Summary

Cooperative multi-hop relay networks progress significantly in recent years. Conventionally, relay stations are used to achieve higher diversity gain and improve link reliability. However, how to choose a relay to obtain higher throughput is rarely discussed in the literature.

This thesis is aiming at proposing the relay selection rules to achieve higher throughput, while maintaining link reliability. We propose two partner selection methods in this thesis. The first one is to calculate throughput corresponding to each relay, and then choose the relay achieving the maximal throughput. Though this method can achieve the highest throughput, its computation cost is quite high. In the second method, we first compare the SNR of the relay link from the source with the SNR of the relay link to the destination, and designate the smaller one as the bottleneck SNR associated with that relay. The bottleneck SNR of each relay is recorded and compared. The relay with the largest bottleneck SNR is selected. Both methods have the similar throughput performance. However, the outage probability of the second method is better than that of the first one. Meanwhile, compared to the conventional signal-based partner selection, the proposed bottleneck SNR approach can achieve higher throughput at the cost of small SNR degradation.

Furthermore, we examine the performance of the considered relay selection rules in the multiple relay case. We find that at the same consumed power level the outage probability and throughput performance in the multi-relay case is indeed worse than those in the one relay case. This is because the multi-relay case yields more power consumption and higher probability in selecting inappropriate relays.

In the traditional method, the transmit power allocated in the relay link from the source is the same as that in the relay link to the destination. Now, we suggest a simple power distribution algorithm to adjust transmit power from the relay as the number of the relays increases. In the suggested power distribution rule, the transmit

power of each relay is inversely proportional to the number of relays, and the sum of the total transmit power from the relay is equal to the transmit power from the source. Our results show that at the same consumed power level the proposed power distribution can improve outage probability, while maintaining throughput even in the multi-relay case. The proposed power allocation can eliminate unnecessary power in the second transmission phase with multiple relays.

To summarize, we first propose two throughput-oriented relay selection rules and provide the trade-off analysis between throughput and reliability. Second, we develop a power distribution algorithm and improve the outage probability even in the multi-relay case. Last but not least, we obtain insights of relay selection rule for the design in a multi-hop relay network.

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CHAPTER 1

Introduction

Cooperative multi-hop relay networks progress significantly recent years. Relay stations (RSs) [1, 2] are used to obtain higher diversity gain and thus better link reliability. The concept of relay transmission was originated from the ad-hoc [3–6] and peer-to-peer networks. Compared to base stations, a relay station has a lower deployment cost and does not need to connect to the backhaul network via cables. Therefore, relay stations are widely used in the infrastructure-based wireless networks, In general, relay station can be classified into two schemes: amplify-and-forward (AF) and decode-and-forward (DF). In this thesis, the DF relay scheme is considered.

Noteworthily, using relay stations may also decrease the system capacity due to two phase transmissions. Therefore, how to choose relays to achieve higher throughput is an important issue, but it is rarely discussed in the literature. Hence, in this thesis we aim to investigate relay selection rules to achieve higher throughput, while maintaining link reliability.

1.1 Problem and Solution

1.1.1 Throughput-Oriented Relay Selection Rules for Single Relay Case

The objective of this study is to design relay selection rules achieving higher throughput while maintaining link reliability. In the literature, many studies have shown that outage probability can be improved by deploying relay stations [7–13]. However, how to choose a relay to achieve higher throughput is rarely discussed. Transmission through a relay station may lower the throughput since it needs two transmission phases. One is from the source to a relay station and the other is from the relay station to the destination. Therefore, how to choose the appropriate relay station to get higher system throughput is an important issue.

We can use an example to illustrate the relay selection problem. As shown in Fig. 1.1, there are N possible relay nodes between the source and the destination. When choosing the relay node close to the source, the throughput in the relay link from the source is higher than that in the link to the destination. As a result, the overall link throughput of the two-hop links will be limited by the lower-throughput. By contrast, when choosing the relay node close to the destination, the throughput in the relay link from the source is lower than that in the link to the destination. Therefore, the overall link throughput of the two-hop links will be limited by the link from the source to the relay. Therefore, how to choose appropriate relays to achieve higher throughput is a crucial question.

We propose two partner selection methods in this thesis. The first one is to calculate throughput corresponding to each relay, and then choose the relay achieving the maximal throughput. Though this method can achieve the highest throughput, computation cost is quite high. In the second method, we first compare the SNRs

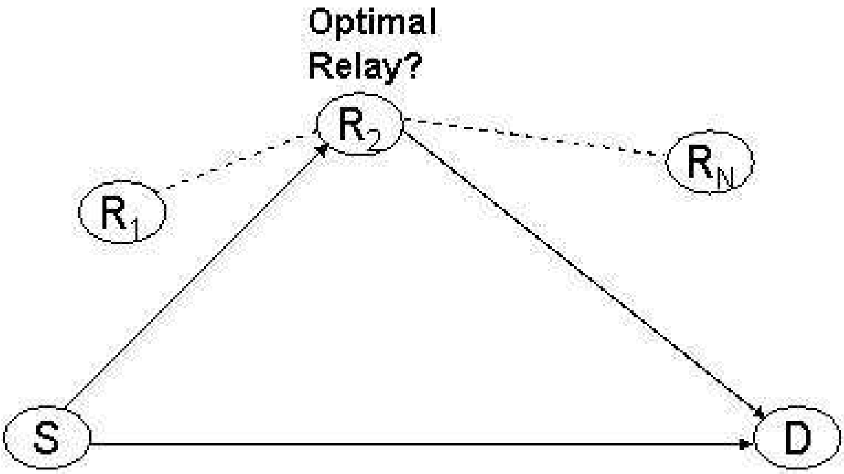

Figure 1.1: A source-destination pair with multiple relay candidates

of the link from the source to relay with that from the relay to the destination, and designate the smaller one as the bottleneck SNR associated with that relay. The bottleneck SNR of each relay is recorded and compared. The relay with the largest bottleneck SNR is selected. Both methods have the similar throughput performance. However, the outage probability of the second method is better than that of the first one. Meanwhile, compared to the conventional signal-based partner selection, the proposed bottleneck SNR approach can achieve higher throughput at a cost of small SNR degradation.

1.1.2 Throughput-Oriented Relay Selection Rules for Multiple Relays Case

Furthermore, we examine the performance of the considered relay selection rules in the multi-relay case. We find that at the same consumed power level the outage probability and throughput performance in the multi-relay case is indeed worse than those in the one relay case. This is because the multi-relay case yields more power consumption and a higher probability of selecting inappropriate relays.

1.1.3 Power Distribution for Throughput-Oriented Relay Selection Rules

In the literature, many studies have shown that at the same consumed power level power distribution in a two-hop relaying network can obtain better outage performance [7, 14, 15]. We would like to examine if power distribution also works well for throughput-oriented relay selection rules. In the traditional method, the transmit power allocated in the link from the source to the relay is the same as that in the link from the relay to the destination. Now, we suggest a simple power distribution algorithm to adjust transmit power for relay nodes when the number of the relays increases. In the suggested power distribution, the transmit power of each relay is inversely proportional to the number of relays, and the sum of the total transmit power from the relay is equal to the transmit power from the source. Our results show that at the same consumed power level the proposed power distribution can improve the outage probability, while maintaining throughput even in the multi-relay case. This is because power allocation can eliminate unnecessary power in the second transmission phase with multiple relays.

1.1.4 Thesis Outline

The rest of the thesis are organized as follows. Chapter 2 introduces the backgrounds on the multi-hop relay in the wireless systems and defines the considered performance metrics. In Chapter 3, we discuss the proposed relay selection rules and the algorithm of power distribution ,and the simulation platform. In Chapter 4, we describe the two proposed relay selection rules. In Chapter 5, we further discuss the two relay selection rules in the multiple relays case. In Chapter 6, we investigate the impact of the power allocation on the two proposed relay selection rules. At last, Chapter 7 gives the concluding remarks and suggestions for the future works.

CHAPTER 2

Background and System Model

In this chapter, we introduce some background knowledge on the cooperative multi-hop relay networks and define a few performance metrics used in this thesis.

2.1 Background on Relay Stations

Multi-hop relay networks were originated from the ad-hoc and peer-to-peer networks. Recent years, the applications of multi-hop relay networks progress significantly. As the result, the relaying techniques have become more advanced and much complicated. The notable features of multi-hop relay network are discussed as follows:

2.1.1 Radio Resources Selection

In a relay network, the radio resources are allocated to the link form the source to the relay and the link from the relay to the destination. There are three kinds of resource allocation schemes [16] as shown below:

- Relaying in the time-domain scheme: The same carrier frequency is operated on both sides of the relay station. The frame structure is used to connect nodes via a time-multiplexing channel. Each user uses a different time-slot to transmit data in the same time division multiple access (TDMA) frame. A TDMA frame is subdivided into three segments in the relay network, one for the direct source-destination link, one for the source-relay link and one for the relay-destination link.

- Relay in the frequency-domain scheme: This scheme operates source and relays at two different carrier frequencies.That is, source transmits data to relay with carrier frequency f_1, and then relay transmits the received data to destination with carrier frequency f_2. This will increase the complexity of the hardware and frequency management.
- Relaying in the hybrid time/frequency domain scheme: The concept was investigated in [17]. The basic idea is that the relays periodically switches between carrier frequency f_1 and f_2. No additional devices are needed for this scheme. However, the fast frequency switching has to be supported, which will increase hardware complexity.

2.1.2 Relay Function Selection

In general, relay station can be classified into two schemes according to its function: (1) Amplify-and-Forward (AF): the relay station received signal and then simply amplify the signal before retransmission; (2) Decode-and-Forward (DF): the relay stations decode received signal and then re-encode the signal before retransmission [18, 19]. In the DF scheme, if the relay node can not correctly detect the massage send from the source then the relay stop forwarding to the destination. However, in the AF scheme the relay do not detect the signal from the source and forward the received signal to the destination as long as the signal arrived. DF scheme ensure the quality of the forwarding signal from the relay to the destination.

2.1.3 Macro-Diversity Function

In this work we assume that the signals from the relay to the destination are synchronous. Therefore we need the property called "Macro-Diversity". Macro-diversity means that the transmitter (source or relay) can serve more than one user at the same time. The receiver (relay or destination) may also communicate with more than one transmitter [20–22]. Therefore the destination can receive multiple copies of the message from the relays and obtain the diversity gain.

2.1.4 Relay Deployment Strategies

In the infrastructure-based networks, the access links are generally sheltered with the buildings or at indoors. This phenomenon is called the non-line-of-sight (NLOS) transmission. However, deploying relays can improve the transmission in the NLOS environment. There are two strategies that can be used to achieve line-of-sight transmission. One is to deploy relays in a vast space according to a careful plan. The other is to increase the antenna height of relays. These two strategies are not mutually exclusive. Therefore, a relaying network can employ both methods to deploy relays.

2.2 Background on Radio Channel Effects

When the destination is far away from the source, the received signal strength is attenuated due to the long distance. Link outage occurs when the received SNR is lower than the required threshold. We denote the link outage probability as P_{outage}.

2.2.1 Radio Channel Characteristics

In this thesis, the impacts of path loss [23] and Rayleigh fading are considered. First, we introduce the path loss model. Subject to path loss, the received power decays with the propagation distance r between the transmitter and the receiver. Assume that the transmission power is P_t, the received power can be written as

$$P_r = P_t \cdot (L_r)^{-1} \quad . \tag{2.1}$$

where the path loss L_r can be written as:

$$L_r = \frac{K \cdot r^{\alpha}}{G_t \cdot G_r} \quad . \tag{2.2}$$

In (3.2) α is the path loss exponent, G_t is the antenna gain of the source transmitter, G_r is the antenna gain of the destination receiver, and K is a coefficient.

Now we introduce the effects of Rayleigh fading. In the wireless channels, the Rayleigh distribution is popular to model the statistical time varying nature of the envelope of received signal, or the envelope of an multipath signal component. The probability density function of a Rayleigh distribution has a probability density function is given by

$$p(r) = \begin{cases} \frac{r}{\sigma^2}\exp(-\frac{r^2}{2\sigma^2}) & (0 \leq r \leq \infty) \\ 0 & (r < 0) \end{cases} \tag{2.3}$$

where σ is the root mean square (rms) value of the received signal before envelope detection, and σ^2 is the time-average power of the received signal before envelope detection.

2.3 System Model and Assumptions

2.3.1 System Model

We consider a two-hop relaying network as shown in Fig. 2.1. There are sixteen nodes numbered from zero to fifteen in the grid topology. We study two extreme cases “best pair” and “worst pair”. For the best-pair case, node 5 is the source and node 6 is the destination. The distance between these two nodes is the shortest one in this topology, this is the reason why we call the best-pair case. The relay nodes are then chosen form the remaining fourteen nodes according to different relay selection rules. For the worst-pair case, node 0 is the source and node 15 is the destination. The distance between these two nodes is the longest one in this topology. The relay nodes are then chosen form the remaining fourteen nodes according to different relay selection rules.

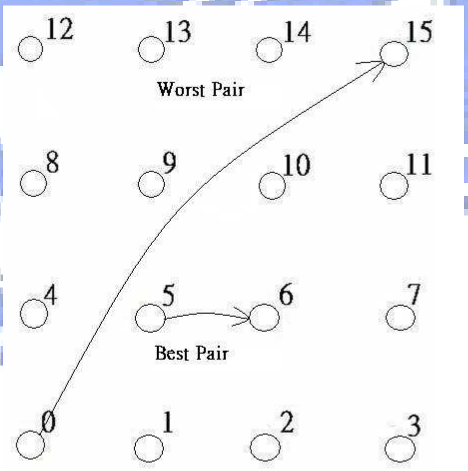

Figure 2.1: System Scenario

2.3.2 Assumptions

The assumptions adopted in this work are itemized below:

- Two hop communication: The possible transmission paths are only two, one is directly from source to destination; the other is from the source via a relay to the destination.

- Rayleigh fading: Assume the wireless channel is under Rayleigh fading.

- Path loss exponent equals four: We use the log path loss model with exponent equals four.

- Maximal ratio combing: The destination use the maximal ratio combing technique to combine signals.

- Perfect synchronization for received signals form multiple relays: When there are multiple copies of information signal transmitted to the destination, we assume these signals arrived at the same time.

2.4 Performance Metrics

Here are some definitions and performance metrics used in this thesis.

2.4.1 Link Outage Probability

The link outage probability is defined to reflect reflects how reliable a communication system can support for a given link quality. For a wireless network system in a Rayleigh fading channel if the received SNR is lower than the required received threshold z_{th} due to signal attenuation, i.e. $P_{outage} = Pr[SNR < z_{th}]$. This situation is called the link outage. We denote the link outage probability as P_{outage}.

2.4.2 Throughput

The throughput is defined to indicate the amount of messages that a communication system is capable to support. We calculate the overall throughput in a two-hop relaying network as:

$$R_{s-r-d} = \frac{L}{t_{s-r-d}} = \frac{L}{\frac{L}{R_{s-r}} + \frac{L}{R_{r-d}}} = (\frac{1}{R_{s-r}} + \frac{1}{R_{r-d}})^{-1} \quad . \tag{2.4}$$

Symbol s represents the source, r is the relay node, d means the destination. L is the assumed packet data size. R_{s-d} is the transmission rate of the link between source and destination. R_{s-rj} is the transmission rate of the link between source and decoded node j. R_{rj-d} is the transmission rate of the link between decoded node j and destination. R_{s-rj-d} is the transmission rate of the link from source via decoded node j to destination.

2.4.3 Total Transmit Power

We define the total transmit power to show the power consumption of the system. In this work the total transmit power is defined as the sum of the transmit power of the source and that of the relays. Total transmit power can be expressed mathematically as:

$$P_{total} = P_s + P_r * N_r \quad . \tag{2.5}$$

where P_{total} is the total transmit power. P_{ts} is the transmit power of the source. P_{rs} is the transmit power of a relay. N_r is the number of relays. Here we assume the transmit power of all relays are the same. We also assume that the transmission rate of the link from the source and that of the link to the destination can be different.

CHAPTER 3

Throughput-Oriented Relay Selection Rules with Single Relay

In this chapter, we propose two relay selection rules. The objective is to achieve higher throughput while maintaining reasonable reliability.The rest of this chapter are organized as follows. In Section 3.1, we introduce the relay selection rules in the literature. In Section 3.2, we propose our first relay selection rule. In Section 3.3, we propose our second relay selection rule. In Section 3.4, we show and discuss the numerical result.

3.1 Relay Selection Rules in the Literature

Here we introduce four kinds of relay selection in the literature.

3.1.1 Pre-Select One Relay

In [7], a relay selection rule intending to achieve high reliability is introduced. This rule is called “pre-select on relay”. It first computes the outage probability of each possible relay node, and choose the one with the minimal outage probability as the relay node, i.e.,

$$i = \arg\min_{\forall j} P_{oj}, j \in \{\text{decoded node index}\} \quad . \tag{3.1}$$

where P_{oj} is the outage probability of jth possible relay. This rule however is poor in outage probability. This is because the computational cost of this rule is high, the time between updates is thereafter long and can not reflect the channel variations.

3.1.2 Signal-Based Relay Selection Rule

In [7], a relay selection rule intending to achieve best outage probability has been proposed. In our work, we term this rule as the "signal-based" relay selection rule. This rule chooses the node which correctly decodes the signal transmitted by the source and has the largest SNR in the link to the destination as the relay:

$$i = \arg\max_{\forall j} SNR_{rj-d}, j \in \{\text{decoded node index}\} \quad . \tag{3.2}$$

Therefore, this rule results in an excellent outage probability.

3.1.3 Threshold-Based Relay Selection Rule

In [8], a simple relay selection rule was introduced. This rule is called the "threshold-based" relay selection rule. This rule chooses all the nodes which correctly decode the signal transmitted by the source as relay nodes:

$$i = j \in \{\text{decoded node index}\} \quad . \tag{3.3}$$

3.1.4 ST-Coded Relay

In [9], a relay selection rule using space-time code is introduced. This rule is called "ST-Coded Relay". This rule chooses all the nodes which correctly decode the signal transmitted by the source as relay nodes:

$$i = j \in \{\text{decoded node index}\} \quad . \tag{3.4}$$

while these selected relays will utilizing space-time codes for transmission. This rule is good in reliability, however the computational cost is high.

3.2 Throughput-Optimal Approach

Our first proposed relay selection rule is called "throughput-optimal" approach. In this approach, we first compute the throughput corresponding to each node in the decoded set,i.e.,

$$R_{s-rj-d} = \frac{L}{t_{s-rj-d}} = \frac{L}{\frac{L}{R_{s-rj}} + \frac{L}{R_{rj-d}}} = (\frac{1}{R_{s-rj}} + \frac{1}{R_{rj-d}})^{-1} \quad . \tag{3.5}$$

where rj is the jth node in the decoded set. The decoded set is composed of nodes which correctly decode the signal transmitted by the source. L is the assumed packet data size. R_{s-d} is the transmission rate of the link between source and destination. R_{s-rj} is the transmission rate of the link between source and decoded node j. R_{rj-d} is the transmission rate of the link between decoded node j and destination. R_{s-rj-d} is the transmission rate of the link from source via decoded node j to destination. Then we choose the node with the maximal throughput as the relay node:

$$i = \arg\max_{\forall j} R_{s-rj-d}, j \in \{\text{decoded node index}\} \quad . \tag{3.6}$$

If there are multiple nodes in the decoded set with the maximal throughput, we choose the one with the maximal SNR in the link to the destination as the relay node.

3.3 Bottleneck SNR Approach

The second proposed relay selection rule is termed the "bottleneck SNR" approach. In this approach, we aim to simplify the computation complexity of the throughput-optimal approach.

Assume $R_{s-rj} \gg R_{rj-d}$ or $R_{rj-d} \gg R_{s-rj}$. Then R_{s-rj-d} can be approximated as R_{rj-d} and R_{s-rj}, respectively. Thus, we have

$$R_{s-rj-d} \cong \min\{R_{s-rj}, R_{rj-d}\} \quad . \tag{3.7}$$

Also assume $R \propto SNR$. We can obtain

$$R_{s-rj-d} \propto \min\{SNR_{s-rj}, SNR_{rj-d}\} \quad . \tag{3.8}$$

Therefore, we can reduce the computational cost of calculating the link transmission rate because we only compare the link signal-to-noise ratios. We first compare the signal-to-noise ratio between source and decoded node j with that between decoded node j and destination. The smaller one is designated as the bottleneck SNR of node j, i.e.,

$$\min\{SNR_{s-rj}, SNR_{rj-d}\} \quad . \tag{3.9}$$

The bottleneck SNR of each relay is recorded and compared. The relay with the largest bottleneck SNR is selected.

$$i = \arg\max_{\forall j}\{\min\{SNR_{s-rj}, SNR_{rj-d}\}\} \quad . \tag{3.10}$$

If there are multiple nodes in the decoded set correspond to the largest bottleneck SNR, we choose the one with the maximal SNR in the link to the destination as the relay node. It can be seen that the bottleneck SNR approach is in the form of "max-min". [13] uses "max-min" relay selection approach to achieve higher reliability.

3.4 Numerical Results

In this section, we examine the outage probability and the throughput performance of the proposed relay selection rules and two more relay selection methods. We consider seven modulation coding schemes (MCSs) in the IEEE 802.16 standard. Table. 3.1

Table 3.1: **The Required SINR And Net Data Rate With Different Modulation Coding Schemes**

MCS	Modulation	Code Rate	SINR	Net Date Rate
1	**BPSK**	**1/2**	**0.0 dB**	**1.29 Mbit/s**
2	**QPSK**	**1/2**	**2.5 dB**	**2.59 Mbit/s**
3	**QPSK**	**3/4**	**6.0 dB**	**3.88 Mbit/s**
4	**16-QAM**	**1/2**	**9.0 dB**	**5.18 Mbit/s**
5	**16-QAM**	**3/4**	**12.0 dB**	**7.77 Mbit/s**
6	**64-QAM**	**2/3**	**16.0 dB**	**10.37 Mbit/s**
7	**64-QAM**	**3/4**	**21.0 dB**	**11.66 Mbit/s**

lists the required SINR and net data rate for the seven MCSs [24]. We estimate system capacity with 10% frame error rate.

3.4.1 Outage Probability and Throughput Performance of Relay Selection Rules in the Best-Pair Case

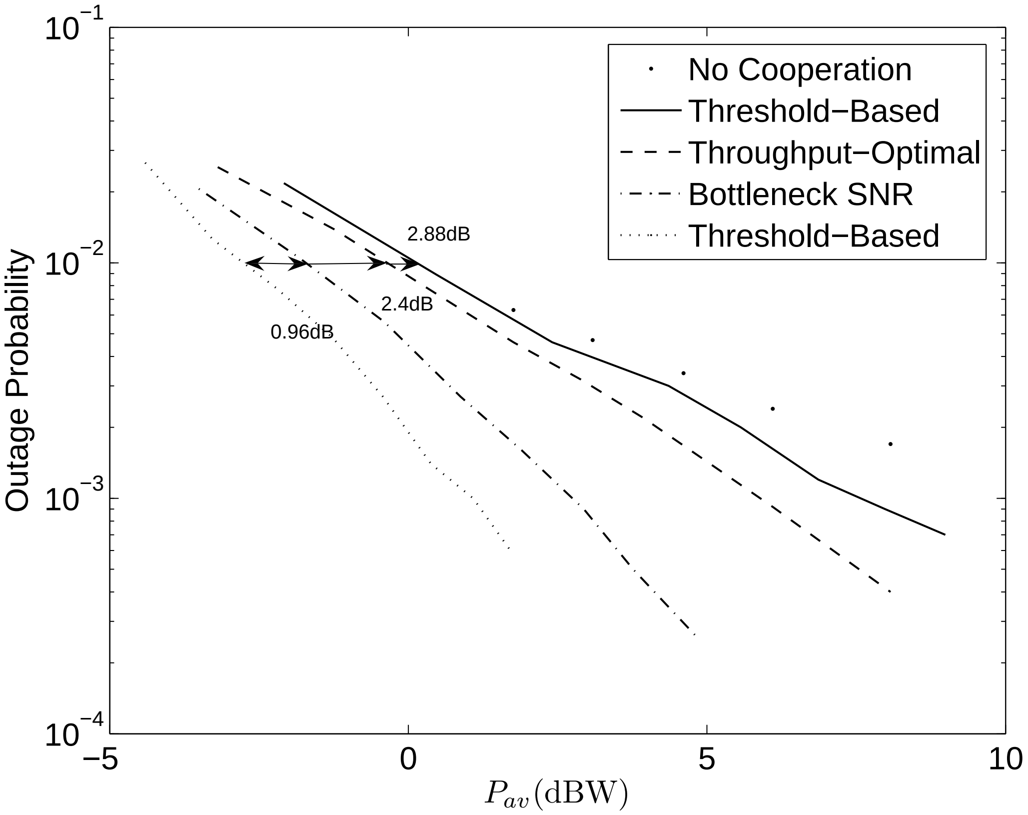

Figure 3.1: Outage probability comparison for various relay selection rules in the best-pair case.

Fig. 4.1 shows the outage probability of various relay selection rules in the best-pair case. The signal-based method has the best outage performance since it chooses the node has the strongest signal strength to the destination. We can use

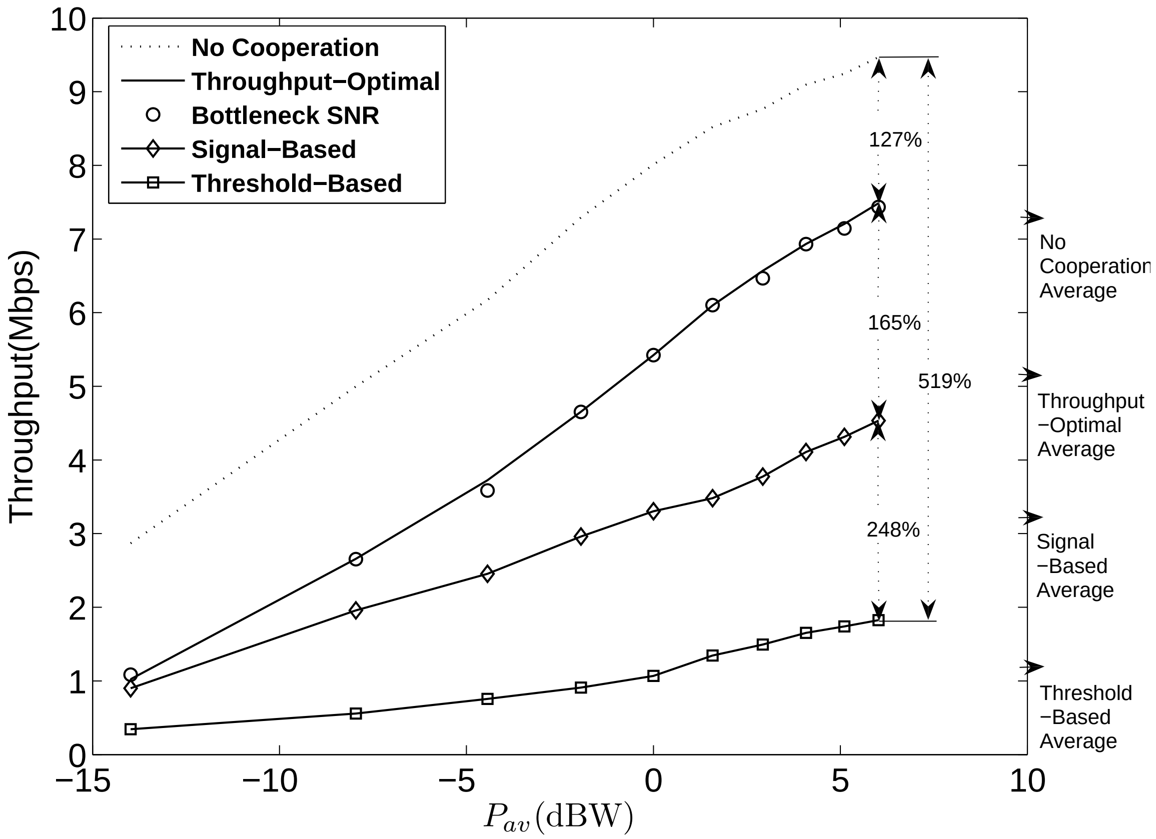

Figure 3.2: Throughput comparison for various relay selection rules in the best-pair case.

the outage performance of the signal-based approach as a lower bound for comparing other relay selection schemes. The threshold-based method has the worst outage performance. For $P_{outage} = 10^{-2}$, it needs more 2.88 dBW than the signal-based approach. This is because it may select relay nodes with weak signal strength to the destination, while consuming the same transmit power as other relays. The throughput-optimal approach has the slightly better outage performance than the threshold-based method. For $P_{outage} = 10^{-2}$, it needs more 2.4 dBW than the signal-based approach. This is due to it may select relay node far from the destination.

Therefore, the signal-to-noise ratio from the relay to the destination is low. The bottleneck SNR approach has a better outage performance than the throughput-optimal approach, while approaching to the outage performance of the signal-based method. For $P_{outage} = 10^{-2}$, it needs more 0.96 dBW than the signal-based approach. The bottle SNR approach keeps choosing relay in the middle region between the source and the destination, hence the signal strength form the chosen relay to the destination will not be too low. From the figure we can also see that without cooperation the outage is very poor since there is no diversity gain.

Fig. 3.2 illustrates the throughput performance of various relay selection rules in the best-pair case. The case without cooperation has the highest throughput. In the range of average consumed power from -14 dBW to 6.5 dBW ,the average throughput is 7.44 Mbps. The threshold-based method has the poorest throughput performance. In the range of average consumed power from -14 dBW to 6.5 dBW ,the average throughput is 1.17 Mbps. At 6.5 dBW the throughput of no cooperation achieves 519% higher than that of the threshold-based approach. This is because it selects all nodes correctly decode the message from the source, therefore in a high probability there is a relay with low throughput is included. The overall throughput then is limited by the relay with low throughput. The signal-based method has a moderate throughput level. In the considered consumed power range the average throughput is 3.18 Mbps, while at 6.5 dBW the throughput of signal-based approach achieves 248% higher than that of the threshold-based approach. This is because it mostly select relay close to the destination. Therefore, the relay is far away from the source and the link between the source and the relay has a poor throughput. As a result, the overall throughput is degraded. The throughput of our proposed two relay selection rules is much better than above two methods. In the considered consumed power range the average throughput is 5.18 Mbps and 5.15 Mbps, respectively. At 6.5 dBW the throughput of these two approaches achieves 165% higher than that of

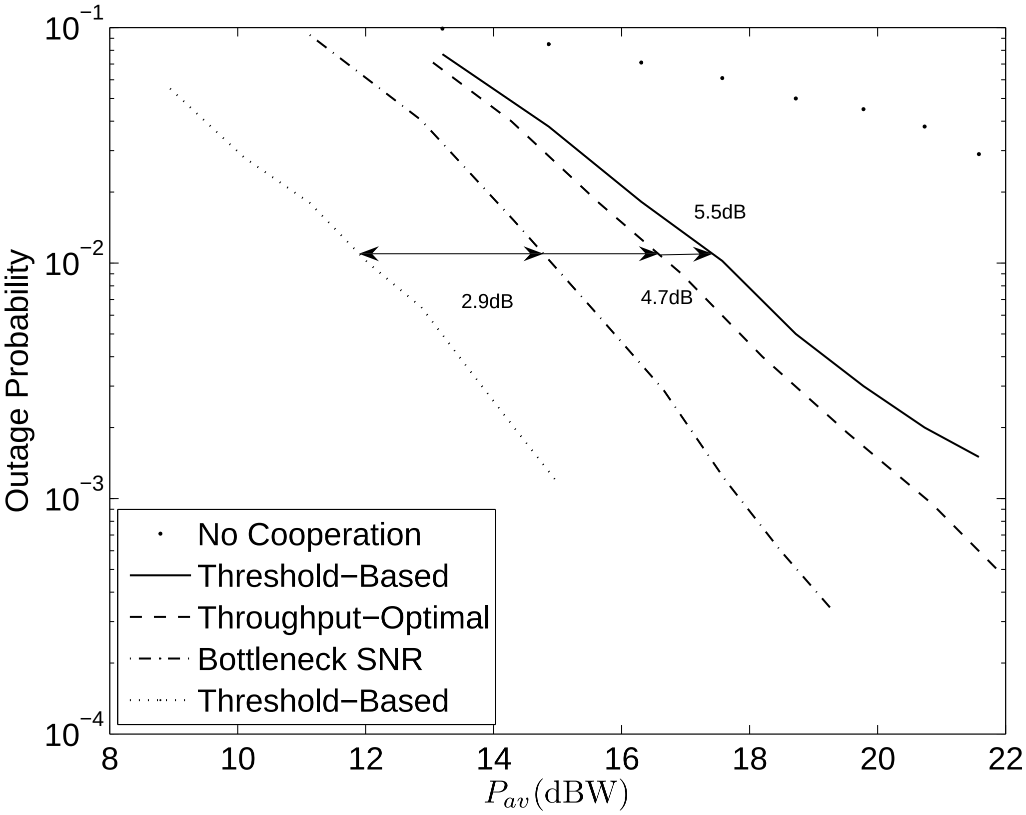

Figure 3.3: Outage probability comparison for various relay selection rules in the worst-pair case.

the signal-based approach. The throughput performance of the two method is almost the same while the bottleneck SNR approach has a simpler computational mechanism and better outage probability. Therefore, in the best-pair case, the bottleneck SNR approach is the best throughput-oriented relay selection rule.

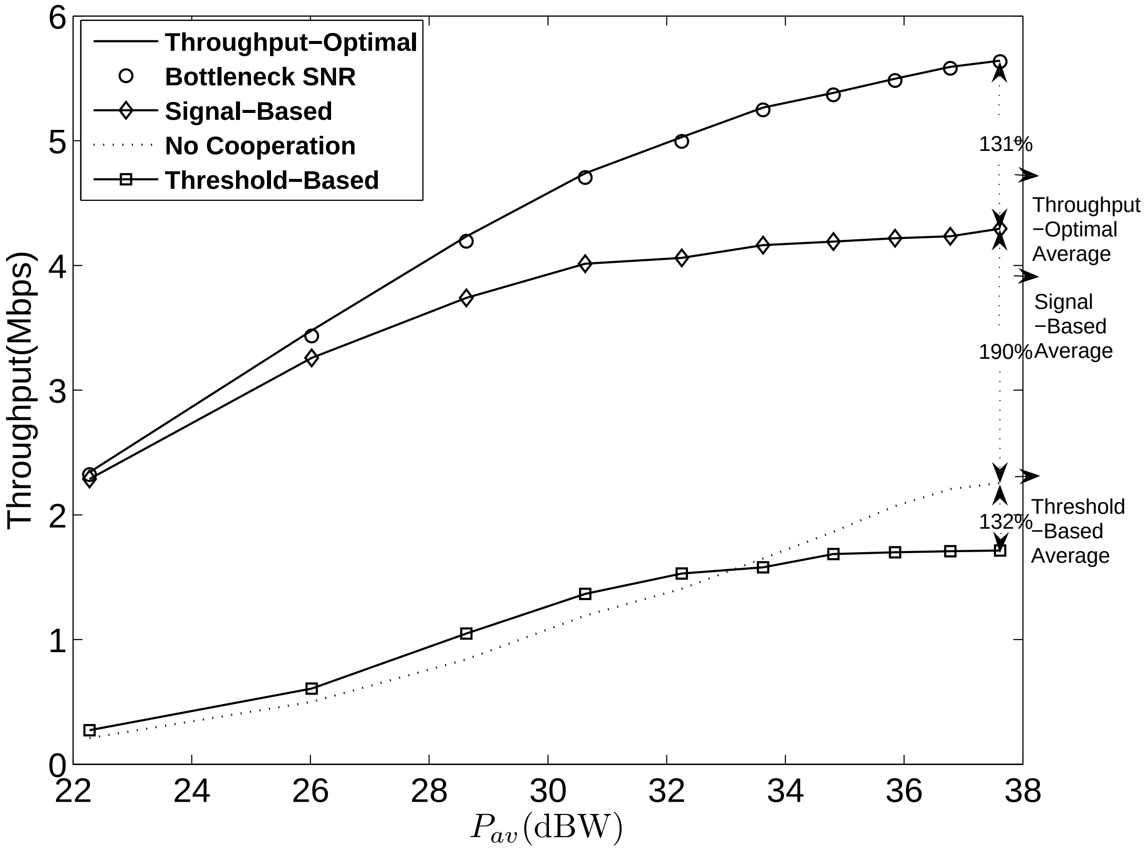

Figure 3.4: Throughput comparison for various relay selection rules in the single relay case.

3.4.2 Outage Probability and Throughput Performance of Relay Selection Rules in the Worst Pair Case

Fig. 3.3 illustrates the outage probability of various relay selection rules in the worst pair case.The signal-based method has the best outage performance. The threshold-based method has the worst outage performance. For $P_{outage} = 10^{-2}$, it needs more 5.47 dBW than the signal-based approach. The throughput-optimal approach has the slightly better outage performance than the threshold-based method. For $P_{outage} = 10^{-2}$, it needs more 4.7 dBW than the signal-based approach. The bottleneck SNR approach has a better outage performance than the throughput-oriented approach while being more close to the outage curve of the signal-based method. For $P_{outage} = 10^{-2}$, it needs more 2.9 dBW than the signal-based approach. We see that the outage performance of no cooperation case is poor since there is no diversity gain.

Fig. 3.4 shows the throughput performance of various relay selection rules in the worst-pair case. The threshold-based method has the poorest throughput performance. In the range of average consumed power from 22.2 dBW to 37.8 dBW,the average throughput is 1.32 Mbps. The throughput of no cooperation case is low since the direct link is in a poor condition in the worst-pair case. In the considered consumed power range the average throughput is 1.42 Mbps, while at 37.8 dBW the throughput of signal-based approach achieves 132% higher than that of the threshold-based approach. The signal-based method has a moderate throughput level In the considered consumed power range the average throughput is 3.85 Mbps, while at 37.8 dBW the throughput of signal-based approach achieves 190% higher than that of the no cooperation case. The throughput of our proposed two relay selection rules is much better than above two methods. In the considered consumed power range the average throughput is 4.72 Mbps and 4.70 Mbps, respectively. At 37.8 dBW the throughput of these two approaches achieves 131% higher than that of the signal-based approach.

The throughput performance of the two methods is almost the same while the bottleneck SNR approach has a simpler computational mechanism and better outage probability. Therefore, we recommend the bottleneck SNR approach as the better throughput-oriented relay selection rule.

Comparing the results in the best-pair case with that in the worst-pair case, we find that in the worst pair case, for the same throughput all rules need more power consumption than that in the best pair case. This is due to that the distance between source and destination in the worst pair case is much longer than that in the best pair case.

CHAPTER 4

Throughput-Oriented Relay Selection Rules with Multiple Relays

In this chapter, we extend the number of relays from only one to multiple. The goal is the same as that in the single relay case: achieving higher throughput while keeping reasonable link reliability.

4.1 The Throughput-Optimal Approach in the Multiple Relay Case

Our first proposed relay selection rule is called "throughput-optimal approach". We choose the relay with the maximal throughput as in the single relay case. Then we select the second and third relay as follows:

$$i_2 = \underset{\forall j}{\arg\max}\, R_{s-rj-d}, j \in \{\text{decoded node index}\}, j \notin \{i_1\} \quad . \tag{4.1}$$

If there are multiple nodes in the decoded set with the maximal throughput, we choose the one with the maximal SNR in the link to the destination as the relay node.

$$i_3 = \underset{\forall j}{\arg\max}\, R_{s-rj-d}, j \in \{\text{decoded node index}\}, j \notin \{i_1, i_2\} \quad . \tag{4.2}$$

More relays are chosen in the same manner.

4.2 The Bottleneck SNR Approach in the Multiple Relay Case

The second proposed relay selection rule is termed the "bottleneck SNR" approach. In this approach, we aim to simplify the computation complexity of the throughput-optimal approach. We choose the first relay as in the single relay case. Then we select the second and third relay as follows:

$$i_2 = \underset{\forall j}{\arg} \max\{\min\{SNR_{s-rj}, SNR_{rj-d}\}\}, j \in \{\text{decoded node index}\}, j \notin \{i_1\} \quad . \tag{4.3}$$

If there are multiple nodes in the decoded set with the maximal throughput, we choose the one with the maximal SNR in the link to the destination as the relay node. The third relay is chosen by:

$$i_3 = \underset{\forall j}{\arg} \max\{\min\{SNR_{s-rj}, SNR_{rj-d}\}\}, j \in \{\text{decoded node index}\}, j \notin \{i_1, i_2\} \quad . \tag{4.4}$$

More relays are chosen in the same manner.

4.3 Numerical Results

In this section, we examine the outage probability and the throughput performance of the proposed relay selection rules and two more relay selection method in the multi-relay case. We consider seven modulation coding schemes (MCSs)in the IEEE 802.16 standard. Table. 3.1 lists the required SINR and net data rate for the seven MCSs [24]. We estimate system capacity with 10% frame error rate

4.3.1 Outage Probability and Throughput Performance of Relay Selection Rules for Multi-Relay, Best Pair Case

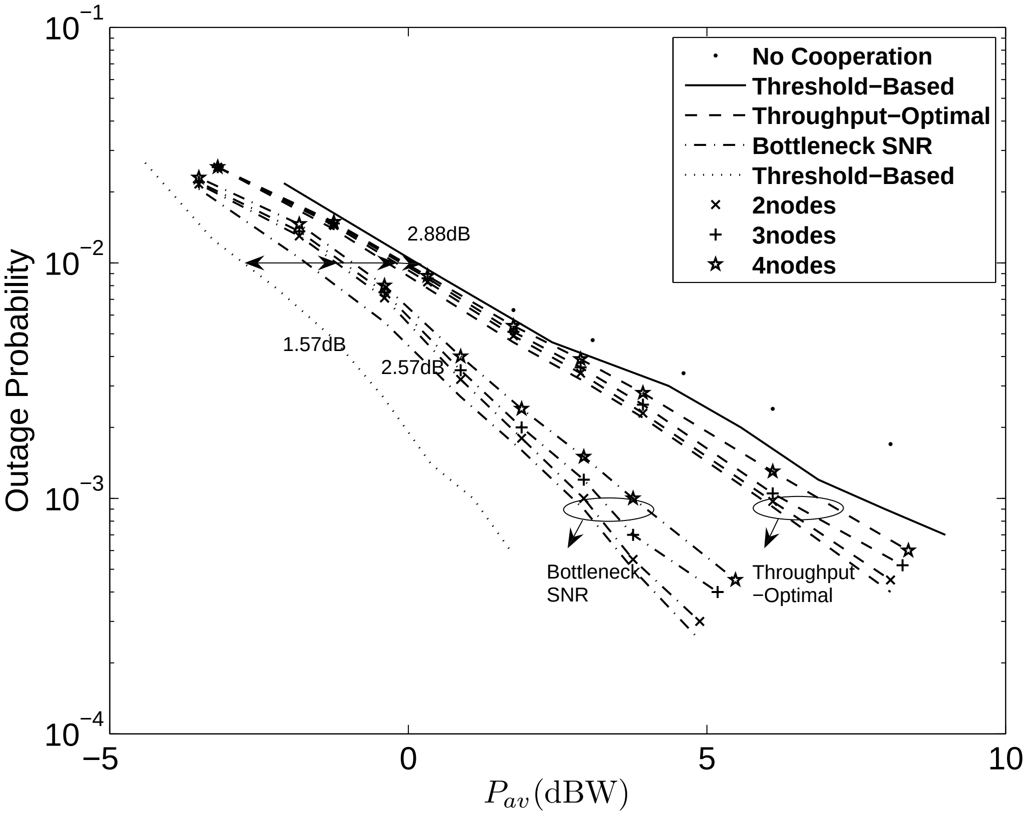

Figure 4.1: Outage Probability comparison for various relay selection rules with multiple relays in the best-pair case.

Fig. 4.1 shows the outage probability of various relay selection rules with multiple relays in the best-pair case. For the throughput-optimal approach, more relay nodes ,poorer the outage probability. For the throughput-optimal approach with 2 relays, at $P_{outage} = 10^{-2}$ it needs more 2.57 dBW than the signal-based approach, higher than 2.4 dBW with single relay. This is due to more power consumption and higher chance to choose nodes close to the source. For the bottleneck SNR approach,

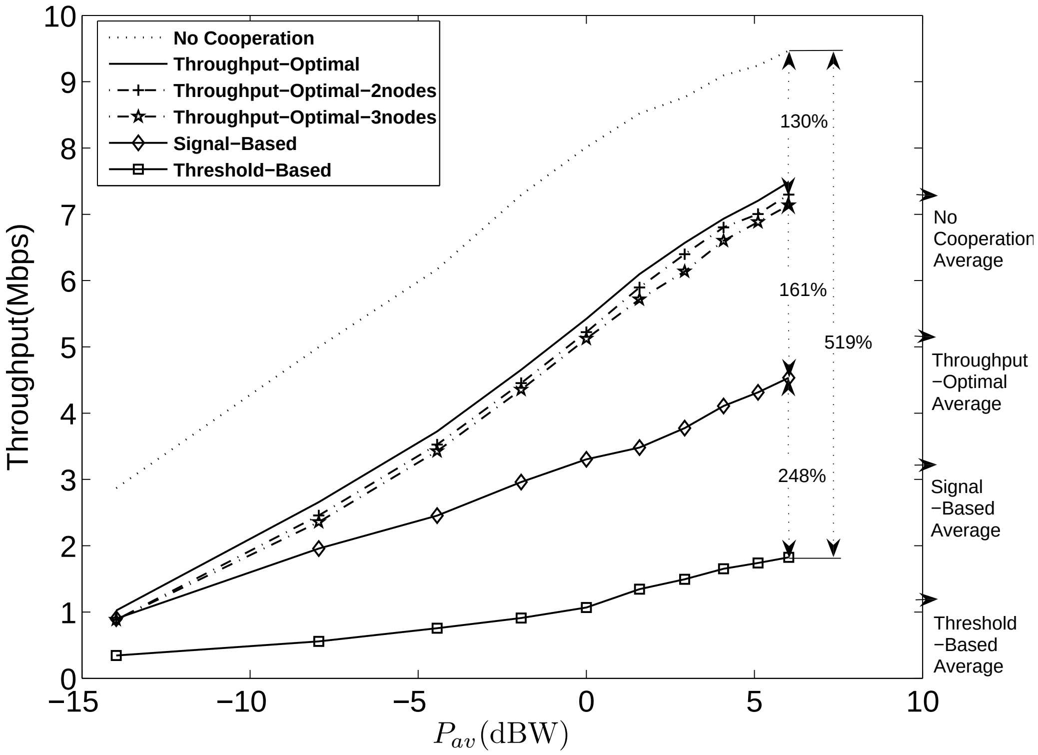

Figure 4.2: Throughput comparison for various relay selection rules with multiple relays in the best-pair case for the throughput-optimal approach.

the trends are the same. More nodes, poorer the outage probability. For throughput-optimal approach with 2 relays, at $P_{outage} = 10^{-2}$ it needs more 1.57 dBW than the signal-based approach, higher than 0.96 dBW with single relay. The reason is the same as the throughput-optimal approach, there is more chances to choose relay nodes far away from the destination and more relay nodes consume more power.

Fig. 4.2 reveals that the throughput of various relay selection schemes, especially for the throughput-optimal approach with multiple relays in the best-pair case. We can see that for the throughput-optimal approach, more relay nodes, poorer the throughput. For throughput-optimal approach with 2 nodes, in the considered con-

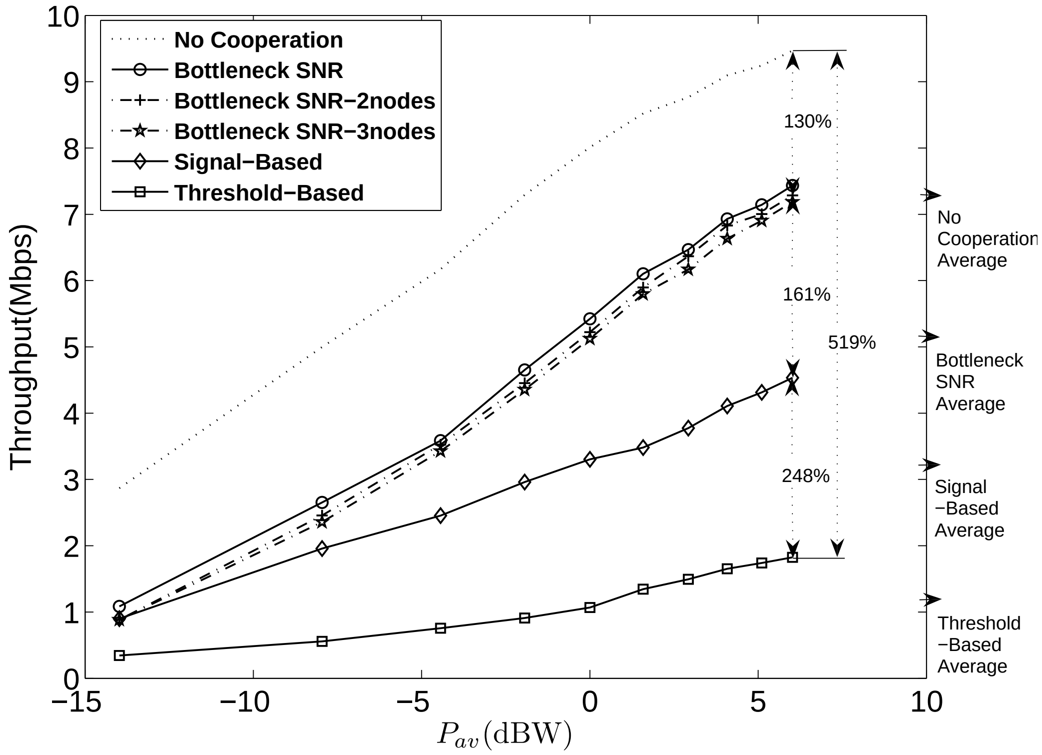

Figure 4.3: Throughput comparison for various relay selection rules with multiple relays in the best-pair case for the bottleneck SNR approach.

sumed power range the average throughput is 4.99 Mbps, lower than 5.18 Mbps in the single relay case. At P_{av}=6.5 dBW the throughput achieves 161% higher than that of the signal-based approach, lower than that with single relay 165%. This is due to more power consumption from more relays and contributed form more chances to choose relay nodes close to the source or the destination. If a relay node is close to the source or to the destination, then one side of the relay node has a low link throughput. Hence, the overall link throughput is limited.

Fig. 4.3 shows the throughput of various relay selection rules, especially for the bottleneck SNR approach with multiple relays in the best-pair case. For the bottleneck SNR approach, more relay nodes, lower the throughput. For bottleneck SNR approach with 2 nodes, in the considered consumed power range the average throughput is 4.99 Mbps, lower than 5.15 Mbps in the single relay case. At P_{av}=6.5 dBW the throughput achieves 161% higher than that of the signal-based approach, lower than that with single relay 165%. This is contributed from more power consumption by more relay nodes and due to higher chances to choose relay nodes close to the source or the destination, then one side of the relay node has a poor link throughput. Therefore, the total link throughput is limited.

From the above three figures, we realize the trend of the outage probability and the throughput for the proposed relay selection rules with multiple relays in the best pair case. We find that as deploying more relay nodes, at the same consumed power level the reliability and throughput performance degrades with the number of relays. this is due to more power consumption and more chances to choose inappropriate relay nodes.

4.3.2 Outage Probability and Throughput Performance of Relay Selection Rules for Multi-relay, Worst-Pair case

Fig. 4.4 shows the outage probability of various relay selection rules for the multi-relay, worst pair case. For throughput-optimal approach with 2 relays, at $P_{outage} = 10^{-2}$ it needs more 4.8 dBW than the signal-based approach, higher than 4.7 dBW in the single relay case. For bottleneck SNR approach with 2 relays, at $P_{outage} = 10^{-2}$ it needs more 3.1 dBW than the signal-based approach, higher than 2.9 dBW in the single relay case.

Fig. 4.5 reveals the throughput of various relay selection schemes especially for the throughput-optimal approach in the multi-relay, worst pair case. For throughput-optimal approach with two nodes, in the considered consumed power range the av-

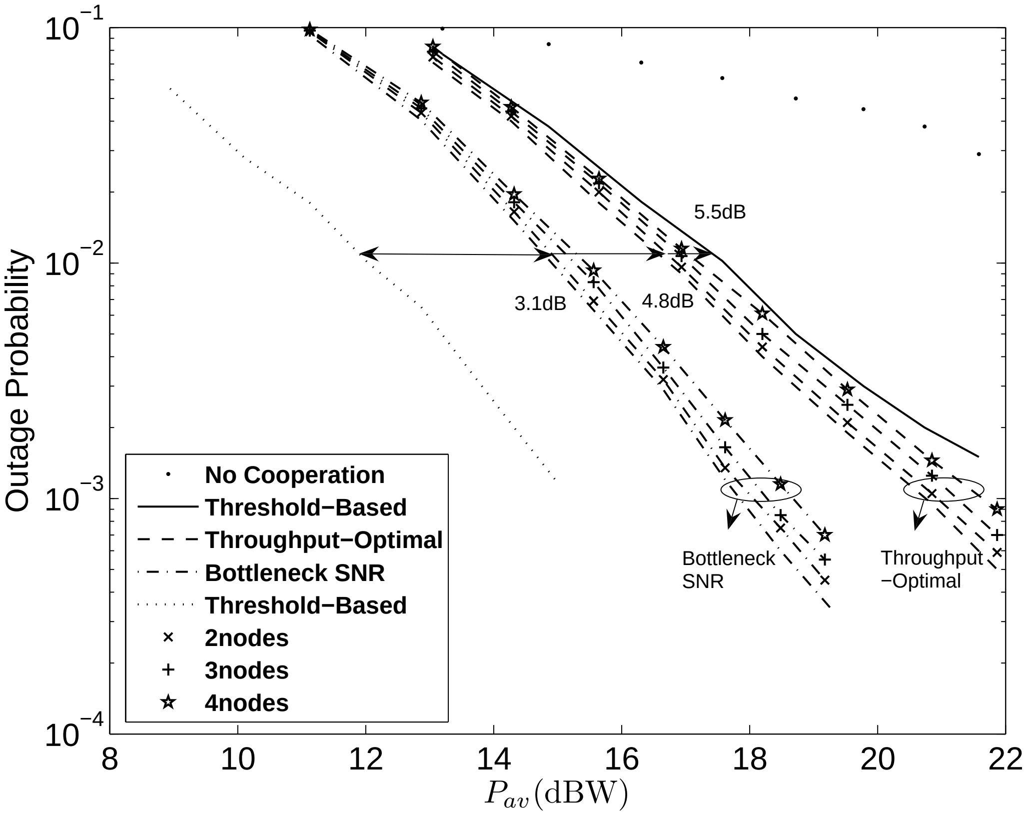

Figure 4.4: Outage Probability comparison for various relay selection rules with multiple relays in the worst-pair case.

erage throughput is 4.63 Mbps, lower than 4.72 Mbps in the single relay case. At P_{av}=37.8 dBW the throughput achieves 129% higher than that of the signal-based approach, lower than that with single relay 131%.

Fig. 4.6 says the throughput of various relay selection rules especially for the bottleneck SNR approach in the multi-relay, worst pair case. For bottleneck SNR approach with 2 nodes, in the considered consumed power range the average throughput is 4.63 Mbps, lower than 4.70 Mbps in the single relay case. At P_{av}=37.8 dBW the throughput achieves 129% higher than that of the signal-based approach, lower than

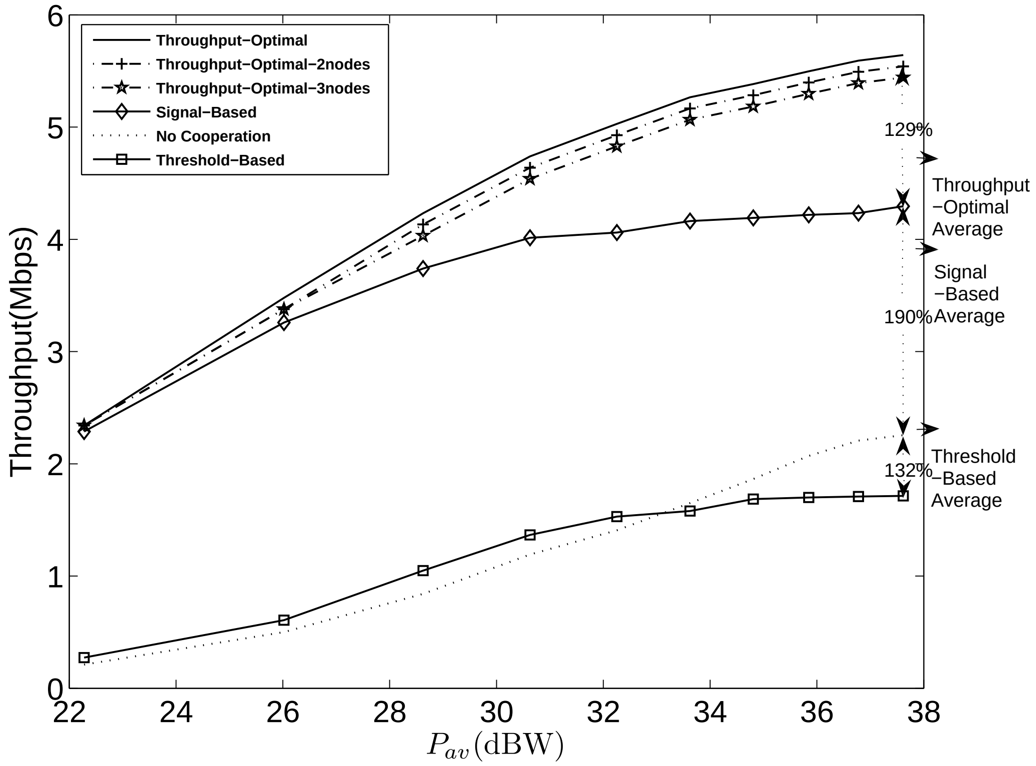

Figure 4.5: Throughput comparison for various relay selection rules with multiple relays in the worst-pair case for the throughput-optimal approach.

with single relay 131%.

From the above three figures, we realize the trend of the outage probability and the throughput for the multiple relays, worst pair case. We observe that applying more relay nodes, at the same consumed power level the reliability and throughput performance degrades with the number of relays. this is due to more power consumption and more chances to choose inappropriate relay nodes.

Table. 4.1 shows the performance loss of utilizing more relays. It computes that at $P_{outage} = 10^{-2}$, how much P_{av} is increased when the number of relays is from one to two. We can know that the loss of the bottleneck SNR approach is larger than that

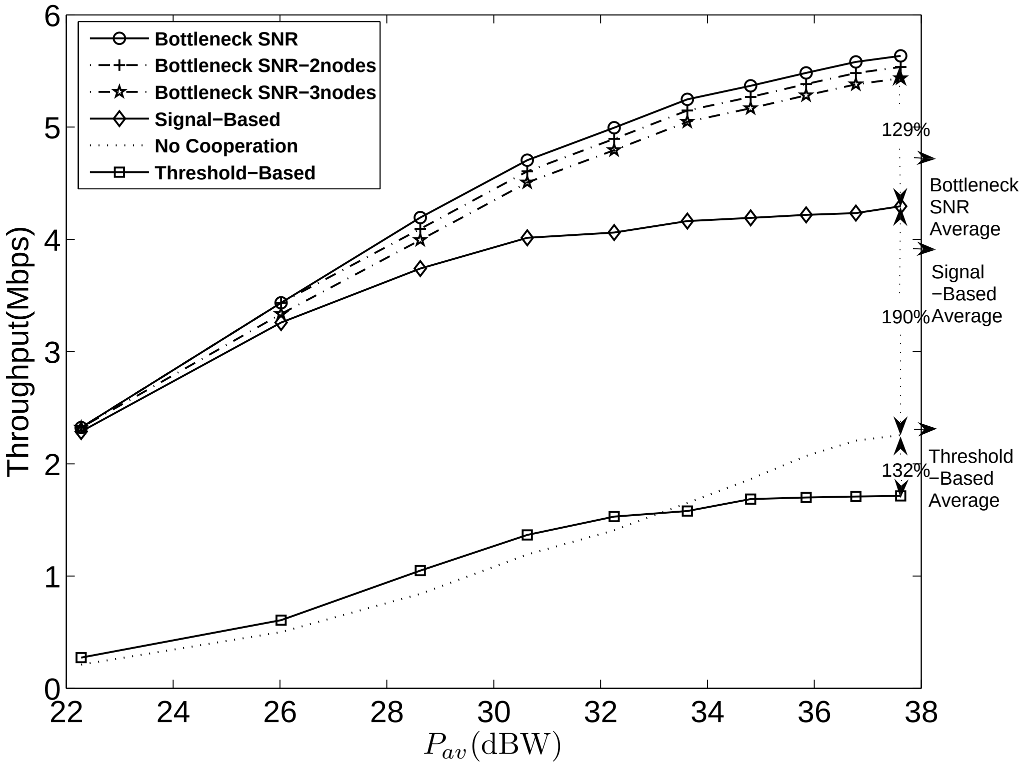

Figure 4.6: Throughput comparison for various relay selection rules with multiple relays in the worst-pair case for the bottleneck SNR approach.

of the throughput-optimal approach. This is because deploying more relays forces the bottleneck SNR approach to have a higher probability to choose relays which is close the the source, this kind of relay has bad effect on outage performance. While the throughput-optimal approach is less sensitive to this situation. From the table we see that the loss in the best-pair case is larger that that in the worst-pair case. In the best-pair case, choosing more relays results in a higher to choose relays which is close the the source, this kind of relay has bad effect on outage performance. While in the worst-pair case this situation is less sensitive since there are many possible candidates between the source and the destination.

Table 4.1: **Performance Comparison Between One Relay and Two Relays**

	Throughput-Optimal	**Bottleneck SNR**
Best-Pair	**-0.17 dB**	**-0.61 dB**
Worst-Pair	**-0.1 dB**	**-0.2 dB**

CHAPTER 5

Effects of Total Relay Transmit Power Constraint for Relay Networks

In this chapter, we investigate the impact of total relay transmit power constraint on relay selection rules. Our goal is to reduce energy consumption, while maintaining throughput.

5.1 Power Allocation for Relay Selection Rules in the Literature

In [7,14,15], power allocation is proved effective in reduce energy consumption. Therefore at the same consumed power level the outage probability becomes lower. In this thesis, we expect that utilizing total relay transmit power constraint on the proposed relay selection rules can achieve lower outage probability at the same consumed power level in addition maintain the throughput performance.

5.2 Total Relay Transmit Power Constraint for Proposed Relay Selection Rules

In the traditional method, the transmit power allocated in the relay link from the source is the same as that in the relay link to the destination. Now, we suggest a total relay transmit power constraint to adjust transmit power from the relay as the number of the relays increases. In the suggested constraint, the transmit power of each relay is inversely proportional to the number of relays, and the sum of the total transmit power from the relay is equal to the transmit power from the source.

$$P_{tr} = \frac{P_{ts}}{N_r} \quad . \tag{5.1}$$

where P_{tr} is the transmit power of a relay. P_{ts} is the transmit power of the source. N_r is the number of relays.

From the above definition, we know that for the single relay case the transmit power of the relay is equal to the transmit power of the source. However, for multiple relays case, the transmit power of a relay is less than the transmit power of the source. Also, the transmit power of a relay is inversely proportional to the number of relays.The total consumed power of a transmission period before power allocation can be expressed as:

$$P_{total} = P_t \times N_r + 1 \quad . \tag{5.2}$$

while after power allocation, the the total consumed power of a transmission period can be expressed as:

$$P_{total} = P_{ts} \times 2 = P_{tr} \times 2 = P_t \times 2 \quad . \tag{5.3}$$

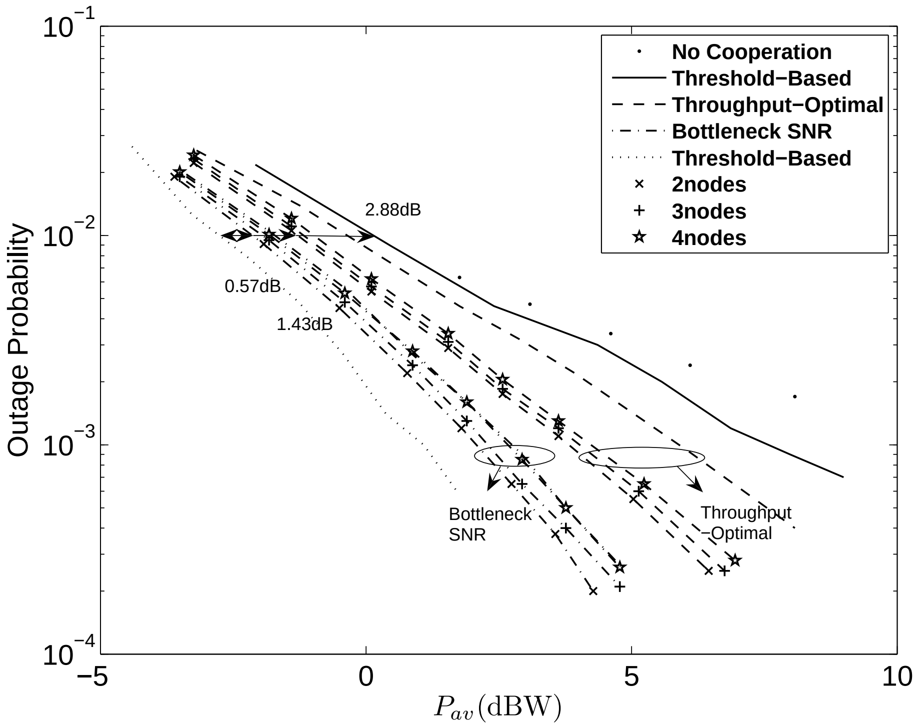

Figure 5.1: The outage probability with multiple relays with the total relay transmit power constraint in the best-pair case.

5.3 Numerical Results

In this section, we investigate the impacts of the total relay transmit power constraint on the proposed relay selection rules. We shall show the influences on the outage probability and throughput performance.

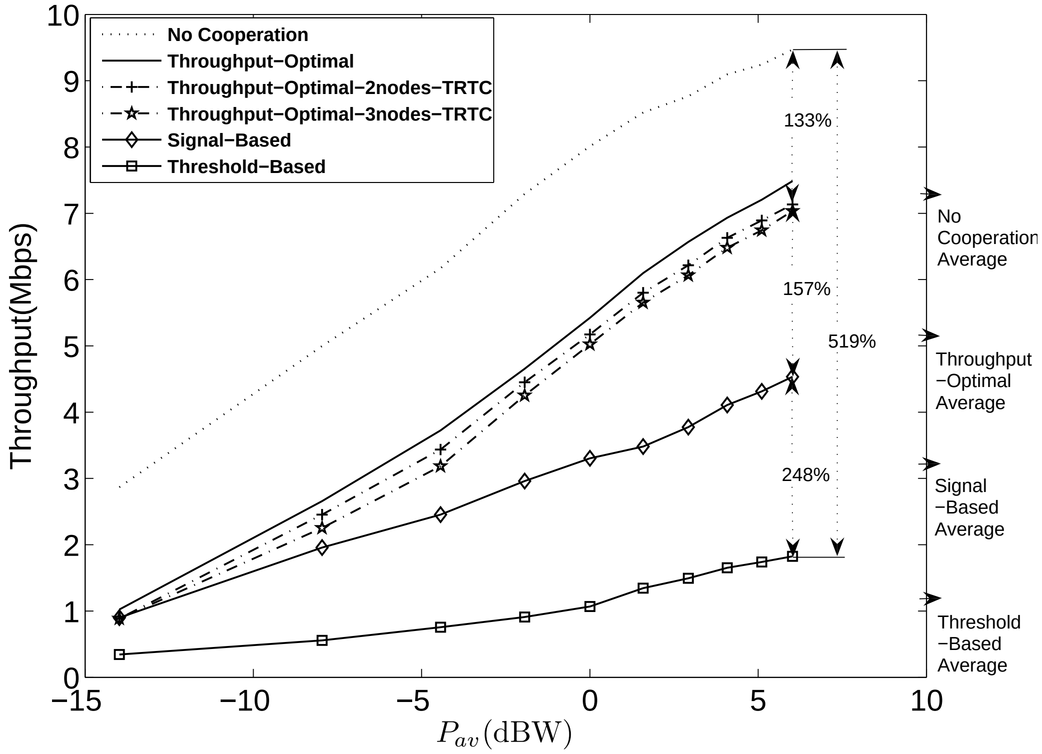

Figure 5.2: Throughput comparison for various relay selection rules with the total relay transmit power constraint in the best-pair case for the throughput-optimal approach.

5.3.1 Outage Probability and Throughput Performance of Relay Selection Rules with Total Relay Transmit Power Constraint, in the Best Pair Case

Fig. 5.1 shows the outage probability of various relay selection rules with the total relay transmit power constraint in the best-pair case. We find that at the same consumed power level the outage probability is better than that without power allocation. For throughput-optimal approach, at $P_{outage} = 10^{-2}$ it needs more 1.43 dBW than the signal-based approach, less than that in the case without the total relay transmit

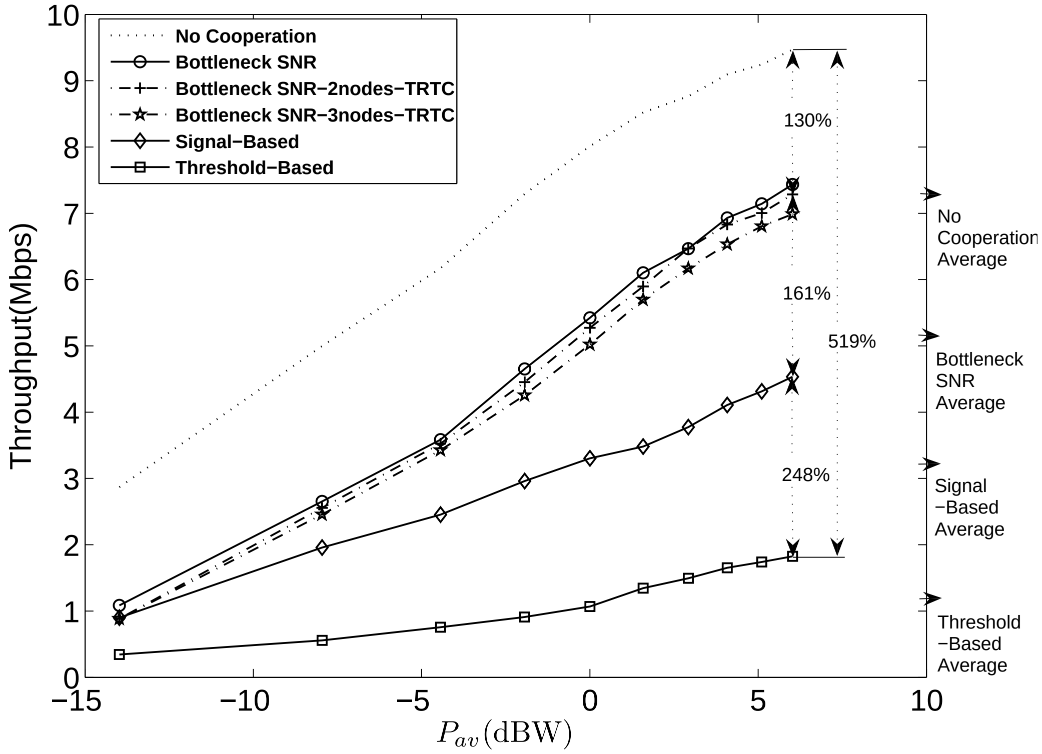

Figure 5.3: Throughput comparison for various relay selection rules with total the relay transmit power constraint in the best-pair case for the bottleneck SNR approach.

power constraint 2.57 dBW. For bottleneck SNR approach, at $P_{outage} = 10^{-2}$ it needs more 0.43 dBW than the signal-based approach, less than that in the case without the total relay transmit power constraint 1.57 dBW. This can be explained by that in the second phase, if we choose multiple relays and each relay uses the same transmit power as that of the source, the power consumed in the second phase is too much and unnecessary.

Fig. 5.2 reveals the throughput of various relay selection schemes especially for the throughput-optimal approach with the total relay transmit power constraint in the best-pair case. For throughput-optimal approach with 2 nodes, in the considered consumed power range the average throughput is 4.91 Mbps, lower than 5.18 Mbps in the single relay case. At P_{av}=6.5 dBW the throughput achieves 161% higher than that of the signal-based approach, lower than that with single relay 165%.

This is due to more power consumption from more relays and contributed form more chances to choose relay nodes close to the source or the destination. If a relay node is close to the source or the destination, then one side of the relay node has a low link throughput. Hence, the overall link is limited to a low throughput.

Fig. 5.3 shows the throughput of various relay selection rules especially for the bottleneck SNR approach with the total relay transmit power constraint in the best-pair case. For bottleneck SNR approach with 2 nodes, in the considered consumed power range the average throughput is 5.02 Mbps, lower than 5.15 Mbps in the single relay case. At P_{av}=6.5 dBW the throughput achieves 161% higher than that of the signal-based approach, lower than that with single relay 165%.

This is contributed from more power consumption by more relay nodes and due to more chances to choose relay nodes close to the source or the destination, then one side of the relay node has a poor link throughput. Therefore, the total link throughput is limited.

From the above three figures, we find that utilizing power allocation appropriately can eliminate wasted power and achieve better performance while keep reasonable throughput. In Chapter 4, we thought that there is no advantage from using multiple relays. However, after using power allocation we find gains through multiple relays. This is an interesting discovery.

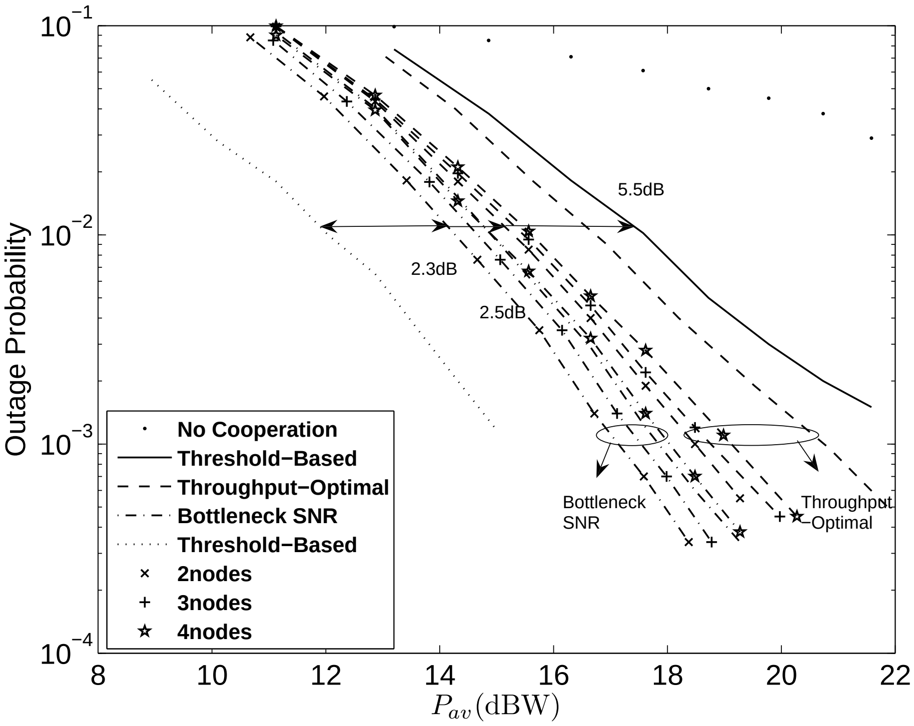

Figure 5.4: Outage probability with the total relay transmit power constraint in the worst pair case.

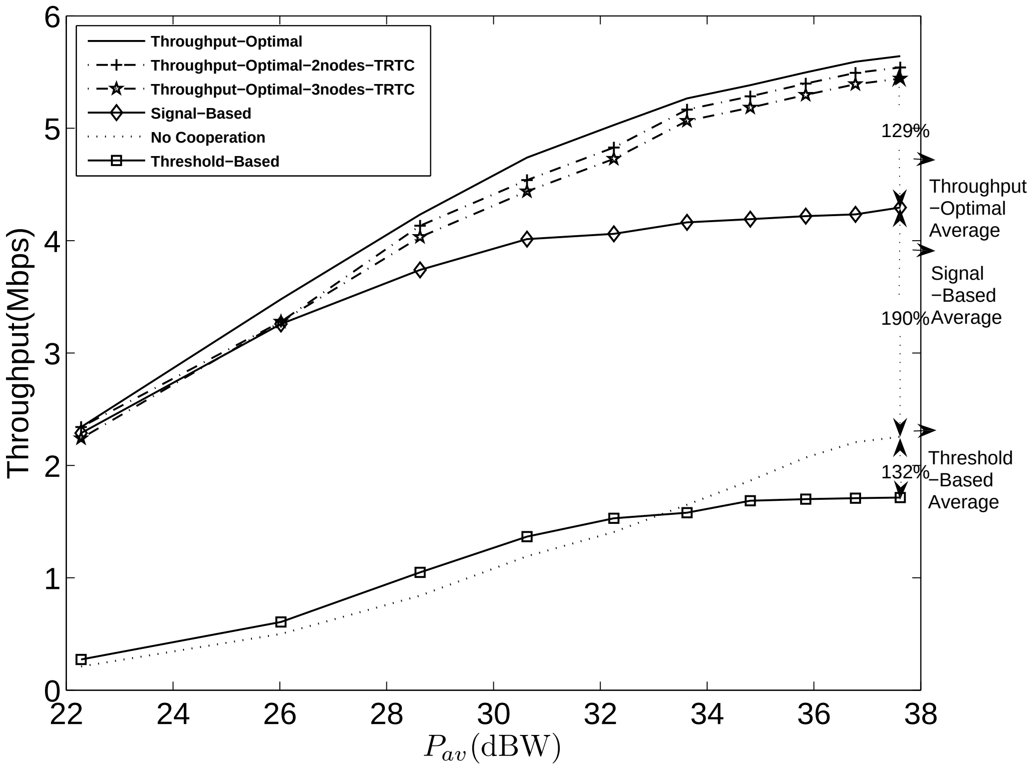

Figure 5.5: Throughput comparison for various relay selection rules with the total relay transmit power constraint in the worst-pair case for the throughput-optimal approach.

5.3.2 Outage Probability and Throughput Performance of Relay Selection Rules with the Total Relay Transmit Power Constraint, in the Worst Pair Case

Fig. 5.4 shows the outage probability of various relay selection rules with the total relay transmit power constraint in the worst pair case. The outage probability is better than that before utilizing the constraint. For throughput-optimal approach, at $P_{outage} = 10^{-2}$ it needs more 2.5 dBW than the signal-based approach, less than

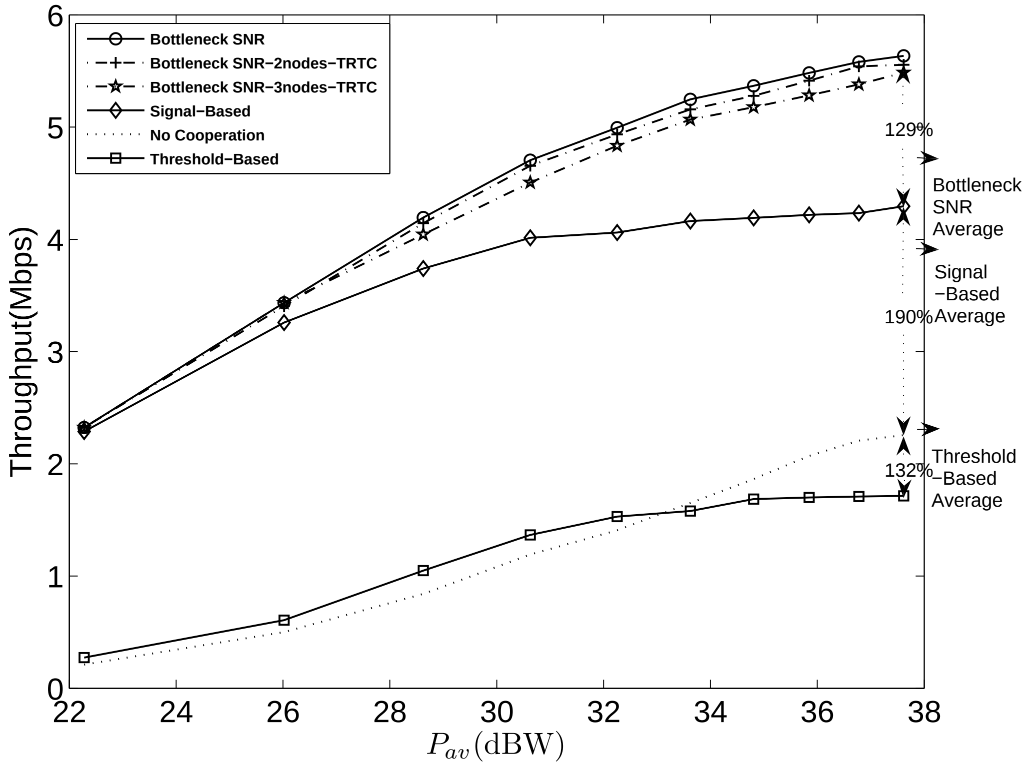

Figure 5.6: Throughput comparison for various relay selection rules with the total relay transmit power constraint in the worst-pair case for the bottleneck SNR approach.

that in the case without the total relay transmit power constraint 4.8 dBW. For bottleneck SNR approach, at $P_{outage} = 10^{-2}$ it needs more 2.3 dBW than the signal-based approach, less than that in the case without the total relay transmit power constraint 3.1 dBW.

Fig. 5.5 reveals the throughput of various relay selection schemes especially for the throughput-optimal approach with the total relay transmit power constraint in the worst pair case. For throughput-optimal approach with 2 nodes, in the considered consumed power range the average throughput is 4.60 Mbps, lower than 4.72 Mbps in

Table 5.1: **The Performance Comparison Before and After Applying Total Relay Transmit Power Constraint for Two-Relays Case**

	Throughput-Optimal	**Bottleneck SNR**
Best-Pair	**1.14 dB**	**1 dB**
Worst-Pair	**2.3 dB**	**0.8 dB**

the single relay case. At P_{av}=37.8 dBW the throughput achieves 129% higher than that of the signal-based approach, lower than that with single relay 131%.

Fig. 5.6 says the throughput of various relay selection rules especially for rule 2 with the total relay transmit power constraint in the worst pair case. For bottleneck SNR approach with 2 nodes, in the considered consumed power range the average throughput is 4.64 Mbps, lower than 4.70 Mbps in the single relay case. At P_{av}=37.8 dBW the throughput achieves 129% higher than that of the signal-based approach, lower than that with single relay 131%.

From the above three figures, we find that utilizing power allocation appropriately can eliminate wasted power and achieve higher reliability while maintain acceptable throughput. In Chapter 4, we thought that there is no advantage from using multiple relays. However, after using the total relay transmit power constraint, we find gains through multiple relays. This is an interesting discovery.

For the bottleneck SNR approach with 2 or 3 relays with power allocation, at the same consumed power level the outage probability is even better than that with single relay. And the throughput is maintained in a reasonable range. Therefore, we would recommend the bottleneck SNR approach with 2 relays with the total relay transmit power constraint as the best throughput-oriented relay selection rule.

Table. 5.1 shows the performance gain of using the total relay transmit power constraint. It computes that at $P_{outage} = 10^{-2}$, how much P_{av} is reduced by using the total relay transmit power constraint in the two-relays case. We can know that the gain of the throughput-optimal approach is larger than that of the bottleneck SNR approach. This is because throughput-optimal approach uses transmit power in a more inefficient way than the bottleneck SNR approach. From the table we do not see significant difference between the best-pair case and the worst-pair case.

CHAPTER 6

Conclusions and Future Research Suggestions

There are three main contributions in this thesis. First, we propose two throughput-oriented relay selection rules to get higher throughput. In the literature, many studies design relay selection schemes aiming at achieve better outage probability. However, there is little effort on analyze how to obtain higher system throughput in the relaying networks. Therefore, in this work we propose two relay selection schemes to achieve higher throughput while maintain reliability. The throughput-optimal approach we suggested has the best throughput, but the outage probability is relatively poor and the computational cost is relatively high. Therefore, we propose the bottleneck SNR approach, which is more simpler and has better outage than the throughput-optimal approach while keeping a similar throughput.

Second, we extend the number of relays from one to multiple. We deploy multiple relays to see if there is any improvement in the outage probability or throughput. However, the simulation results are disappointing. At the same consumed power level the outage probability and throughput are both degraded while deploy multiple relays. More relays, poorer outage probability and throughput.

Last but not least, we present the impacts of power allocation on the proposed relay selection rules. We suggest a simple power distribution algorithm here. Excitingly, we find that at the same consumed power level power allocation can improve the outage probability in the multi-relay case while keeping similar throughput. The result for the bottleneck SNR approach with two nodes with power allocation is even better than that of it with single relay. This discovery shows that appropriately utilize power distribution can eliminate unnecessary power and obtain better performance.

6.1 Throughput-Oriented Relay Selection Rules

In Chapter 3, we propose two partner selection methods. The first one is to calculate throughput corresponding to each relay, and then choose the relay achieving the maximal throughput. Though this method can achieve the highest throughput, computation cost is quite high. In the second method, we first compare the SNRs of the link from the source to relay with that from the relay to the destination, and designate the smaller one as the bottleneck SNR associated with that relay. The bottleneck SNR of each relay is recorded and compared. The relay with the largest bottleneck SNR is selected. Both methods have the similar throughput performance. However, the outage probability of the second method is better than that of the first one. Meanwhile, compared to the conventional signal-based partner selection, the proposed bottleneck SNR approach can achieve higher throughput at the cost of small SNR degradation.

6.2 Throughput-Oriented Relay Selection Rules in the Multiple Relay Case

In Chapter 4, we examine the performance of the considered relay selection rules in the multiple relay case. We find that at the same consumed power level the outage probability and throughput performance in the multi-relay case is indeed worse than those in the one relay case. This is because the multi-relay case yields more power consumption and higher probability in selecting inappropriate relays.

6.3 Power Allocation for the Proposed Relay Selection Rules

In the traditional method, the transmit power allocated in the relay link from the source is the same as that in the relay link to the destination. Now, we suggest a simple power distribution algorithm to adjust transmit power from the relay as the number of the relays increases. In the suggested power distribution rule, the transmit power of each relay is inversely proportional to the number of relays, and the sum of the total transmit power from the relay is equal to the transmit power from the source. Our results show that at the same consumed power level the proposed power distribution can improve outage probability, while maintaining throughput even in the multi-relay case. This is because the proposed power allocation can eliminate unnecessary power in the second transmission phase with multiple relays.

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