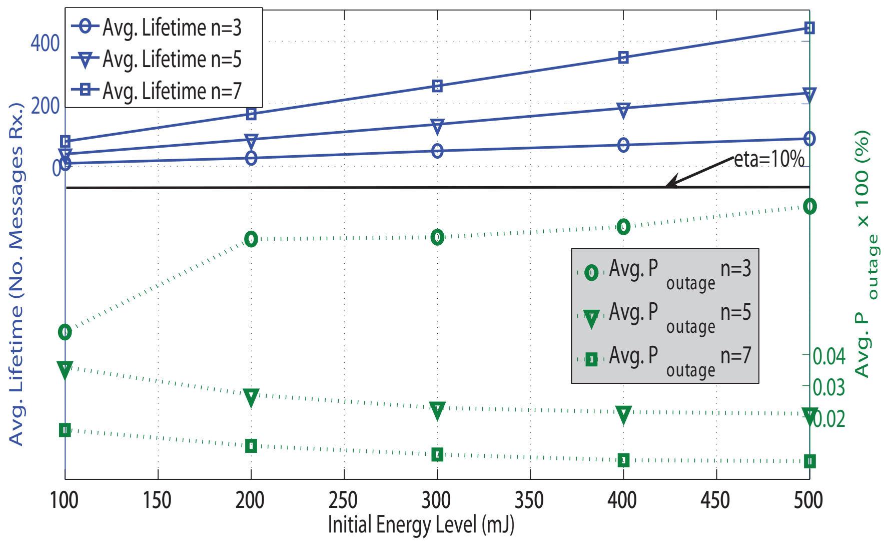

Figure 2.3: The average lifetime and $\overline{P_{\text{outage}}}$ ("Avg. P_{outage}") in MOP and $N = 3, 5, 7$: the system model of [3] ©[2009] IEEE

that occurs before the end of the lifetime. When none of the relays can satisfy γ_{th} and the destination inspects that the $\overline{P_{\text{outage}}} > \eta$, the network is considered to be inoperable. In low $\boldsymbol{E_0}$ where the lifetimes are usually between 10-15 messages, one outage can change the value of the $\overline{P_{\text{outage}}}$ significantly. In general, we expect $\overline{P_{\text{outage}}}$ to approach 100% as $\boldsymbol{E_0} \to 0$ as shown in Figure 2.2. However, due to our interpretation of N_{out}, our future results at low $\boldsymbol{E_0}$ will differ from Figure 2.2.

Figure 2.3 shows that in the system in [3], there is a significant gap between $\eta =$ 10% and $\overline{P_{\text{outage}}}$. More specifically, $\overline{P_{\text{outage}}}$ decreases from 10% to less than 1% as N increases from 3 to 7. This suggests that if we introduce opportunistic transmission in favorable time slots, we can decrease the transmission power required to satisfy γ_{th} at the expense of increasing P_{outage}. Hence, the gap between η and $\overline{P_{\text{outage}}}$ can be utilized efficiently. Our investigation shows that in the strategies studied in [3], if $P_{\max}$ and E_{0k} are sufficiently large, the relays transmit even in very poor channel conditions. Refraining from transmitting at such times conserve a significant amount of energy, thereby extending the lifetime while still ensuring $P_{\text{outage}} < \eta$. To this end, we introduce a transmit power threshold, P_{soft}, above which relays do not transmit. This transmit power threshold modification to the algorithm is shown by the dashed box in Figure 2.1. It must be noted that a not carefully designed transmit power threshold may causes violation of η.

We should expect $\overline{P_{\text{outage}}}$ to approach system outage probability in (2.6) as $\boldsymbol{E_0}$ increases. When E_{0k} for all relays (all k) are much larger than the physical transmit power limit of the amplifiers at the relay, $E_{0k} >> P_{\max}$, the maximum allowable transmit power (P'_k) in $P'_k = min\{E_{0k}, P_{\max}\}$ can be assumed to be $P'_k = P_{\max}$ for a large duration of network lifetime. Thus, we can substitute (2.5) in (2.6) and write:

$$\begin{aligned} P_{\text{outage}} &= \prod_{k=1}^{N} P_{\text{out}}(P_{\max}) \\ &= \prod_{k=1}^{N} 1 - [e^{-(\frac{\gamma_{th}}{P_S\sigma_{Sk}^2} + \frac{\gamma_{th}}{P_{\max}\sigma_{kD}^2})} \sqrt{\beta} K_1(\sqrt{\beta})] \\ &= (1 - [e^{-(\frac{\gamma_{th}}{P_S\sigma_{Sk}^2} + \frac{\gamma_{th}}{P_{\max}\sigma_{kD}^2})} \sqrt{\beta} K_1(\sqrt{\beta})])^N, \end{aligned} \tag{2.8}$$

where $\beta \triangleq \frac{4(\gamma_{th}^2+\gamma_{th})}{P_S P_{\max}\sigma_{kD}^2\sigma_{Sk}^2}$. We use (2.8) to compare P_{outage} at $\boldsymbol{E_0}$= 500 with the $\overline{P_{\text{outage}}}$ results in Figure 2.3. For example, for $N = 7$, (2.8) yields $P_{\text{outage}} = 0.4\%$ which can be observed in Figure 2.3. For $N = 5$ and $N = 3$, we can show that, $P_{\text{outage}} = \overline{P_{\text{outage}}} = 2\%$, $P_{\text{outage}} = \overline{P_{\text{outage}}} = 9.45\%$, respectively.

We now describe a method for finding the maximum transmit power threshold, P_{soft}, that ensure $P_{\text{outage}} < \eta$. Consider N relays, each with a large amount of initial energy i.e. $E_{0k} >> P_{max}$. Recall the system outage probability from (2.6), where P_k' and P_k should satisfy, i.e $P_k' = \min\{E_{0k}, P_{\max}\}$ and $P_k \leq \min\{E_{0k}, P_{\max}\}$. We introduce a new soft transmit power threshold, P_{soft}, which P_k' and P_k should satisfy, e.g $P_k' = \min\{E_{0k}, P_{\max}, P_{\text{soft}}\}$ and $P_k \leq \min\{E_{0k}, P_{\max}, P_{\text{soft}}\}$

We want relays to hold a message if P_k computed from (2.4), satisfying the $P_k' = \min\{E_{0k}, P_{\max}\}$, is larger than P_{soft}. Hence, in order to save energy, P_{soft} should be less than the physical transmit power restriction of the amplifiers at the relays, $P_{\max}$. Assuming the initial energy of the relays are large $\boldsymbol{E_0} >> P_{max}$, then $P_{\text{soft}} < E_{0k}$ and thus, P_{soft} dominates the restriction on P_k', i.e. $P_k' = P_{\text{soft}}$ and we can substitute P_{soft} for P_k' in (2.6):

$$
\begin{aligned}
P_{\text{outage}} &= \prod_{k=1}^{N} P_{\text{out}}(P_{\text{soft}}) \\
&= \prod_{k=1}^{N} 1 - [e^{-(\frac{\gamma_{th}}{P_S\sigma_{Sk}^2} + \frac{\gamma_{th}}{P_{\text{soft}}\sigma_{kD}^2})}\sqrt{\beta}K_1(\sqrt{\beta})] \\
&= (1 - [e^{-(\frac{\gamma_{th}}{P_S\sigma_{Sk}^2} + \frac{\gamma_{th}}{P_{\text{soft}}\sigma_{kD}^2})}\sqrt{\beta}K_1(\sqrt{\beta})])^N. \qquad (2.9)
\end{aligned}
$$

where $\beta \triangleq \frac{4(\gamma_{th}^2+\gamma_{th})}{P_S P_{\text{soft}}\sigma_{kD}^2\sigma_{Sk}^2}$. The maximum allowable transmit power, P_{soft}, to ensure that $P_{\text{outage}} < \eta$ can be calculated in the following:

$$
\begin{aligned}
\eta &> P_{\text{outage}} \\
&> (1 - [e^{-(\frac{\gamma_{th}}{P_S\sigma_{Sk}^2} + \frac{\gamma_{th}}{P_{\text{soft}}\sigma_{kD}^2})}\sqrt{\beta}K_1(\sqrt{\beta})])^N \qquad (2.10)
\end{aligned}
$$

Each relay can use (2.10) to compute P_{soft}, e.g. Table 2.1 shows that for $N = 3$ and $P_{\text{soft}} = 71.3\text{mW}$ at each relay will result an outage probability of each relay, denoted

η	N	$P_{outage\ Single\ Relay}$	P_{soft}(mW)
10%	3	46.42%	71.3
	5	63.1%	22.6
	7	71.9%	14.5
	9	77.4%	11.2
	20	89.1%	6.2

Table 2.1: P_{soft} for $N = 3, 5, 7, 9, 20$ and $\eta = 10\%$ ©[2009] IEEE

by $P_{outage\ Single\ Relay}$, to be 46.42% to ensure $P_{\text{outage}} < \eta$. Moreover, the high initial energy level allows the network a longer network lifetime in which the proposed scheme can discourage more messages from transmitting during adverse channel conditions to save more energy. Hence, we expect the $P_{\text{outage}} \to \eta$ at high $\boldsymbol{E_0}$.

As discussed before, P_k computed from (2.3) satisfies $0 < P_k \leq \min\{E_{0k}, P_{\max}, P_{\text{soft}}\}$. If discrete transmit power level amplifiers are used at the relays, P_k is chosen from the nearest discrete higher power level at which each relay can transmit. If the nearest discrete transmit power level at the relay is $P_{\max}$, then employing P_{soft} will not improve the lifetime. The increase in the system outage probability in our proposed algorithm is the cost paid to prevent the network from investing the majority of its energy resources when the channel conditions are very poor for all paths. In our proposed algorithm relays acquire P_{soft} without complex computations or extra RF exchange which makes it fair to compare its performance with those of [3]. Each relay can generate P_{soft} locally given the REI and N.

The restriction imposed by the proposed algorithm can be summarized as:

- $0 < P_k \leq \min\{E_{0k}, P_{\max}, P_{\text{soft}}\}$

- $P'_k = \min\{E_{0k}, P_{\max}, P_{\text{soft}}\}$

In the next section, we examine the performance improvements of MOP, MEI, MRE, and MTP in [3] obtained with the proposed P_{soft} scheme.

2.3 Simulation and Results

The network lifetimes and $\overline{P_{\text{outage}}}$ for four S-CRSs for the proposed algorithm are studied using computer simulations. The initial energy levels for all relays are 100 mJouls (mJ) or higher to produce low variant lifetimes and outages averaged over 10000 lifetimes in *Monte Carlo* simulations. This allows a valid comparison between the $\overline{P_{\text{outage}}}$ and P_{outage}. We initialize the parameters of the simulation to those studied in [3] for fair comparisons. The source power and the threshold SNR are chosen to be $P_s = 12$ dBm, $\gamma_{th} = 8$ dB, respectively. Complex Gaussian channel gain and AWGN with zero means and unit variances are assumed in the simulations. The Number of relays, maximum physical transmit power restriction, and system outage probability threshold are chosen to be $N = 5$, $P_{\max} = 82.25$ mW, and $\eta = 10\%$, respectively.

We consider amplifiers with continuous and discrete power level at the transmitters of relays. Each relay calculates the P_{soft} from (2.5) and (2.10), i.e P_{soft} is computed for several N in Table 2.1. Let L denote the number of discrete equidistance power level intervals at the relays, i.e. for $L = 5$, $P_k \in \{16.45, 32.9, 49.35, 65.8, 82.25\}mW$. In the simulations, we consider $L = \{contineous(L \rightarrow \infty), 5, 10\}$.

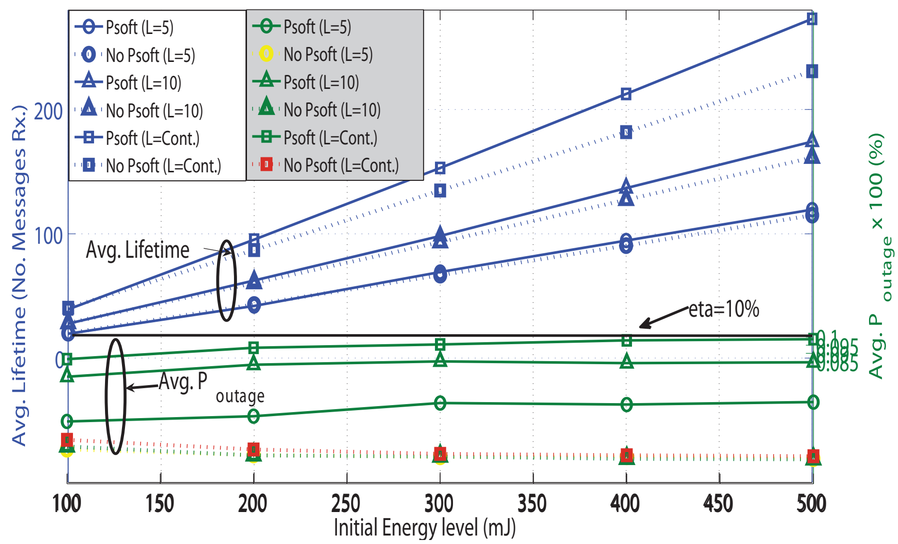

Figure 2.4: The average lifetime and $\overline{P_{\text{outage}}}$ ("Avg. P_{outage}") in MTP for $N = 5$: the network with and without P_{soft} ©[2009] IEEE

The values at which the parameters are initialized during the simulations are summarized in Table 2.2.

η	N	P_s (dBm)	$P_{\max}$(mW)	$\gamma_{th}(dB)$	σ^2_{Sk}	σ^2_{kD}	L	P_{soft} (mW)
10%	5	12	82.25	8	1	1	5,10, continuous	22.6

Table 2.2: Values of the Parameters in the Simulations

Figures 2.4, 2.5, 2.6, and 2.7 show the lifetime and $\overline{P_{\text{outage}}}$ of [3] and the proposed algorithm in conjunction with MPT, MEI, MRE, and MOP, respectively. Introducing P_{soft} increases the lifetime drastically, while $\overline{P_{\text{outage}}}$ satisfies $\eta = 10\%$. Note that lifetime improvement is reduced as L decreases from *continuous* to 5, i.e when L is discrete, the first power level greater than P_k may be high and the effect of the proposed strategy decreases.

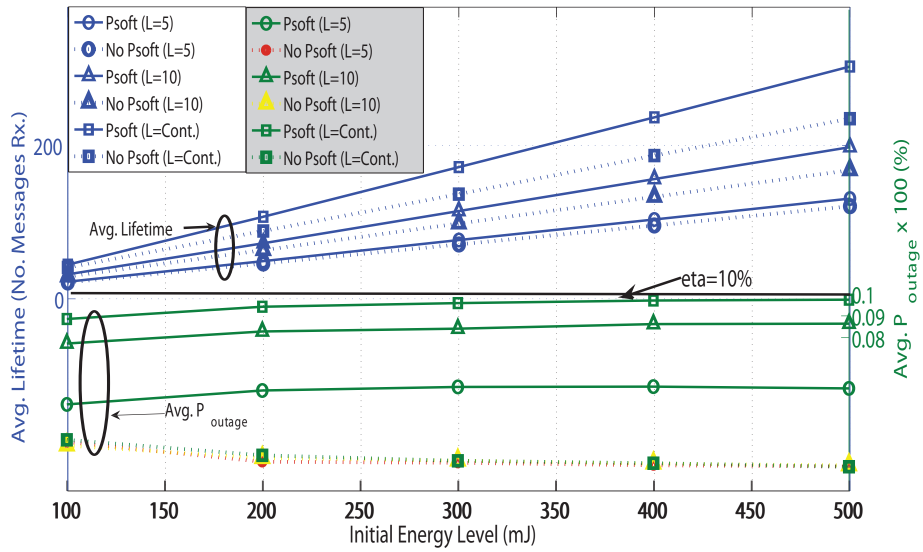

Figure 2.5: The average lifetime and $\overline{P_{\text{outage}}}$ (”Avg. P_{outage}”) in MEI for $N = 5$: the network with and without P_{soft} ©[2009] IEEE

Figure 2.8 shows the lifetime and $\overline{P_{\text{outage}}}$ of [3] and the proposed algorithm for various initial energy level of relays in conjunction with MPT for $N = 3$. When initial energy level for all the relays is 250 mJ or higher, the proposed algorithm improves the lifetime from the results in [3]. When initial energy of relays are high, the cumulative energy savings (due to prevention of transmission in bad channel conditions) over the lifetime is significant. Thus, for small number of relays ($N \leq 3$), we suggest a hybrid algorithm, which uses just MTP for low initial energy levels and the proposed algorithm in conjunction with MTP for high initial energy levels.

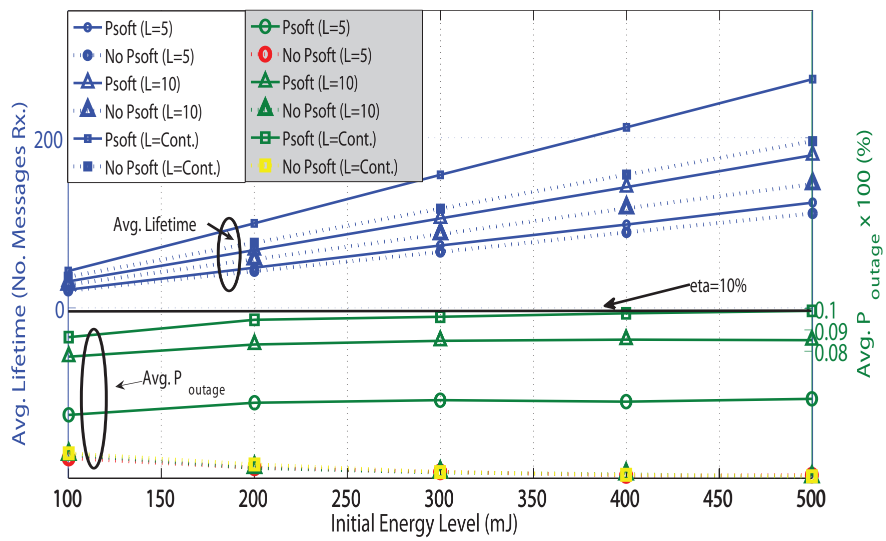

Figure 2.6: The average lifetime and $\overline{P_{\text{outage}}}$ ("Avg. P_{outage}") in MRE for $N = 5$: the network with and without P_{soft} ©[2009] IEEE

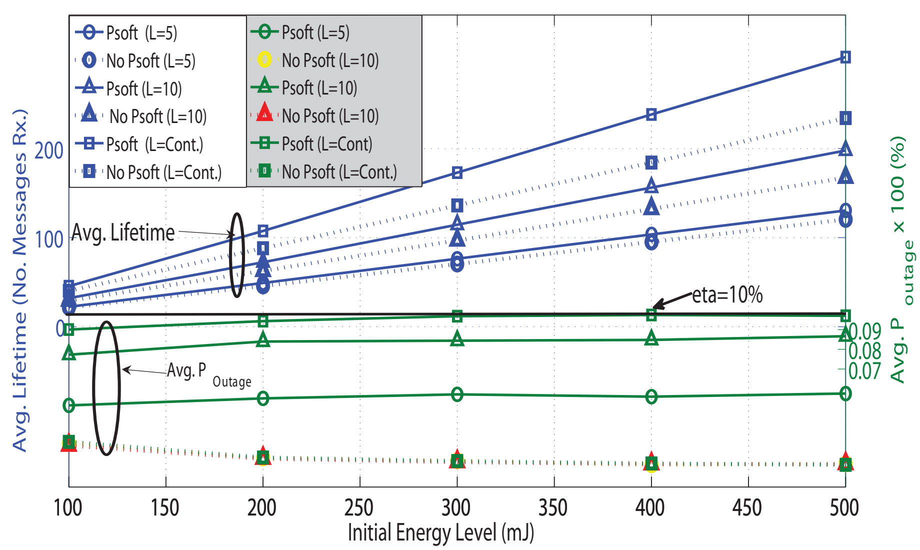

Figure 2.7: The average lifetime and $\overline{P_{\text{outage}}}$ ("Avg. P_{outage}") in MOP for $N = 5$: the network with and without P_{soft} ©[2009] IEEE

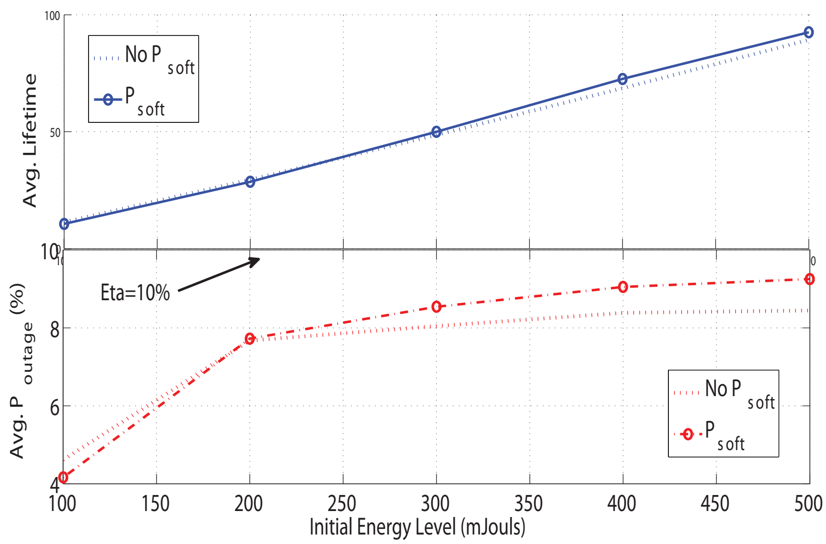

Figure 2.8: The average lifetime and $\overline{P_{\text{outage}}}$ ("Avg. P_{outage}") in MOP for $N = 3$: the network with and without P_{soft} ©[2009] IEEE

Chapter 3

The Diversity Scheme and Dynamic Transmit Power Threshold

In the previous chapter, we proposed a scheme for improving the network lifetime based on a transmit power threshold at the relays which remaind constant throughout the lifetime of the network. In [37], a diversity method which exploits the existence of the source-destination link is used to study the bit error rate (BER) performance of a wireless relay network. However, a selected relay retransmits the source message with a constant gain and without any considerations on the portion of the SNR obtained from the the source-destination link.

We propose a diversity scheme which exploits the existence of a source-destination path to improve the lifetime and system outage probability of the selective network. In contrast to the diversity scheme in [37], in the proposed scheme the destination informs the relay of the SNR deficiency which needs to be made up by a selected relay. The an algorithm based on a dynamic transmit power threshold is used to improve the lifetime.

In Sections 3.1, 3.2, 3.3, and 3.4, we describe the diversity scheme, the diversity scheme

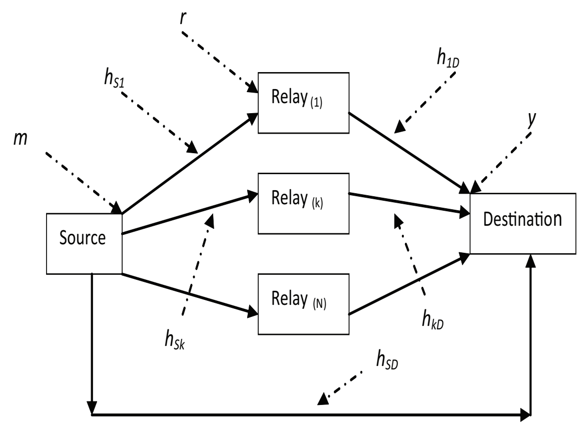

Figure 3.1: System Model ©[2009] IEEE

system model, the diversity scheme with the transmit power threshold algorithm, and some simulation results, respectively.

3.1 Proposed Diversity Scheme

The source broadcasts a pilot signal and the message signal in Phase I. Each relay estimates the CSI for its path from the source. At the end of Phase I, if the source-destination SNR, γ_{SD}, satisfies γ_{th} ($\gamma_{SD} \geq \gamma_{th}$), then the source can begin the transmission of a new message. Otherwise, the destination sends a pilot signal along with information about the γ_{SD} to the relays. Each relay estimates the CSI for its path to the destination. Knowledge of γ_{SD} allows relays to make up for the deficiency in an energy efficient way.

Each relay k uses (2.4) to calculate the minimum P_k that it could use to satisfy the required SNR. In the simulation results presented in section 3.4, we assume that the each relay knows, γ_{SD}, exactly and the relays may transmit at any power level. In

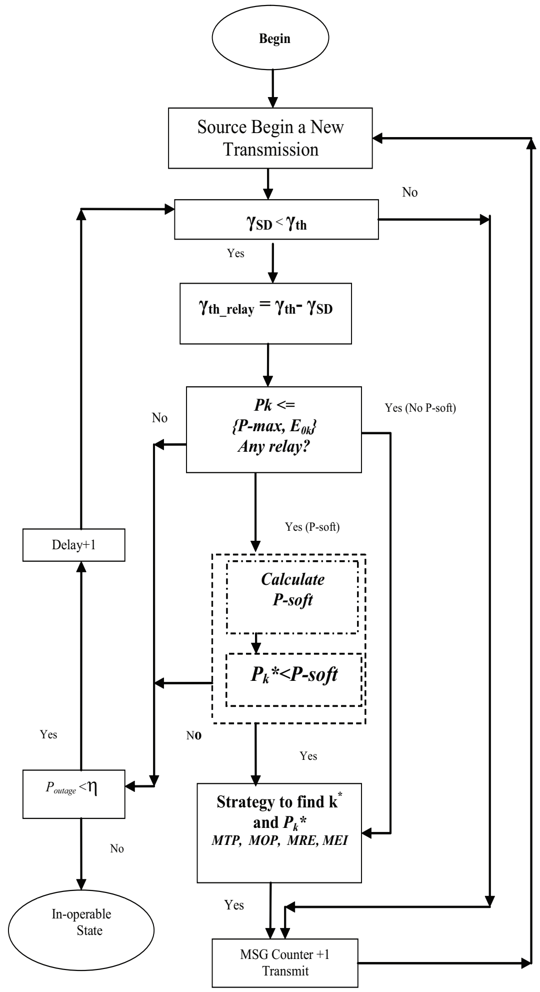

Figure 3.2: Flowchart of the dynamic transmit power threshold in the proposed diversity scheme ©[2009] IEEE

many practical applications, relays may transmit at discrete power levels only.

If there exists no relay which can satisfy γ_{th} with P_k such that $0 < P_k \leq min\{P_{\max}, E_{0k}\}$, an outage occurs. If destination compute P_{outage} such that $P_{\text{outage}} \leq \eta$, the outage is the result of adverse channel conditions and the network continues to transmit messages. If $P_{\text{outage}} > \eta$, the outage is the result of low residual energy. More attempts to transmit will violate η and hence, the network is considered inoperable. The destination determines if the network is inoperable by using the REI of all relays in the computation of the P_{outage}.

If there is at least one relay which can satisfy γ_{th} with P_k such that $0 < P_k \leq min\{P_{\max}, E_{0k}\}$, a relay is selected to transmit in Phase II based on the selective cooperative relay strategy [3] (MPT, MOP, MEI, MRE). The selection strategies aim at maximizing the network lifetime by using a relay which has a relatively good channel condition or residual energy level. These strategies are described in details in Section 1.2.5.

Each selective strategy picks the appropriate relay, denoted by k^*, and its corresponding transmission power, denoted by P_k^*, to satisfy the remainder SNR required. At this stage, the network has successfully received a message under the given constraint and the amount of energy corresponding to the power P_k^* will be subtracted from the residual energy of the k^* relay. The procedure described is illustrated in the flow chart diagram in Figure 3.2. The dashed box in the figure refers to the energy conserving algorithm in conjunction with the proposed diversity scheme which will be discussed next.

3.2 Diversity Scheme System Model

The system model is the same as Section 2.1 except that there is a direct source-destination link as shown in Figure 3.1. The MRC receiver at the destination receives any message over two phases as follows:

- Phase I: Receives the source broadcast signal intended for the relays.
- Phase II: Receives the signal forwarded by one of the relays.

The sum of the SNR achieved from the source in Phase I and the kth relay in Phase II must satisfy γ_{th} for a message to be received successfully.

We denote the source-destination channel gain by h_{SD} as shown in Figure 3.1. Since the destination receives the signals in Phases I and II, we denote the noise at the destination in Phase I by $w_D[I]$, and the noise at the destination in Phase II by $w_D[II]$. We briefly review the notations used in the system model of Chapter 2. The signals received at the kth relay and destination in Phases I and II are [3] [37]:

$$r_k[I] = \sqrt{P_s} h_{Sk} m + w_k \ , \tag{3.1}$$

$$y[I] = \sqrt{P_s} h_{SD} m + w_D[I] \ , \tag{3.2}$$

and

$$y[II] = G_k r_k[I] h_{kD} + w_D[II], \tag{3.3}$$

where [I] and [II] denote the signals in Phases I and II. In (3.1) and (3.2), m is the unit energy signal corresponding to the source messages, $r_k[I]$ and $y[I]$ are the signals received at the kth relay and destination in Phase I, and $y[II]$ is the received signal at the destination in Phase II. Similar to previous chapter, we denote the noise at the k^{th} relay in Phase I by w_k. P_S and P_k are the transmit powers of the source and the kth relay, respectively. The gain at the kth relay, G_k, in Phase II is $\sqrt{\frac{P_k}{P_S|h_{Sk}|^2+1}}$.

3.2.1 Equivalent SNR and P_{outage}

The equivalent SNR, γ_{eq}, and P_{outage} differ from those of Chapter 2 due to the effect of the source-destination link. γ_{eq} at the output of the destination MRC combiner is the sum of the SNR of the source-destination link, γ_{SD}, from Phase I and the SNR at the destination from a path passing through the kth AF relay [6], denoted by γ_{SkD}:

$$\gamma_{SD} = P_S|h_{SD}|^2, \tag{3.4}$$

and

$$\gamma_{SkD} = \frac{P_S|h_{Sk}|^2 P_k|h_{kD}|^2}{P_S|h_{Sk}|^2 + P_k|h_{kD}|^2 + 1}. \tag{3.5}$$

Thus,

$$\gamma_{eq} = \gamma_{SD} + \gamma_{SkD}. \tag{3.6}$$

Assuming each relay can obtain γ_{SD} and the CSI about its own links, it can compute minimum required power, P_k, to satisfy $\gamma_{eq} \geq \gamma_{th}$ using (3.6). A system outage occurs if $\gamma_{eq} < \gamma_{th}$, i.e. the direct source-destination link does not satisfy γ_{th} in Phase I and none of the relays can satisfy $\gamma_{th} - \gamma_{SD}$ in Phase II. The transmit power at the relays are restricted by $P_{\max}$ and E_{0k} such that $0 < P_k \leq min\{P_{\max}, E_{0k}\}$. Assuming that each message is transmitted in one unit time, we can compare $P_{\max}$ and E_{0k}.

The probability that the source-destination path is in outage in Phase I, given the source power and the source-destination link gain variance, denoted by σ_{SD}^2, is [6]:

$$P[\gamma_{SD} < \gamma_{th}] = 1 - \exp(\frac{\gamma_{th}}{P_S \sigma_{SD}^2}). \tag{3.7}$$

We denote the maximum allowable transmission power of the kth relay by P_k', i.e. $P_k' = min\{P_{\max}, E_{0k}\}$. The outage probability of a single path consisting of an AF relay as a function of P_k', is [3]:

$$P_{\text{out}}(P_k'|\gamma_{SD}) = 1 - [e^{-(\frac{\gamma_{th}-\gamma_{SD}}{P_S \sigma_{Sk}^2} + \frac{\gamma_{th}-\gamma_{SD}}{P_k' \sigma_{kD}^2})} \sqrt{\beta} K_1(\sqrt{\beta})], \tag{3.8}$$

where $K_1(.)$ is the modified Bessel function of the second kind of order 1 and $\beta \triangleq \frac{4(\gamma_{th}^2+\gamma_{th})}{P_S P_k' \sigma_{kD}^2 \sigma_{Sk}^2}$. The variance of the channel gain from the source to kth relay and from the kth relay to the destination are denoted by σ_{Sk}^2 and σ_{kD}^2, respectively.

We can derive the system outage probability, P_{outage}, as:

$$\begin{aligned} P_{\text{outage}} &= P[\gamma_{SD} < \gamma_{th}] \prod_{k=1}^{N} P_{\text{out}}(P_k'|\gamma_{SD}) \\ &= P[\gamma_{SD} < \gamma_{th}] \prod_{k=1}^{N} P[\gamma_{SkD} < \gamma_{th}|\gamma_{SD}] \\ &= P[\gamma_{SD} < \gamma_{th}] \prod_{k=1}^{N} P[\gamma_{SkD} < \gamma_{th} - \gamma_{SD}] \\ &= [1 - \exp(\frac{\gamma_{th}}{P_S \sigma_{SD}^2})] \prod_{k=1}^{N} [1 - (\exp(-(\frac{\gamma_{th}-\gamma_{SD}}{P_S \sigma_{Sk}^2} + \frac{\gamma_{th}-\gamma_{SD}}{P_k' \sigma_{kD}^2})) \sqrt{\beta} K_1(\sqrt{\beta}))] \end{aligned} \tag{3.9}$$

where the product term is the probability that all of N paths are in outage. A lifetime improvement strategy aims to increase the number of successfully received messages under the constraints that $\gamma_{eq} \geq \gamma_{th}$ and $P_{\text{outage}} < \eta$.

3.3 Diversity Scheme with Dynamic Transmit Power Threshold

The dynamic transmit power threshold scheme aims to restrict relays from transmitting in adverse channel conditions and ensuring $P_{\text{outage}} < \eta$. It is dynamic because the threshold changes in every transmission based on the SNR obtained from source-destination link, γ_{SD}. Recall that $\overline{P_{\text{outage}}}$ is defined as:

$$\overline{P_{\text{outage}}} \triangleq \frac{\sum_{i=1}^{MC} N_{\text{out}}[i]}{\sum_{i=1}^{MC} N_{\text{out}}[i] + \sum_{i=1}^{MC} N_{\text{rx}}[i]}, \tag{3.10}$$

where $N_{\text{out}}[i]$ is the number of time slots in outages during the ith lifetime and $N_{\text{rx}}[i]$ is the number of time slots in which a message is successfully received during the ith lifetime, and MC is the number of points in *Monte Carlo* simulation.

In Figure 3.4, $\overline{P_{\text{outage}}}$ of the proposed diversity scheme is shown (S-D Path). $\overline{P_{\text{outage}}}$ of the proposed diversity scheme has a significant gap from $\eta = 10\%$ requirement which can be utilized for the sake of saving energy by introducing opportunistic transmission at the relays during good channel conditions.

In the S-CRSs studied in [3], if $0 < P_k \leq min\{P_{\max}, E_{0k}\}$ is satisfied, the k^* relay could

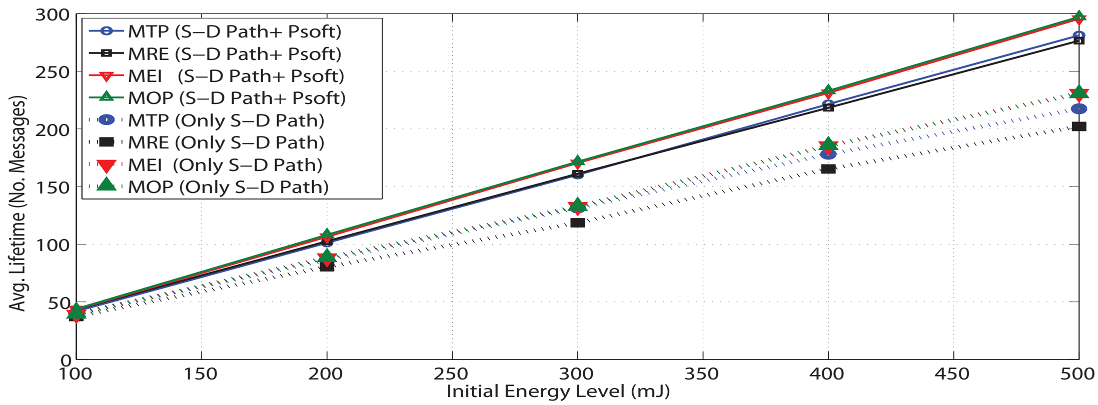

Figure 3.3: The average lifetime in 4 S-CRSs (MTP, MRE, MEI, MOP) and $N = 5$: the diversity scheme without P_{soft} ("Only S-D path") and the diversity scheme with P_{soft} ("S-D path+ P_{soft}") ©[2009] IEEE

use all its residual energy to transmit even in poor channel conditions. The proposed transmit power threshold in Chapter 2 allows the system to hold the message from transmitting in adverse channel conditions and waits for better channel conditions in the subsequent time slots. Although, this method increases the outage instants during the lifetime of the system, it allows the system to conserve energy during poor channel conditions. For the proposed diversity scheme, we introduce a dynamic transmit power threshold that prevents the relaying nodes from using a large amount of power to relay messages as long as their deferral will not cause a violation to η. This power limitation based modification to the algorithm is shown by the dashed box in Figure 3.2.

Relays will not send the message if the power required exceeds P_{soft}, i.e $0 < P_k \leq min\ \{P_{\text{soft}}\ , P_{\max}, E_{0k}\}$. We emphasize that if the scheme that calculates P_{soft} is not carefully designed, the transmit power threshold may cause the P_{outage} to increase above

η. Let's assume there are N relays with relatively large amount of residual energy, i.e. $E_{0k} >> P_{max}$. Using the same arguments as Section 2.2, we replace P'_k with P_{soft} in (3.8):

$$\begin{aligned} & P_{\text{outage}} \\ = \ & [1-\exp(\tfrac{\gamma_{th}}{P_S\sigma^2_{SD}})][1-(\exp(-(\tfrac{\gamma_{th}-\gamma_{SD}}{P_S\sigma^2_{Sk}}+\tfrac{\gamma_{th}-\gamma_{SD}}{P_{\text{soft}}\sigma^2_{kD}}))\sqrt{\beta}K_1(\sqrt{\beta}))]^N, \end{aligned} \tag{3.11}$$

where $\beta \triangleq \frac{4(\gamma^2_{th}+\gamma_{th})}{P_S P_{\text{soft}}\sigma^2_{kD}\sigma^2_{Sk}}$. The maximum transmit power threshold which ensures $P_{\text{outage}} < \eta$ we can be calculated from:

$$\begin{aligned} \eta > \ & P_{\text{outage}} \\ > \ & [1-\exp(\tfrac{\gamma_{th}}{P_S\sigma^2_{SD}})][1-(\exp(-(\tfrac{\gamma_{th}-\gamma_{SD}}{P_S\sigma^2_{Sk}}+\tfrac{\gamma_{th}-\gamma_{SD}}{P_{\text{soft}}\sigma^2_{kD}}))\sqrt{\beta}K_1(\sqrt{\beta}))]^N. \end{aligned} \tag{3.12}$$

The value of the γ_{SD} varies in each transmission depending on the source-destination link gain and thus P_{soft} computed in (3.12) varies for each transmission. The increase in delay and actual outage of the system in our proposed method are the cost paid to prevent the nodes from investing the majority of its energy resources in relaying messages during bad channel conditions.

The proposed P_{soft} scheme is a low complex method which enables each relay to compute P_{soft} locally. P_{soft} is calculated dynamically at the beginning of Phase II of each transmission with the aid of the new γ_{SD} information delivered by the destination.

3.4 Simulation Results

We show the lifetime and $\overline{P_{\text{outage}}}$ of the proposed scheme in conjunction with the selection relay strategies using computer simulations. In our simulations, the source power and threshold SNR are chosen to be $P_s = 12$ dBm and $\gamma_{th} = 8$ dB, respectively. The relay channel gain and receiver noise are assumed to have unit variances and identically and independently distributed. The number of relays, system outage probability threshold, and physical power limit at the relays are chosen to be $N = 5$, $\eta = 10\%$, and $P_{\max} = 82.25$ mW, respectively. $\eta = 10\%$ in [3] is considered as a good indication of the low residual energy level at the relays. We assume that the relays are located at equal distances from the source and destination and source-destination path suffers more attenuation, i.e. $\sigma^2_{SD} = \frac{1}{4}$. The residual energy levels of the batteries are presented in mJ and they are all the same at the beginning of the lifetime. The results are averaged over 10000 lifetimes in a *Monte Carlo* simulations. The values at which the parameters are initialized during the simulations are summarized in Table 3.1.

η	N	P_s (dBm)	$P_{\max}$(mW)	$\gamma_{th}(dB)$	σ^2_{Sk}	σ^2_{kD}	σ^2_{SD}	L
10%	5	12	82.25	8	1	1	$\frac{1}{4}$	$(\rightarrow \infty)$ continuous

Table 3.1: Values of the Parameters in the Simulations

Figure 3.3 shows the lifetime of the proposed diversity scheme (S-D Path) with P_{soft} ($S{-}D\ Path{+}P_{\text{soft}}$). When the dynamic transmit power threshold subject to $P_{\text{outage}} < \eta$ is used with the diversity scheme, the lifetime increases up to 30%. The lifetime are simulated for MOP, MEI, MTP, and MRE.

The results also show that the proposed algorithm successfully increases but maintains

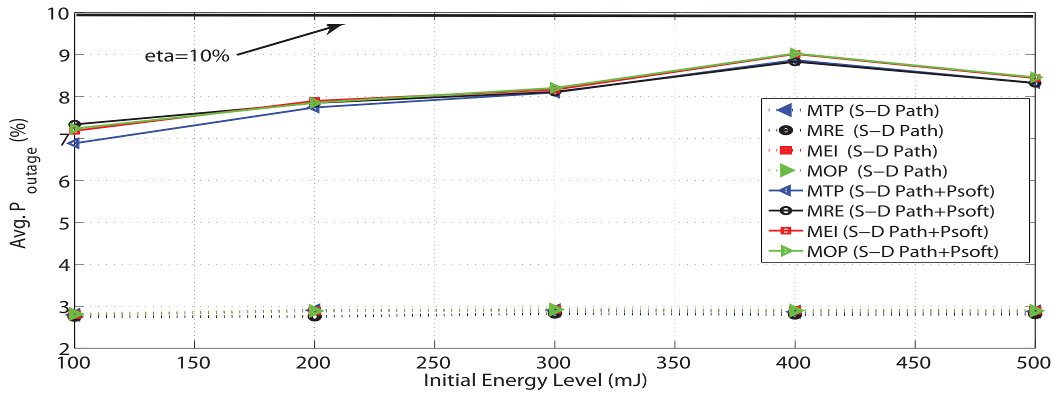

Figure 3.4: $\overline{P_{\text{outage}}}$ in 4 S-CRSs (MTP, MRE, MEI, MOP) and $N = 5$: the diversity scheme without P_{soft} ("Only S-D path") and the diversity scheme with P_{soft} ("S-D path+ P_{soft}") ©[2009] IEEE

the $\overline{P_{\text{outage}}}$ below the system outage probability requirements, $\eta = 10\%$. Note that the gap between the $\overline{P_{\text{outage}}}$ and η which can be utilized has enabled the proposed algorithm to improve the lifetime drastically.

We also observe that the dynamic transmit threshold scheme does not utilized the gap completely in Figure 3.4. Although the proposed algorithm creates a platform to improve the lifetime subject to satisfying η, it is not maximizes the lifetime and it may not be considered to be an optimized solution.

Chapter 4

The Delay Reduction Scheme

For convenience, we will refer to the system models described in Chapters 2 and 3 as System Models A and B, respectively. Similarly, the proposed algorithms in Chapters 2 and 3 are referred to as Algorithms A and B, respectively.

In this chapter, we investigate the average of maximum delay, $\overline{D_{\max}}$, that a message may experience during a lifetime of the network for Algorithms A and B.

Algorithms A and B were proposed to improve the network lifetime ensuring that $P_{\text{outage}} < \eta$ and they do not take $\overline{D_{\max}}$ into account. This $\overline{D_{\max}}$ parameter is important for urgent, high priority messages, e.g. control messages. In 4.2, we propose a scheme to reduce the effects of Algorithms A and B on $\overline{D_{\max}}$.

4.1 Impact of Algorithms A and B on $\overline{D_{\max}}$

Recall that Algorithms A and B are based on a transmit power threshold (P_{soft}) such that transmission is postponed if the power required to satisfy $\gamma_t h$ exceeds P_{soft}. As a

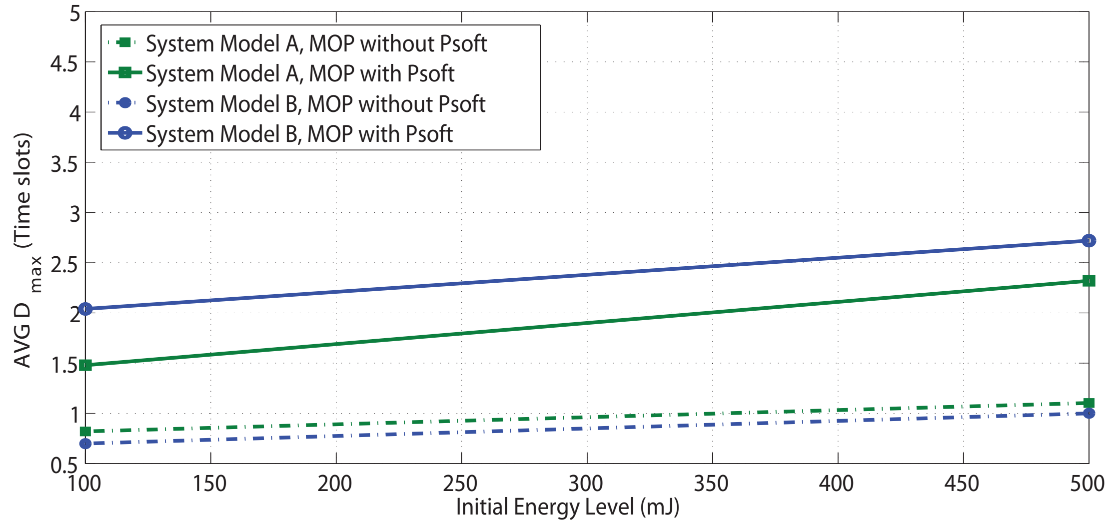

Figure 4.1: $\overline{D_{\max}}$ as a function of $\boldsymbol{E_0}$ in MOP and $N = 5$: System Model A and B without P_{soft} and System Models A and B with Algorithms A and B ("with P_{soft}")

result a relay may cause a message to experience long delays. Note that even though these algorithms may result in messages experiencing delays, they still ensure that $P_{\text{outage}} < \eta$.

Algorithms A and B can increase $\overline{D_{\max}}$ as shown in Figure 4.1. The system parameter values are initialized to those of Tables 2.2 and 3.1.

Figure 4.1 shows that $\overline{D_{\max}}$ is increased with the proposed P_{soft} scheme. For brevity, only the $\overline{D_{\max}}$ for MOP is discussed here; similar results for MEI and MTP are shown in Appendix B. The delay degradation caused by the proposed P_{soft} scheme depends on the system model and initial relay energy levels. The degradation is greater with

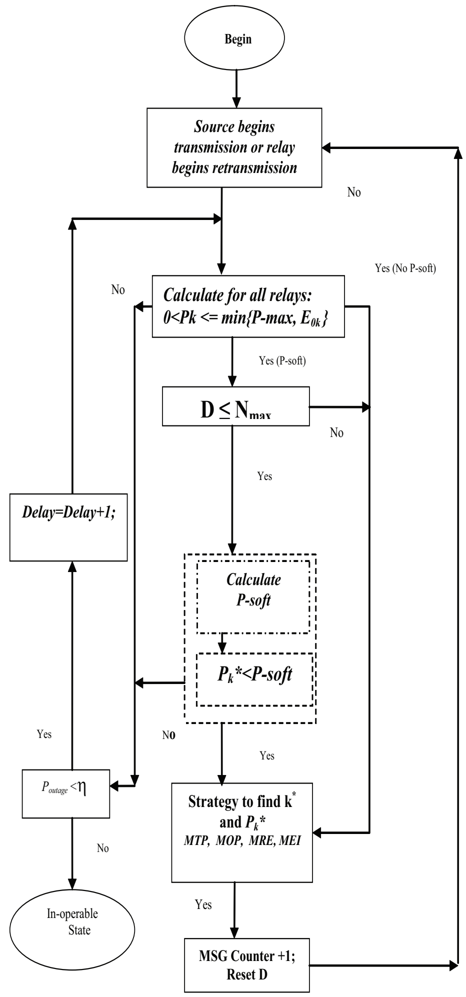

Figure 4.2: Flowchart of Algorithm A'

System Model B. Recall that each relay computes P_{soft} based on $\gamma_{th} - \gamma_{SD}$ for each transmission. When the source-destination link gain is relatively good, computed P_{soft} based on $\gamma_{th} - \gamma_{SD}$ is very small which can result longer delays. The advantage of the proposed P_{soft} scheme is an improved lifetime subject to $P_{\text{outage}} < \eta$ as shown in

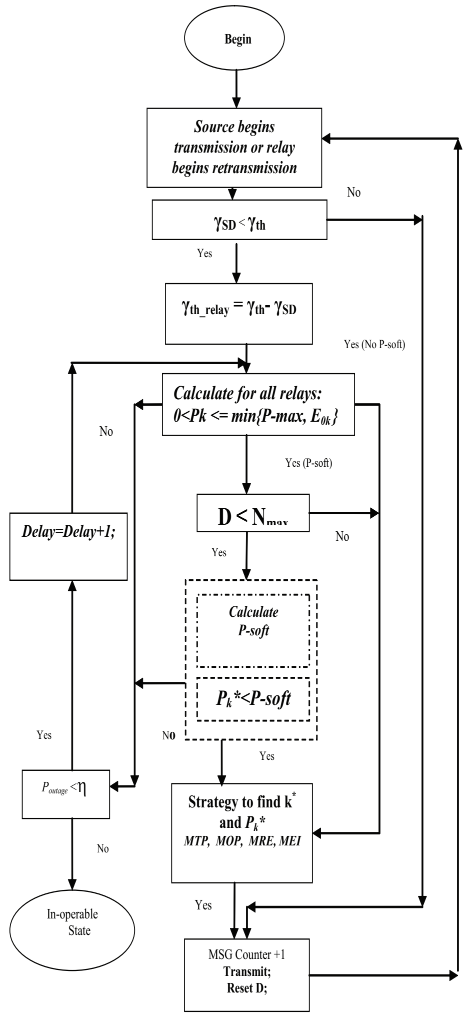

Figure 4.3: Flowchart of Algorithm B'

previous chapters.

4.2 Strategy to Improve $\overline{D_{\mathbf{max}}}$

In order to improve the message delay characteristics, we propose a scheme in which the P_{soft} transmit power restraint is suspended if the message experiences a delay, D, which exceeds $N_{\max}$ time slots. The resulting changes to Algorithms A and B can be summarized as:

- if $D > N_{\max}$, then the transmit power, P_k, is upper bounded $P_k \leq min\{P_{\max}, E_{0k}\}$; otherwise, $P_k \leq min\{P_{\text{soft}}, P_{\max}, E_{0k}\}$.

After a message is successfully received at the destination, the transmission of a new message is started. Flow charts for the modified algorithms are shown in Figures 4.2 and 4.3.

The delay control algorithms allow the network to save energy (when $D \leq N_{\max}$) and to reduce delays when $D > N_{\max}$. For convenience, We will refer to the modified Algorithms A and B as Algorithms A' and B', respectively.

4.3 Simulation Results

The average lifetime and $\overline{D_{\max}}$ were studied using computer simulations. The system parameter values used are listed in Tables 2.2 and 3.1. $\overline{D_{\max}}$ in MOP without P_{soft} for System Model A and B varies from less than a time slot to more than two time slots as shown in Figure 4.1. We set the $N_{\max}$ equal to the values of $\overline{D_{\max}}$ in MOP without the P_{soft} scheme in Figure 4.1, in order to enforce the network to reduce the impact of P_{soft} on $\overline{D_{\max}}$.

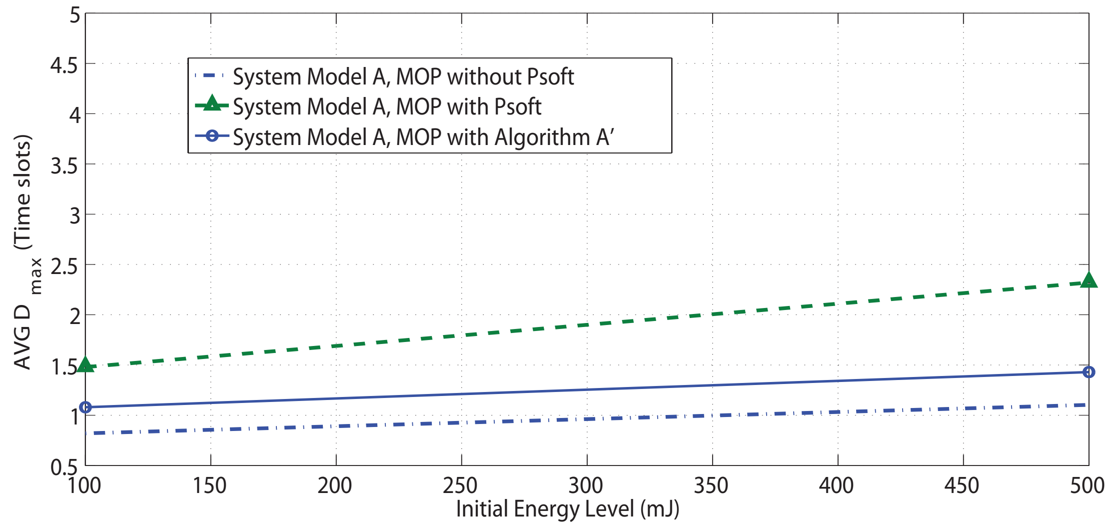

Figure 4.4: $\overline{D_{\max}}$ as a function of $\boldsymbol{E_0}$ in MOP and $N = 5$: System Model A without P_{soft}, with P_{soft}, and with Algorithm A'

We show $\overline{D_{\max}}$ of System Model A in MOP without P_{soft}, with Algorithms A and A' in Figure 4.4. Figure 4.5 exhibits $\overline{D_{\max}}$ of these algorithms for System Model B. Figures 4.4 and 4.5 show that Algorithms A' and B' have lower $\overline{D_{\max}}$ values than of Algorithm A and B. However, there exist a gap between $\overline{D_{\max}}$ curves of MOP without P_{soft} and MOP with Algorithms A' and B'. This is the result of the following scenarios:

1. When P_{soft} is disabled, outage happens when no relay can satisfy γ_{th} with P_k such that $0 < P_k \leq min\{P_{\max}, E_{0k}\}$. This generally does not take more than one time slot outages.

2. When Algorithms A' and B' enforce P_{soft} which may cause an outage, $N_{\max}$ is reached and P_{soft} scheme is disabled. Hence, system reduces to Scenario 1.

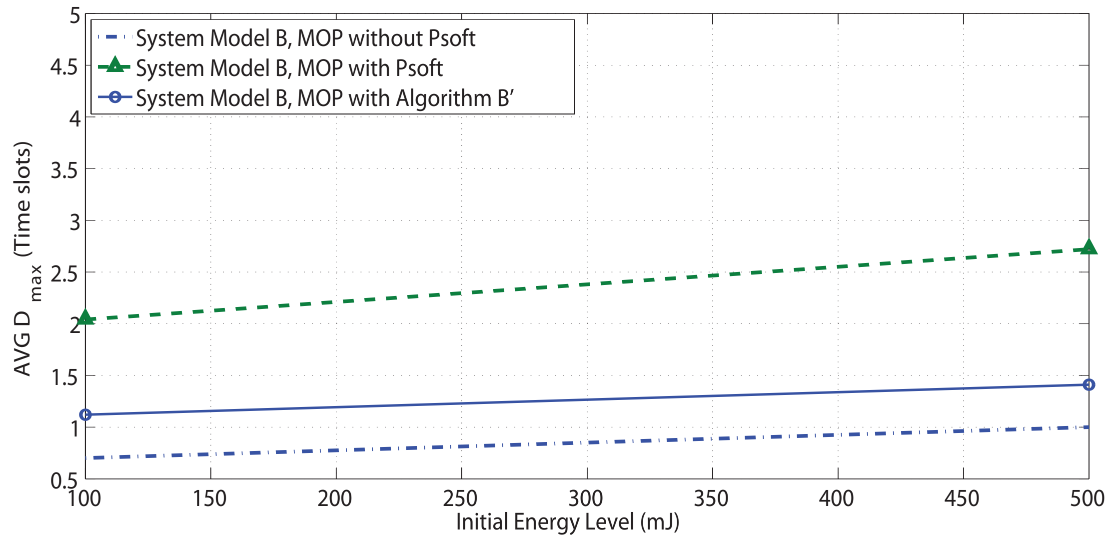

Figure 4.5: $\overline{D_{\max}}$ as a function of $\boldsymbol{E_0}$ in MOP and $N = 5$: System Model B without P_{soft}, with P_{soft}, and with Algorithm B'

The impacts of Algorithm A' on the average lifetime of System Model A is shown in Figures 4.6. The lifetime decreases from the lifetime of Algorithm A because Algorithm A' disables the P_{soft} restriction in some instant which causes the system to use higher transmission power than the threshold. In other instants, Algorithm A' conserves energy by enabling P_{soft}. Hence, the results show that Algorithm A' allows a trade-off between $\overline{D_{\max}}$ and average lifetime.

The impacts of Algorithm B' on the average lifetime of System Model B is shown in Figures 4.7. The Algorithm B' exhibits similar characteristics to Algorithm A', i.e average lifetime decrease due to Algorithms B'. Moreover, Figures 4.8 and 4.9 show that Algorithms A' and B' have successfully ensured $P_{\text{outage}} < \eta = 10\%$.

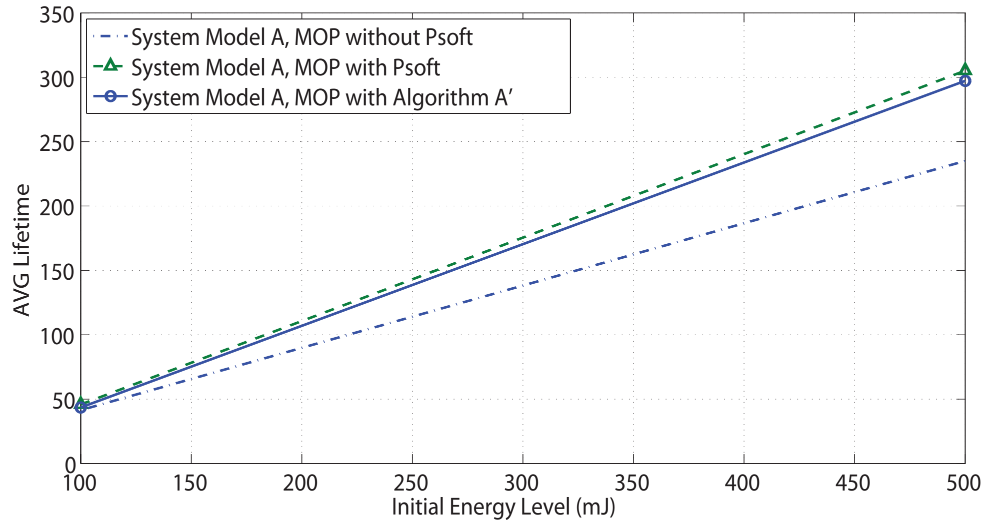

Figure 4.6: The average lifetime as a function of $\boldsymbol{E_0}$ in MOP and $N = 5$: System Model A without P_{soft}, with P_{soft}, and with Algorithm A'

Hence, Algorithms A' and B' have improved the lifetime and $\overline{D_{\max}}$ while satisfying $P_{\text{outage}} < \eta = 10\%$

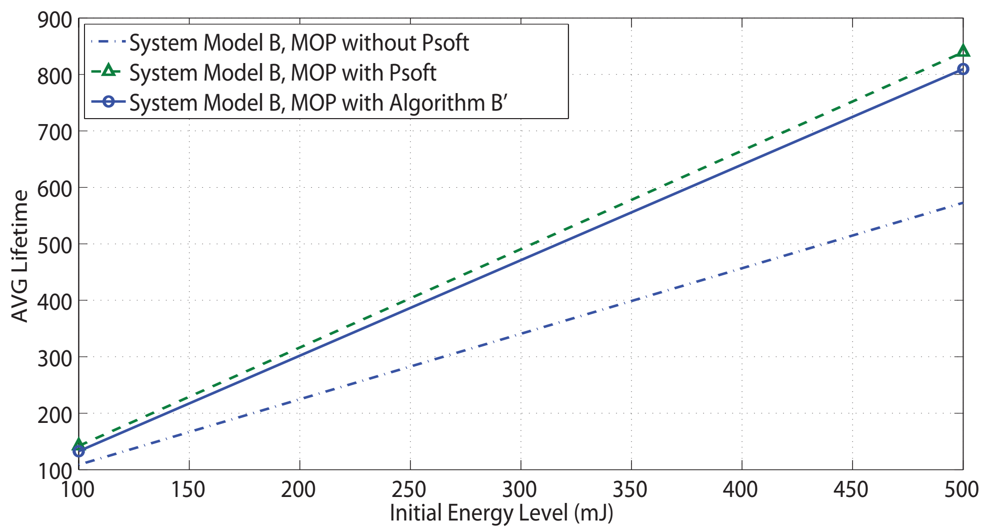

Figure 4.7: The average lifetime as a Function of $\boldsymbol{E_0}$ in MOP and $N = 5$: System Model B without P_{soft}, with P_{soft}, and with Algorithm B'

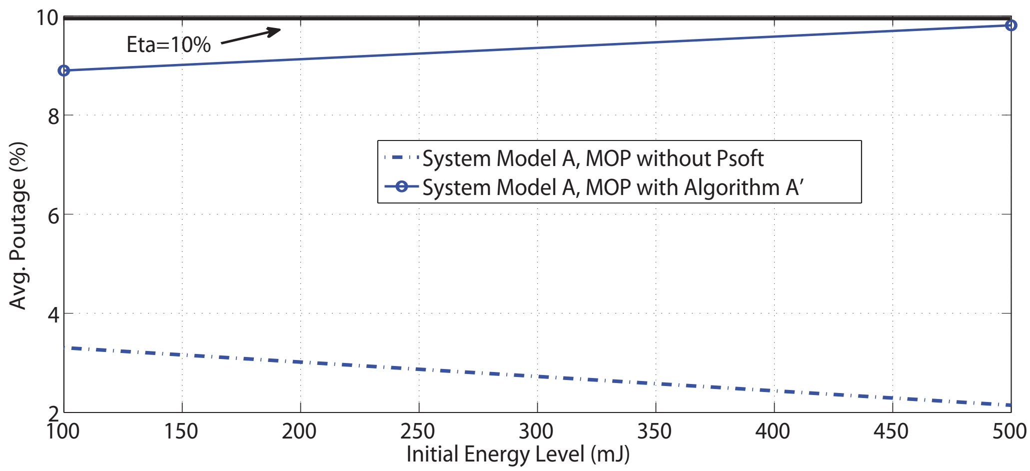

Figure 4.8: $\overline{P_{\text{outage}}}$ as a function of $\boldsymbol{E_0}$ in MOP and $N = 5$: System Model A without P_{soft} and with Algorithms A'

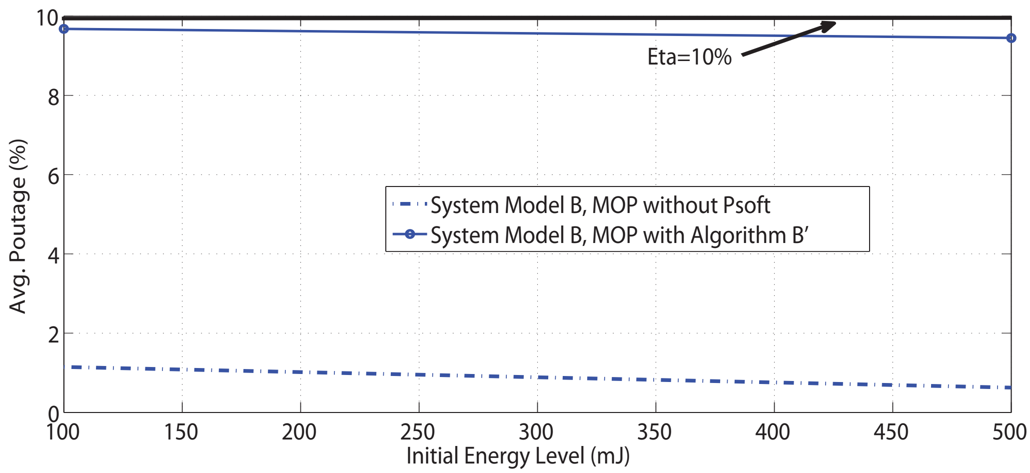

Figure 4.9: $\overline{P_{\text{outage}}}$ as a function of $\boldsymbol{E_0}$ in MOP and $N = 5$: System Model B without P_{soft} and with Algorithms B'

Chapter 5

Relevant Issues

The number of relays, channel gain variances (σ_{Sk}^2 and σ_{kD}^2), and noise power play crucial roles in the simulation results. These parameters were kept the same throughout the simulations in the previous chapters for fair comparisons. We study the effects of varying each parameter on the performances of Algorithms A' and B'. For brevity, we simulate the lifetime and P_{outage} of the algorithms for MOP in this section. Note that in previous chapters, we have shown the results as a function of $\boldsymbol{E_0}$ mJ for a fixed N. The results here, are simulated as a function of N for a fixed initial energy level at all relays in MOP. Some of the performances of Algorithms A' and B' in MEI and MTP are shown in Appendices C and D.

5.1 Number of Relays (N)

In S-CRSs, one selected relay which has relatively better channel links (and/or residual energy) is selected to transmit. When N increases, the network can exploit more number of links before selecting a relay to transmit. Hence, the diversity factor enables the network to save energy and to improve the lifetime. In this section the average lifetime, the average lifetime per relay, and $\overline{P_{\text{outage}}}$ of Algorithms A' and B' in MOP and $\boldsymbol{E_0 = 300}$mJ are simulated and discussed.

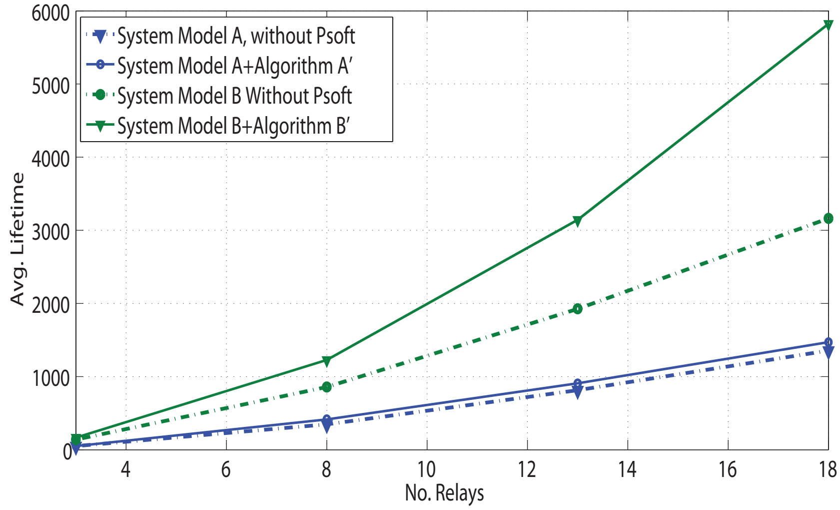

Figure 5.1: The average lifetime in MOP and $\boldsymbol{E_0}$= 300 mJ: System Models A and B with Algorithms A' and B', respectively.

We show the average lifetime and the average lifetime time per relay for the two system models in Figures 5.1 and 5.2, respectively.

The average lifetime of the network for each N illustrates the number of successfully received messages in the network by including the energy contribution of the extra relays as shown in Figure 5.1. In contrast, the average lifetime per relay in 5.2 shows the gain in the lifetime of each relay as new relays are added to the network.

Depending on the source power, the results show that Algorithm B' can improve the lifetime more drastically than Algorithm A'. For example, at N = 18 Algorithm B'

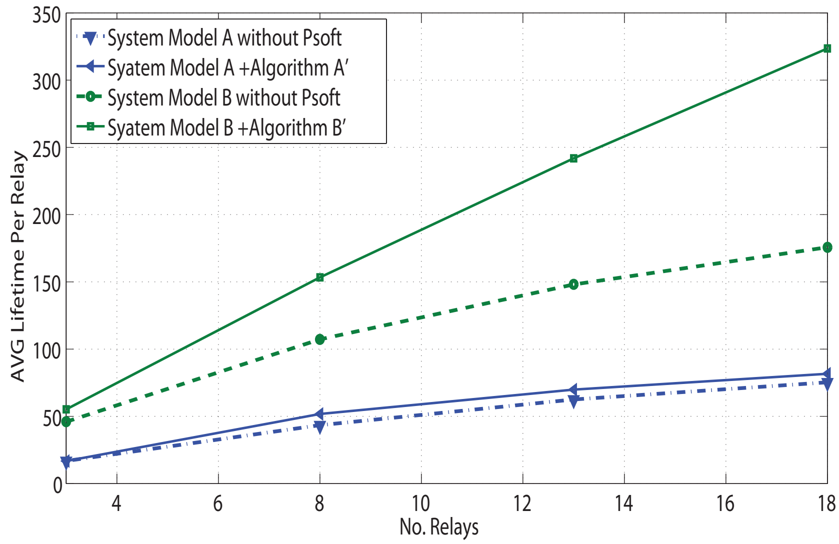

Figure 5.2: The average lifetime per relay in MOP and $\boldsymbol{E_0}$= 300 mJ: System Models A and B with Algorithms A' and B', respectively.

improves the average lifetime per relay from 175 to 320 received messages while Algorithm A' improves the average lifetime per relay from 75 to 81 received messages. If we increase $\boldsymbol{E_0}$ to a higher level, Algorithms A' and B' can save more energy and improve the lifetime further.

Figure 5.3 shows that Algorithms A' and B' improve the lifetime of the networks by maintaining $P_{\text{outage}} < \eta = 10\%$. Hence, the proposed algorithms enable the network to improve lifetime subject to $P_{\text{outage}} < \eta$ as N increases. In Appendix C, we show the performances (lifetime and P_{outage}) of Algorithm A' and B' in MEI and MTP.

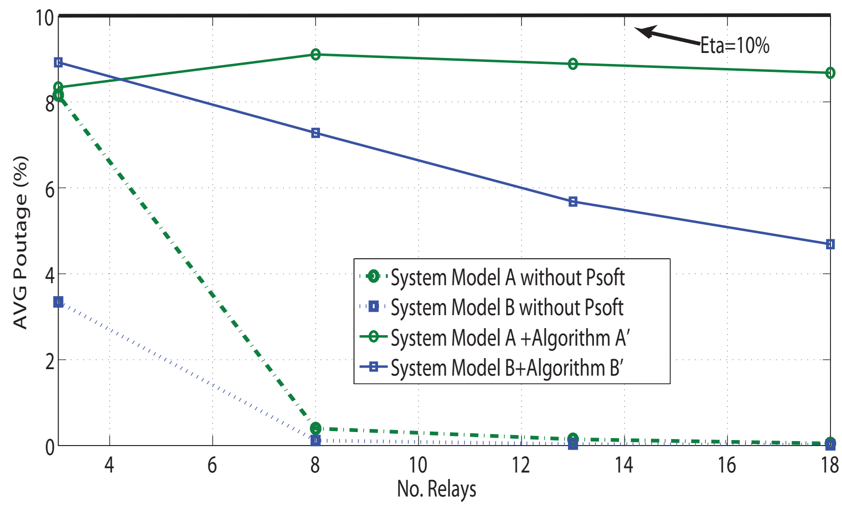

Figure 5.3: $\overline{P_{\text{outage}}}$ in MOP and $\boldsymbol{E_0}$= 300 mJ: System Models A and B with Algorithms A' and B', respectively.

5.2 Channel Gain Variances

The relay channel gains in Chapters 2 and 3 are assumed to be independent, circularly symmetric complex Gaussian random variable with unit variances and zero means, i.e. $\mathcal{CN}(0, 1)$. In Chapter 3, the gain variance of the source-destination link is chosen to be $\sigma_{SD}^2 = \frac{1}{4}$.

In order to study the effects of the channel gain variance on the performances of algorithms A' and B', we consider the following cases:

1. Case I: $\sigma_{Sk}^2 = \sigma_{kD}^2 = 1$.
2. Case II: $\sigma_{Sk}^2 = 1$ and $\sigma_{kD}^2 = 0.8$.

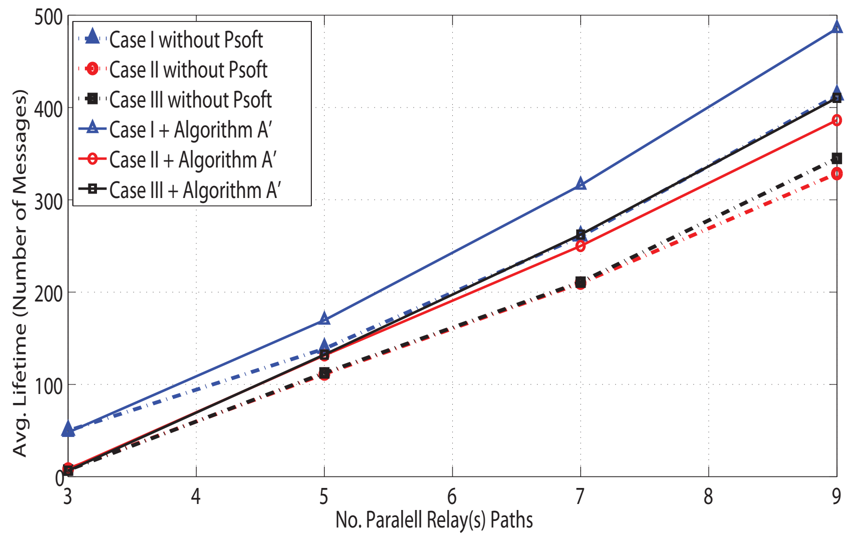

Figure 5.4: The average lifetime in MOP and $\boldsymbol{E_0}$= 300 mJ: System Model A with Algorithm A'

3. Case III: $\sigma^2_{Sk} = 0.8$ and $\sigma^2_{kD} = 1$.

The lifetime of Case I, II, and III for the System Models A and B in MOP and $\boldsymbol{E_0 = 300}$mJ are shown in Figures 5.4 and 5.5, respectively.

Given the fixed transmit power at the source (P_s = 12dB), Figures 5.4 and 5.5 show that Case III yields a better lifetime than Case II. In Case II, the relays have to compensate for the low relay-destination channel gains to satisfy γ_{th} which causes the relays to drain faster than in Case III. Moreover, Case I has a longer lifetime due to better channel gain in both links, i.e. $\sigma^2_{Sk} = \sigma^2_{kD} = 1$.

Next, we study the impact of the noise power on the lifetime of Algorithms A' and B'.

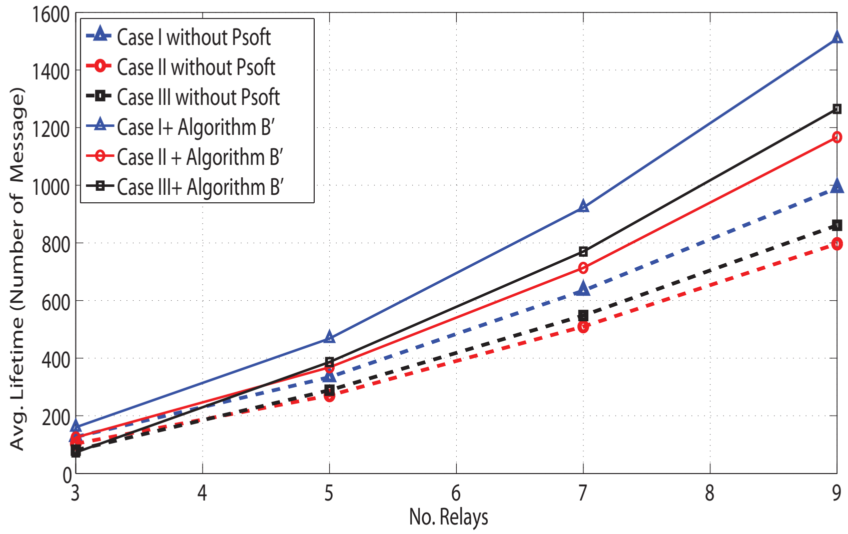

Figure 5.5: The average lifetime in MOP and $\boldsymbol{E_0}$= 300 mJ: System Model B with Algorithm B'

5.3 Noise Power

In Chapters 2 and 3, we assumed additive white gaussian noise (AWGN) with unit variances at the relays and the destination. We further simplified (3.6) by choosing the noise power to be $N_0 = 1$. We rewrite (3.6) without the those assumption in order to analyze the impacts of the noise power on the average lifetime of Algorithms A' and B' as follows:

$$\gamma_{eq} = \frac{P_S|h_{Sk}|^2 P_k|h_{kD}|^2}{P_S|h_{Sk}|^2 N_D + P_k|h_{kD}|^2 N_k + N_k N_D} \tag{5.1}$$

We investigate the impacts of the noise power on the average lifetime of Algorithms A' and B' using two methods:

- Method I: The relay and destination have the same noise power, i.e. $N_D = N_k = N_0$
- Method II: The relay and destination have different noise power.

We simplify (5.1) in Method I :

$$\gamma_{eq} = \frac{P_S|h_{Sk}|^2 P_k|h_{kD}|^2}{P_S|h_{Sk}|^2 N_0 + P_k|h_{kD}|^2 N_0 + N_0^2}. \tag{5.2}$$

Simulation results from using Method I allows us to investigate the impacts of the noise power on the performance of Algorithms A' and B'. We consider the following 2 cases for Method I:

- Case I_N: $N_0 = 1$
- Case II_N: $N_0 = 0.5$

The simulation results from using Method II can show which noise power, relay or destination, has a more crucial role on the performances of the Algorithms A and B. We consider the following 2 cases for Method II:

- Case III_N: $N_D = 0.5$ and $N_k = 1$.
- Case IV_N: $N_D = 1$ and $N_k = 0.5$.

The average lifetime for Cases I_N, II_N, III_N, and IV_N in MOP and $\boldsymbol{E_0 = 500}$mJ are shown in 5.6. In all the four cases, Algorithm A' allows saving in energy of the network and hence, improvements in the lifetime of the systems by ensuring $P_{\text{outage}} < \eta$. The

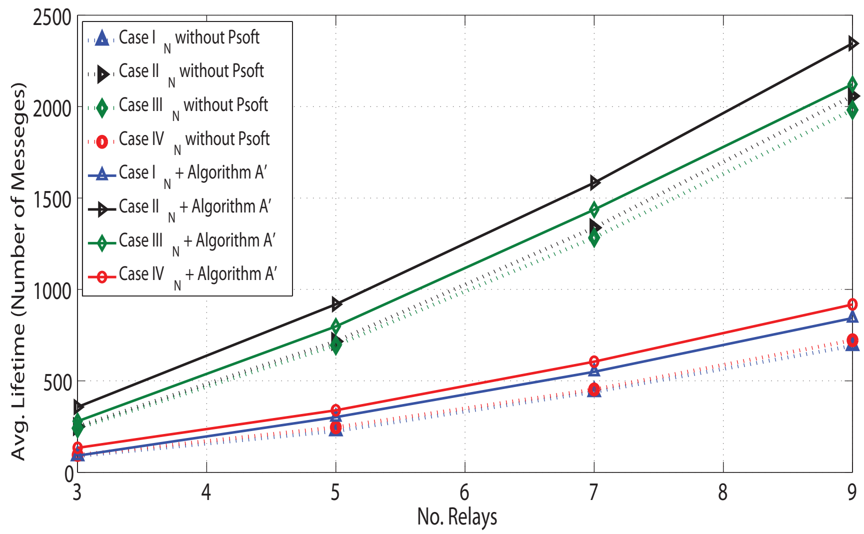

Figure 5.6: The average lifetime in MOP and $\boldsymbol{E_0}$= 300 mJ: System Model A with Cases I_N, II_N, III_N, and IV_N

results also show that when the noise power at the destination is low, Algorithm A' improves the lifetime drastically because relays have to use less energy to satisfy γ_{th}.

Given the fact that P_s is relatively large ($P_s = 12$ dBm) and constant in each transmission, the noise power at the destination plays an important role in the lifetime. Our investigation shows that the average transmit powers at the kth relay, $\overline{P_k}$, for System Models A nd B is about 10 dBm and 5 dBm in system model A and B, respectively. If P_s is reduced to a value close to the value of $\overline{P_k}$, then the noise power of the the relay and destination will have the same impact of the average lifetime of the system. Reduction of the noise power at the destination can allow the relays to use less P_k to satisfy γ_{th} and consequently to improve the lifetime.

Figure 5.7 shows the average lifetime of System Model B for the four cases in MOP.

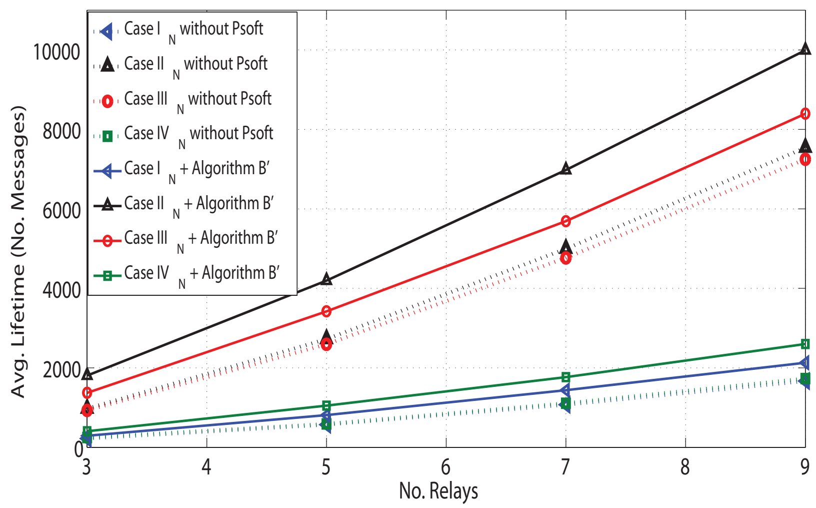

Figure 5.7: The average lifetime in MOP and $\boldsymbol{E_0}$= 300 mJ: System Model B with Cases I_N, II_N, III_N, and IV_N

The average lifetimes exhibit the same characteristics as those in System Model A. The impact of the noise power on the average lifetime of Algorithms A' and B' in MEI and MTP is similar to those of MOP.

Chapter 6

Conclusions and Future Work

6.1 Conclusion

Two algorithms, based on a transmit power threshold, are proposed to improve wireless relay network lifetime. Furthermore, the proposed algorithms have been modified to incorporate a mechanism to limit the delay that a message may experience during the lifetime due to transmit power threshold algorithms. The main contributions and results of this thesis can be summarized as follows:

- In Chapter 2, we proposed an algorithm that discourages the relays from using large energy expenditure for transmission under adverse channel conditions and favors transmissions in time slots with favorable channel conditions. This is done via a soft transmit power threshold P_{soft} which remains constant during the lifetime of the network. The proposed algorithm exploits the large gap which exists between the system outage probability requirement (η) and the average fraction, ($\overline{P_{\text{outage}}}$), of time slots which experience an outage. Our simulation results results show that the proposed algorithm can yield large improvements in the lifetime for all the Selective Cooperative Relay Strategies (S-CRS) when $N > 3$ [1].
- In Chapter 3, we proposed an opportunistic diversity scheme, which exploits the

source-destination link. The system outage probability for the proposed scheme is derived. A new dynamic transmit power threshold (P_{soft}) is introduced to limit the relays from using an inordinate amount of energy when all relays have adverse channel conditions. The dynamic P_{soft}, in conjunction with the diversity scheme improves the network lifetime drastically and ensures $P_{\text{outage}} \leq \eta$ is met [2].

- The results from Chapters 2 and 3 show that a message may experience a large delay due to the P_{soft} transmit power scheme. To address this problem, we proposed in Chapter 4 a scheme to reduce the delay. The simulation results show that the proposed scheme greatly reduce the delay at the cost of a small reduction in network lifetime.

6.2 Recommendations on Future Works

The costs of acquiring CSI for the relays are not considered in the proposed algorithms because reciprocity for the relay-destination links are assumed and each relay uses the pilot signals from the source and destination to calculate the CSI about its own links. Assuming the source and destination are not restricted in energy supply, the relays only use a small energy expenditure to compute CSI. If the relay-destination links are not reciprocal and channel gains vary in every time slot, then each relay needs to send a pilot signal to the destination before each transmission in order for the destination to feedback the CSI to each relay. In the (S-CRSs) studied, each relay acquires CSI before each transmission which can consume a considerable amount of energy.

In contrast to S-CRSs where relays are chosen based on their channel gains and residual energies, we are proposing a cooperative relay strategy in which a relay is chosen

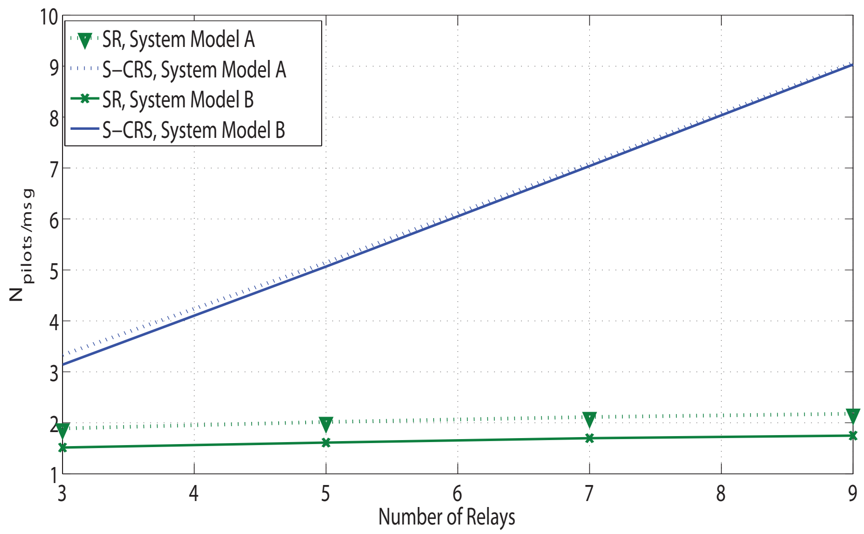

Figure 6.1: $\overline{Pilots}_{\mathrm{msg}}$ and $\boldsymbol{E_0} = 300$mJ: SR and S-CRSs for System Models A and B

randomly to forward a message. In the proposed sequential random (SR) selective cooperative strategy , the number of pilots, $Pilots_{\mathrm{msg}}$, per successfully received message at all relays is less than that of S-CRSs. In Figure 6.1, we show the average number of pilots, $\overline{Pilots}_{\mathrm{msg}}$, per received message for SR and S-CRSs. In the random strategy, the network compromises between the energy saving from fewer number of acquired CSI and the extra energy consumption in transmission due to lack of CSI availability at all relays.

Bibliography

[1] S. A. Mousavifar, T. Khattab, and C. Leung, “A predictive strategy for lifetime maximization in selective relay networks,” in *Proc. Sarnoff Symposium*, Princeton, NJ, U.S.A., 2009, pp. 1–6.

[2] ——, “Lifetime maximization with predictive power management in selective relay networks,” in *Proc. Personal, Indoor and Mobile Radio Communications Symposium 2009 (PIMRC 2009)*, Tokyo, Japan, Sep. 2009, pp. 67–72.

[3] W. J. Huang, Y. W. Hong, and C. J. Kuo, “Lifetime maximization for amplify-and-forward cooperative networks,” in *Proc. IEEE Wireless Communications and Networking Conference*, Las Vegas, Nevada, U.S.A., May 2008, pp. 814–818.

[4] X. Bao and J. Li, “Efficient message relaying for wireless user cooperation: Decode-amplify-forward (daf) and hybrid daf and coded-cooperation,” *IEEE Transactions on Wireless Communications*, vol. 6, pp. 3975–3984, Nov. 2007.

[5] P. Lusina, R. Schober, and L. Lampe, “Diversity-multiplexing trade-off of the hybrid non-orthogonal amplify-decode and forward protocol,” in *Proc. IEEE International Symposium on Information Theory*, Toronto, Canada, Jul. 2008, pp. 2375–2379.

[6] M. O. Hasna and M.-S. Alouini, "End-to-end performance of transmission systems with relays over rayleigh-fading channels," *IEEE Transaction on Wireless Communications*, vol. 2, pp. 1126–1131, Nov. 2003.

[7] ——, "Optimal power allocation for relayed transmissions over rayleigh-fading channels," *IEEE Transaction on Wireless Communications*, vol. 3, pp. 1999–2004, Nov. 2004.

[8] M. D. Renzo and F. Graziozi, "On the performance of csi-assisted cooperative communications over generalized fading channels," in *Proc. IEEE International Conference on Communications*, Beijing, China, May 2008, pp. 1001–1007.

[9] W. J. Huang, F. H. Chiu, and C. J. Kuo, "Comparison of power control schems for relay sensor networks," in *Proc. IEEE International Conference on Acoustics, Speech and Signal Processing*, Honolulu, Hawai'i, U.S.A., Apr. 2007, pp. 477–480.

[10] R. Madan, N. B. Mehta, A. F. Molisch, and J. Zhang, "Energy-efficient cooperative relaying over fading channels with simple relay selection," in *Proc. IEEE Global Telecommunications Conference*, San Francisco, CA, U.S.A., Aug. 2006, pp. 1–6.

[11] J. He and P. Y. Kam, "Exact bit error probability of cooperative space-time block coding with amplify-and-forward strategy," in *Proc. IEEE International Conference on Communications*, Beijing, China, May 2008, pp. 4591 – 4595.

[12] M. Badr, E. C. Strinati, and G. C. Belfiore, "Optimal power allocation for hybrid amplify-and-forward cooperative networks," in *Proc. IEEE Vehicular Technology Conference*, Marina Bay, Singapore, May 2008, pp. 2111–2115.

[13] T. Q. Duong, D. B. Ha, H. A. Tran, and N. S. Vo, "Symbol error probability of distributed-alamouti scheme in wireless relay networks," in *Proc. IEEE Vehicular Technology Conference*, Marina Bay, Singapore, May 2008, pp. 648–652.

[14] S. Barbarossa and G. Scutari, "Distributed space-time coding for multihop networks," in *Proc. IEEE International Conference on Communications*, Paris, France, Jun. 2004, pp. 916–920.

[15] J. N. Laneman and G. W. Wornell, "Energy efficient antenna sharing and relaying for wireless networks," in *Proc. IEEE Wireless Communications and Networking Conference (WCNC)*, Chicago,IL, USA, Sep. 2000, pp. 7–12.

[16] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity-part i: System description," *IEEE Transaction on Wireless Communications*, vol. 51, pp. 1927–1938, Nov. 2003.

[17] ——, "User cooperation diversity-part ii: Implementation aspects and performance analysis," *IEEE Transaction on Wireless Communications*, vol. 51, pp. 1927–1948, Nov. 2003.

[18] H. Rong, Z. Zhang, and P. Larsson, "Cooperative relaying based on alamouti diversity under aggregate relay power constraints," in *Proc. IEEE Vehicular Technology Conference*, Melbourne, Australia, May 2006, pp. 2563–2567.

[19] N. Ahmed, M. A. Khojastepour, A. Sabharwal, and B. Aazhang, "Outage minimization with limited feedback for the fading relay channel," *IEEE Transaction on Wireless Communications*, vol. 54, pp. 659–669, Apr. 2006.

[20] J. Adeane, M. R. D. Rodrigues, and I. J. Wassell, "Optimum power allocation in cooperative networks," in *Postgraduate Research Conference in Electronics,*

Photonics, Communications and Networks, and Computing Science (PREP 2005), Lancaster, UK, Mar. 2005, pp. 23–24.

[21] Y. Liang and V. V. Veeravalli, "Resource allocation for wireless relay channels," in *Proc. Conference Record of the Thirty-Eighth Asilomar Conference on Signals, Systems, and Computers*, CA, U.S.A., Nov. 2004, pp. 1902–1906.

[22] R. Mochado and B. F. Filho, "A cooperative diversity scheme with partial channel knowledge at the cooperating nodes," in *Proc. IEEE International Conference on Communications*, Beijing, China, May 2008, pp. 4580 – 4585.

[23] T. A. Tsiftsis, G. K. Kotsopoulos, and S. A. Pavlidou, "Ber analysis of collaborative dual-hop wireless transmissions," *Electronics Letters*, vol. 40, pp. 679– 681, May 2004.

[24] M. Chen and S. Serbetli, "Distributed power allocation for parallel relay networks," in *Proc. IEEE Global Telecommunications Conference*, St. Louis, MO, U.S.A., Dec. 2005, pp. 1–5.

[25] Y. Li, B. Vucetic, Z. Zhendong, and M. Dohler, "Distributed adaptive power allocation for wireless relay networks," in *Proc. IEEE Vehicular Technology Conference*, Dublin, Ireland, Mar. 2007, pp. 948–958.

[26] Z. Yi and L. M. Kim, "Diversity order analysis of the decode-and-forward cooperative networks with relay selection," *IEEE Transaction on Wireless Communications*, vol. 51, pp. 1167–1171, May 2008.

[27] Y. A. Chau and K. Y. haung, "Channel statistics and performance of cooperative selection diversity with dual-hop amplify-and-forward relay over rayleigh fading

channels," *IEEE Transaction on Wireless Communications*, vol. 7, pp. 1779–1785, May 2008.

[28] Z. Zhong, S. Zhu, and G. Lv, "Distributed space-time coding based on amplify-and-forward protocol," in *Proc. Communications and Networking in China*, China, Oct. 2006, pp. 1–5.

[29] K. Tourki, M. S. Aluini, and L. Deneire, "Blind cooperative diversity using distributed space-time coding in block fading channels," in *Proc. IEEE International Conference on Communications*, Beijing, China, May 2008, pp. 4596–4600.

[30] M. O. Hasna and M.-S. Alouini, "A performance study of the dual hop transmissions with fixed gain relays," *IEEE Transaction on Wireless Communications*, vol. 3, pp. 1963–1968, Nov. 2004.

[31] A. Bletsas, A. Khisti, D. Reed, and A. Lippman, "A simple cooperative diversity method based on network path selection," *IEEE Journal on Selected Area in Communications*, vol. 24, pp. 659–672, Mar. 2006.

[32] A. Swami, Q. Zhao, Y. Hong, and L. Tong, *Wireless Sensor Networks: Signal Processing and Communications*, 1st ed., ser. Course of Theoretical Physics. Oxford; New York: John Willy & Sons., 2007, vol. 3.

[33] J. Chang and L. Tassiulas, "Maximum lifetime routing in wireless sensor networks," *IEEE/ACM Transactions on Networking*, vol. 12, pp. 609–619, Aug. 2004.

[34] Y. T. Hou, Y. Shi, H. D. Sherali, and S. F. Midkiff, "On energy provisioning and relay node placement for wireless sensor networks," *IEEE Transaction on Wireless Communications*, vol. 4, pp. 2579–2590, Sep. 2005.

[35] T. Himsoon, W. P. Siriwongpairat, Z. Han, , and K. J. Liu, "Lifetime maximization via cooperative nodes and relay deployment in wireless networks," *IEEE Journal on Selected Area in Communications*, vol. 25, pp. 306–317, Feb. 2007.

[36] W. J. Huang, Y. W. Hong, and C. C. J. Kuo, "Discrete power allocation for lifetime maximization in cooperative networks," in *Proc. Vehicular Technology Conference*, Baltimore, MD, U.S.A., Oct. 2007, pp. 581–585.

[37] S. Ikki and M. Ahmed, "Performance of multiple-relay cooperative diversity systems with best relay selection over rayleigh fading channels," *EURASIP Journal on Advances in Signal Processing*, vol. 2008, no. 145, Mar. 2008.

Appendix A

List of Publications

Chapters 2 and 3 are largely based on two conference papers previously published by IEEE which retains the original copy rights of those works.

S. A. Mousavifar, T. Khattab, and C. Leung, " A predictive strategy for lifetime maximization in selective relay networks," in Proc. Sarnoff Symposium, Princeton, NJ, U.S.A., 2009, pp. 1-6.

S. A. Mousavifar, T. Khattab, and C. Leung, "Lifetime maximization with predictive power management in selective relay networks," in Proc. Personal, Indoor and Mobile Radio Communications Symposium 2009 (PIMRC 2009), Tokyo, Japan, Sep. 2009, pp. 67-72.

Appendix B

The Delay Reduction Scheme in MEI and MTP

The average lifetime , $\overline{D_{max}}$, and $\overline{P_{\text{outage}}}$ for MTP and MEI are shown using computer simulations. The system parameters are initialized to those of Tables 2.2 and 3.1.

The same arguments on the simulation results of MOP discussed in Section 4.3 hold for simulation results of MEI and MTP. The average lifetime, $\overline{P_{\text{outage}}}$, and $\overline{D_{max}}$ are reduced when Algorithms A' and B' are introduced to the network. The results show that by compromising very little in the lifetime of the network Algorithms A' and B' can reduce the $\overline{D_{max}}$ drastically in the network.

Figures B.1 and B.2 show the impact of the algorithms on the average lifetime in MEI and MTP, respectively. Figures B.3 and B.4 show the impact of the algorithms on $\overline{D_{max}}$ in MEI and MTP, respectively. And Figures B.5 and B.6 show the impact of the algorithms on $\overline{P_{\text{outage}}}$ in MEI and MTP, respectively.

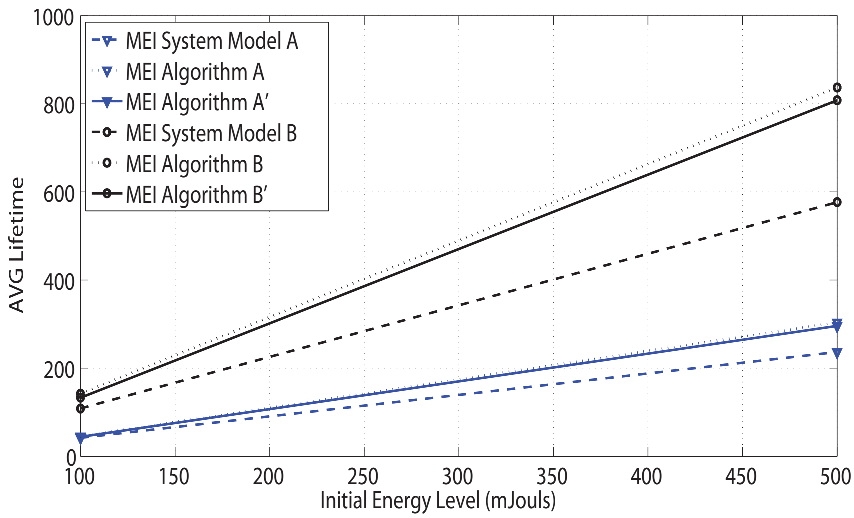

Figure B.1: The impact of Algorithms A, B, A', and B' on the average lifetime in MEI and $N = 5$

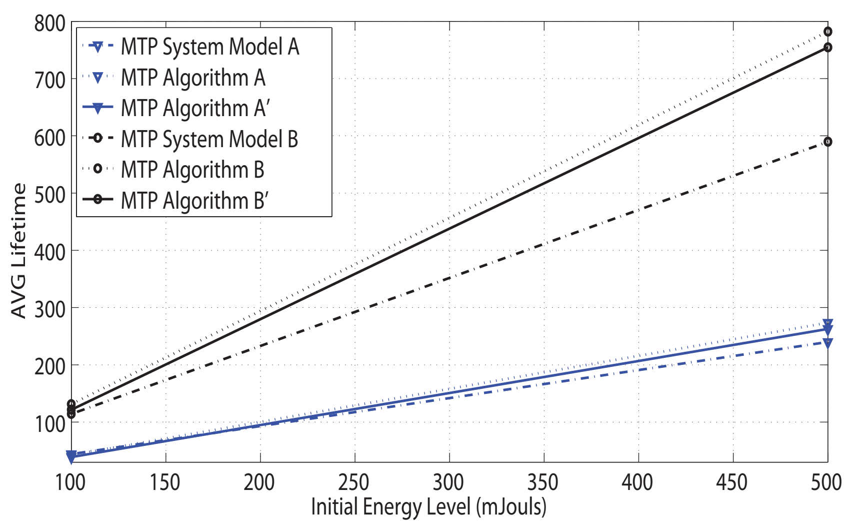

Figure B.2: The impact of Algorithms A, B, A', and B' on the average lifetime in MTP and $N = 5$

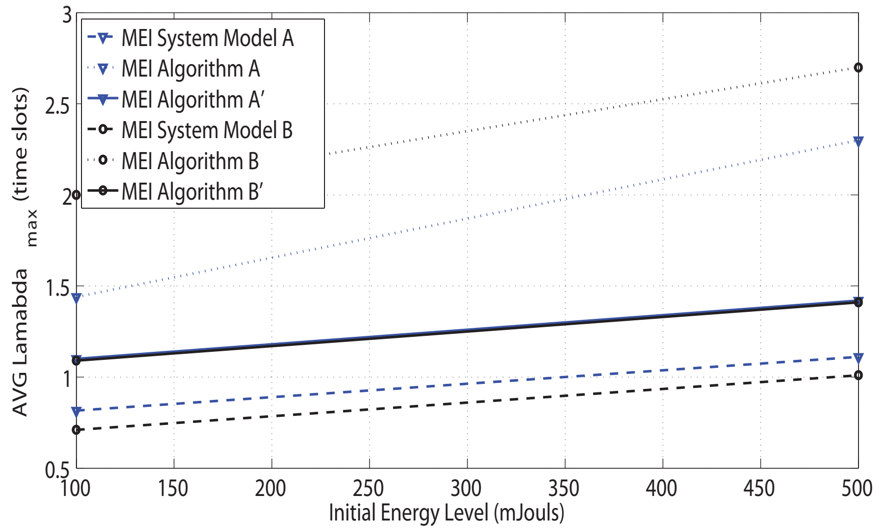

Figure B.3: The impact of Algorithms A, B, A', and B' on $\overline{D_{max}}$ in MEI and $N = 5$

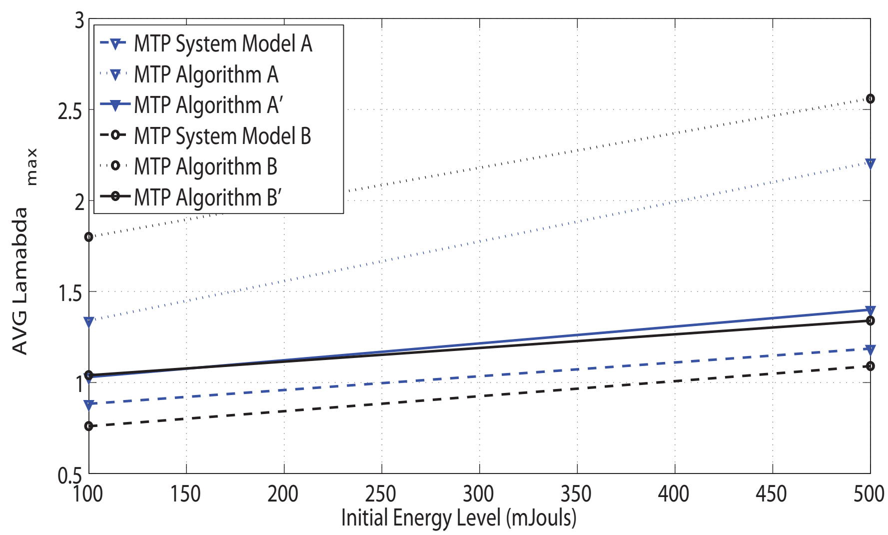

Figure B.4: The impact of Algorithms A, B, A', and B' on $\overline{D_{max}}$ in MTP and $N = 5$

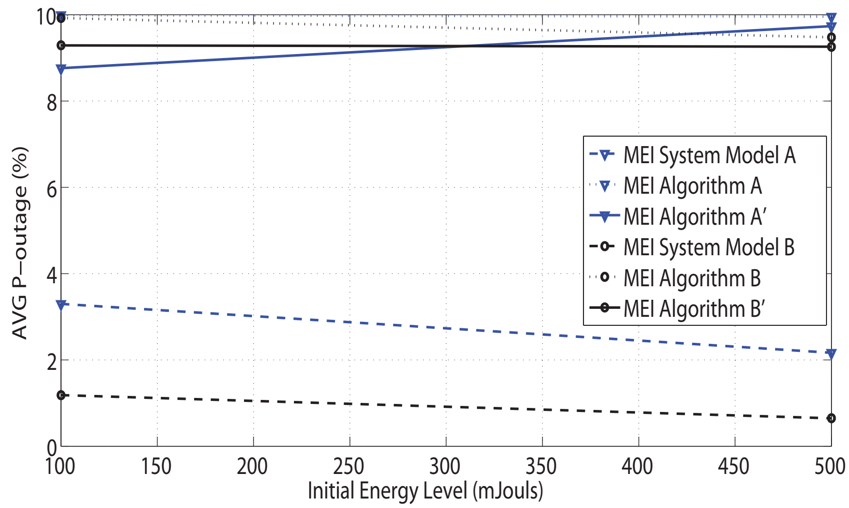

Figure B.5: The impact of Algorithms A, B, A', and B' on $\overline{P_{\text{outage}}}$ in MEI and $N = 5$

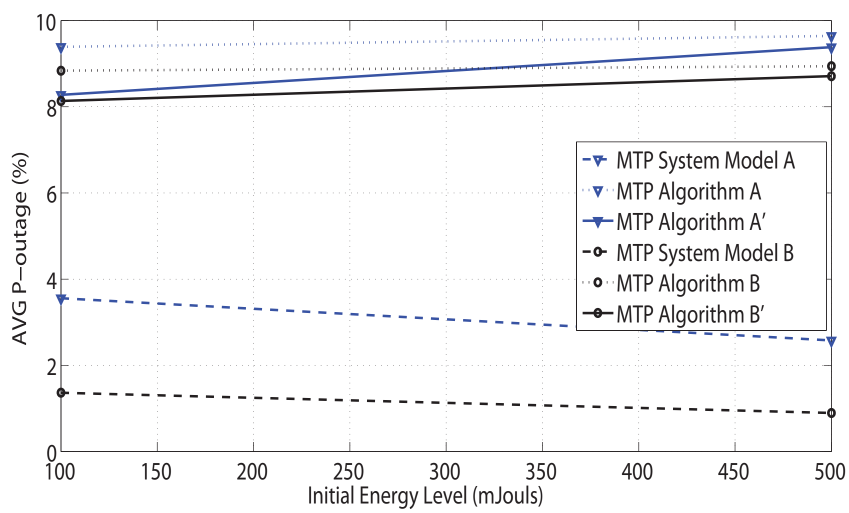

Figure B.6: The impact of Algorithms A, B, A', and B' on $\overline{P_{\text{outage}}}$ in MTP and $N = 5$

Appendix C

Impact of N on the Lifetimes in Algorithms A' and B' in MEI and MTP

The average lifetime for the two system models in MEI and MTP are shown in Figures C.1 and C.2, respectively. The results show that the lifetime increases drastically as the number of relays increases.

The average lifetime per relay for the two system models in MEI and MTP are shown in Figures C.3 and C.4, respectively. The results can show the gain in the lifetime of each relay as new relays are introduced to the network.

The discussions on the impact of N on the lifetime of Algorithms A' and B' in MOP hold for MEI and MTP.

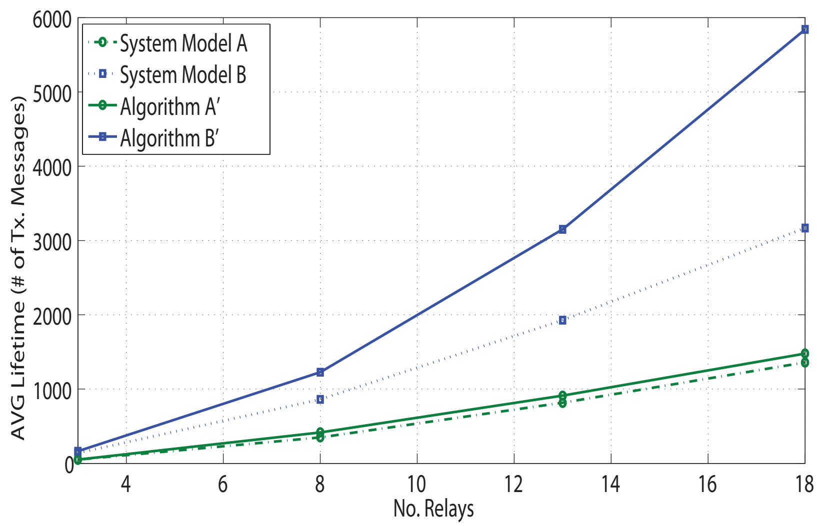

Figure C.1: The average lifetime in MEI and $\boldsymbol{E_0}$= 300mJ: System Model A and B without P_{soft} ("System Model A") and System Model A and B with Algorithms A' and B', respectively

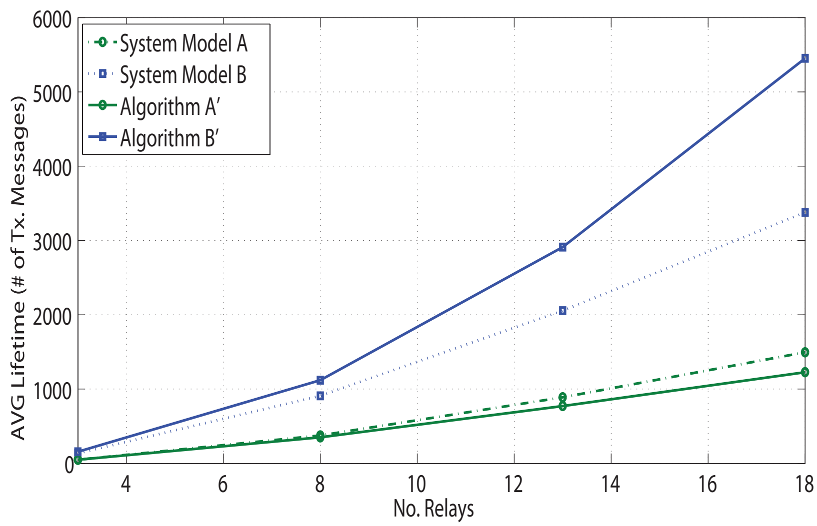

Figure C.2: The average lifetime in MTP and $\boldsymbol{E_0}$= 300mJ: System Model A and B without P_{soft} ("System Model A") and System Model A and B with Algorithms A' and B', respectively

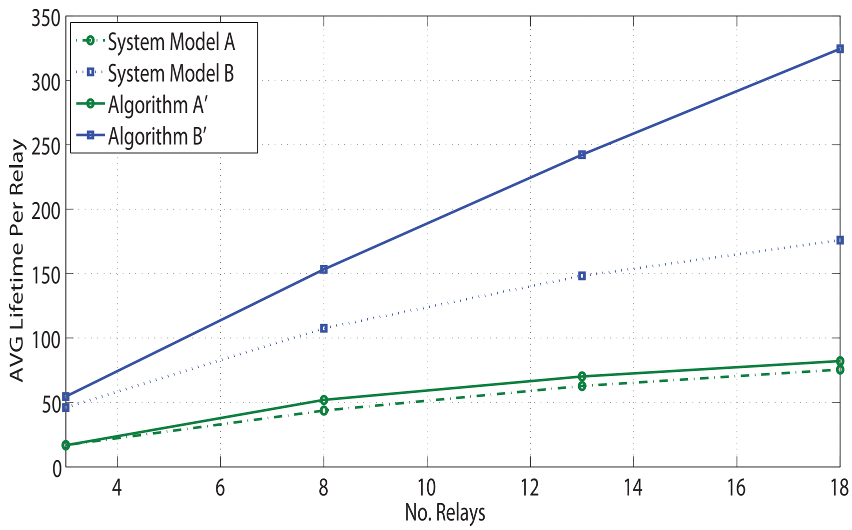

Figure C.3: The average lifetime per relay in MEI and $\boldsymbol{E_0}$= 300mJ: System Model A and B without P_{soft} ("System Model A") and System Model A and B with Algorithms A' and B', respectively

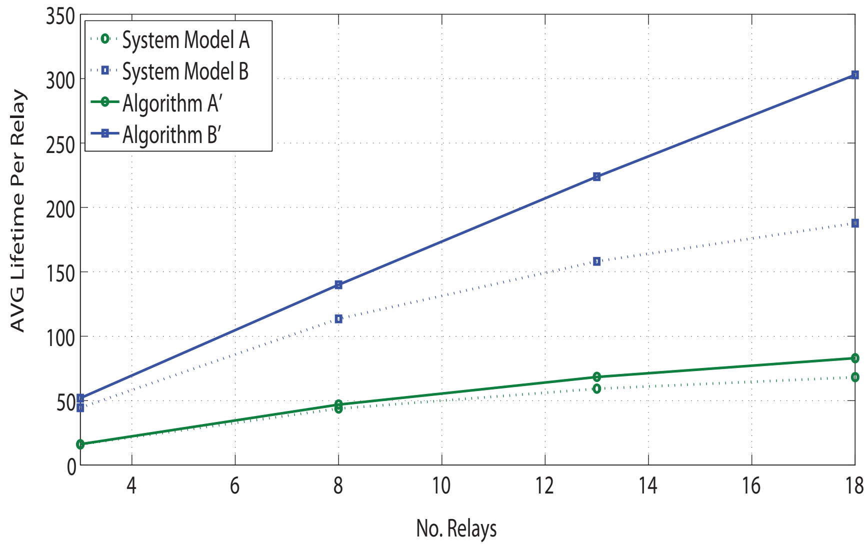

Figure C.4: The lifetime per relay in MTP and $\boldsymbol{E_0}$= 300mJ: System Model A and B without P_{soft} ("System Model A") and System Model A and B with Algorithms A' and B', respectively

Appendix D

Impact of Channel Gain Variances on the Lifetime in MEI

The discussions on the impact of Channel Gain Variances on the lifetime of Algorithms A' and B' in MOP hold for MEI. We briefly refer to the three case of channel gain variations discussed in Section 5.2:

1. Case I: $\sigma^2_{Sk} = \sigma^2_{kD} = 1$
2. Case II: $\sigma^2_{Sk} = 1$ and $\sigma^2_{kD} = 0.8$
3. Case III: $\sigma^2_{Sk} = 0.8$ and $\sigma^2_{kD} = 1$

The lifetime of Algorithms A' and B' in MEI (for Cases I, II, and III) are shown in Figures D.1 and D.2, respectively. The dashes lines refer to the system without the proposed algorithms and the markers specify the same channel conditions, i.e. circle markers refer to Case II in which $\sigma^2_{Sk} = \sigma_{kD^2} = 1$.

The results show that in when the channel gain variance of the source-relay or relay-destination decreases Algorithms A' and B' improve the lifetimes. However, on average in Cases II and III the channel gains are less than Case I and the relays must contribute more energy to satisfy γ_{th}. Hence, in Case I Algorithms A' and B' improve the lifetimes

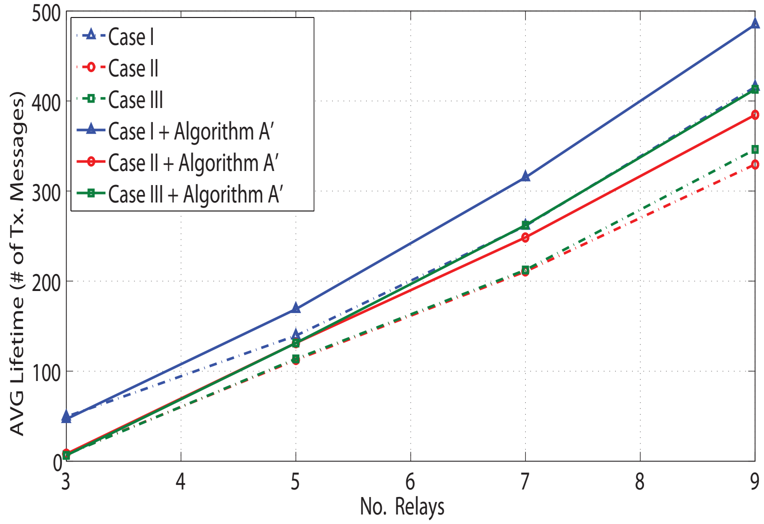

Figure D.1: The impact of channel variances on the average lifetime in MEI: System Model A with Algorithm A'

more than Case I and III.

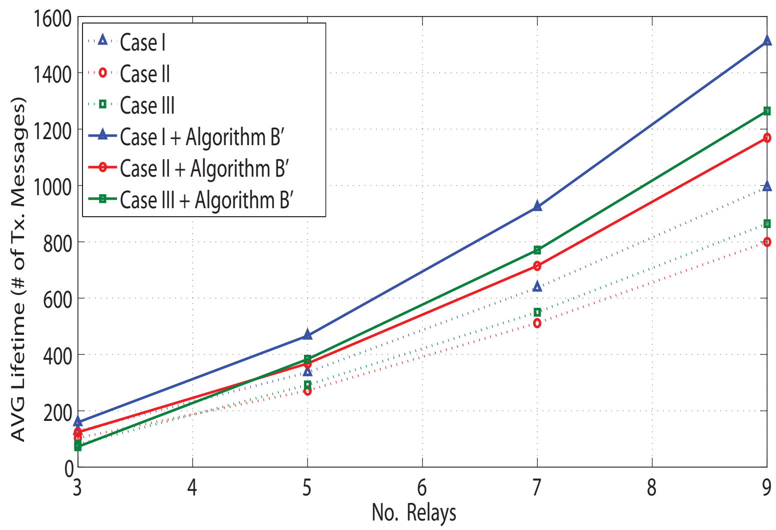

Figure D.2: The impact of channel variances on the average lifetime in MEI: System Model B with Algorithm B’