Cross layer analysis and optimization of relay networks

by

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To my parents and wife

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CHAPTER I

Introduction

Recently, there has been significant interest in relay networks. Due to the wireless signal power attenuation with transmission distance, using relays in a wireless network can make wireless networking more bandwidth and energy efficient at the expense of requiring multiple transmissions for a single packet. Relay networks require a medium access (MAC) protocol because it involves multiple hop transmission for communication between the source and destination. In a decentralized wireless network, MAC protocols should be defined and accounted in performance analysis because the channel access can consume significant energy and bandwidth resources. The channel access protocol has largely been ignored in most previous investigations. As such, there exists a need for analysis and optimization of the relay networks performance (energy and throughput) taking into account the MAC layer as well as the physical layer. In this thesis, we investigate the performance of relay networks considering both the physical layer and the MAC layer and propose a MAC protocol for relay networks.

Relay transmission affects both the physical layer and the MAC layer. As an example, Figure 1.1 compares direct transmission and relay transmission when a relay is located in the middle of the source and destination. Because there is less signal attenuation due to the shorter one hop distance, relay transmission can use

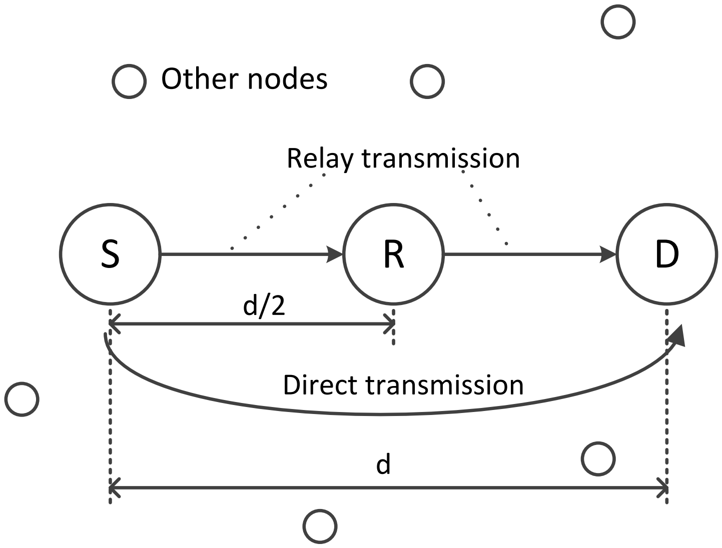

Figure 1.1: System model

lower transmit power to achieve the same capacity with direct transmission. When a transmit power P_t is used, the capacity for relay transmission is [36]

$$C_{DF} = \min\left(\log_2\left(1+\frac{P_t}{d_{sr}^{\alpha}N_0W}\right), \log_2\left(1+\frac{P_t}{d_{sd}^{\alpha}N_0W}+\frac{P_t}{d_{rd}^{\alpha}N_0W}\right)\right)(bps/Hz) \tag{1.1}$$

where N_0 is the noise power spectral density and W is bandwidth used for communication for decode-and-forward relay transmission, which is one of the widely used relay transmission schemes. The capacity for amplify-and-forward relay transmission, which is another widely used relay transmission scheme is [36]

$$C_{AF} = \log_2\left(1+\frac{P_t}{d_{sd}^{\alpha}N_0W}+f\left(\frac{P_t}{d_{sr}^{\alpha}N_0W}, \frac{P_t}{d_{rd}^{\alpha}N_0W}\right)\right) \tag{1.2}$$

where

$$f(x,y) = \frac{xy}{x+y+1}. \tag{1.3}$$

At the same time, the use of lower transmit power level leads to less channel contention and MAC overheads for each hop because the signal travels shorter distance.

However, relay transmission requires two packet transmissions, one from the source and the other from the relay. Also relay transmission requires the source node to contend for channel access when transmitting to the relay and requires the relay node to contend for the channel access when transmitting to the destination. As such, cross layer analysis considering both the physical layer and MAC layer is needed to understand and optimize the performance of relay networks. Previous research on relay networks typically only considered the physical layer assuming that the channel access is granted without any overhead. This thesis proposes a model for the cross layer analysis and optimization. This cross layer approach enables a realistic understanding of the performance of relay networks.

Relay network research started from Van der Meulen's seminal work on a three terminal channel [56] and [55]. The capacity for relay channels was studied by Cover and Gamal [15]. Several relaying strategies have been proposed such as amplify-and-forward (AF) and decode-and-forward (DF), selection relaying, and incremental relaying [36] and their diversity gain was analyzed [36], [3], [45], and [59]. In amplify-and-forward scheme, the source transmits information in the first interval. During the first interval, the relay receives the signal from the source. During the second interval, the relay transmits the received signal after compensating the signal attenuation by amplifying the received signal. The relay does not decode the received signal so it also amplifies noise at its receiver. The destination decodes the received signals from the source and relay after the second interval by a proper combining method. In decode-and-forward scheme, the source transmits information in the first interval. The relay receives signal from the source and decodes the information during the interval. In the second interval, the relay re-encodes and transmits the decoded information. The destination combines signals from the source and relay, and decode the information. Selection relaying scheme uses relaying in the second interval only when the channel between the source and relay is good. When the channel gain is less than a certain threshold, the source repeats the same information with the first interval. In incremental relaying, the destination transmits either acknowledgement or negative acknowledgement after the first interval. When it is acknowledgement indicating successful reception, the relay does not repeat the received signal. When it is negative acknowledgement after unsuccessful reception, the relay repeats the received signal during the second interval.

In standard AF and DF only one relay is allowed to help transmission between the source and destination. Space-time coded cooperative diversity scheme that allows simultaneous relaying from multiple relays was proposed in [37] and shown to achieve diversity gain. In the first interval, the source transmits information to the destination. Those relays that can fully decode the information utilize a space-time code to cooperatively and simultaneously transmit the information to the destination using the same frequency band. Because of the space-time code, the destination can decompose and combine those multiple signals. When the phase information is given, the source and relays can use beamforming by matching the phase of transmitted signal as proposed in [50]. It was shown that this achieves diversity gain but it required the channel state including the phase be known at the transmitter. There also has been research on developing practical coding for cooperative communication as in [53] and [29].

Because relay networks use cooperative communication, it can be easily combined with network coding [2]. Physical network coding (PNC) [60] that uses the network coding nature of electro-magnetic waves that superimpose the simultaneously transmitted signals also has been proposed. Two way relay channel [58] has attracted significant interests in network coding research. In [48], cooperative strategies such as DF, AF, and CF were shown to achieve network coding with full duplex relays in two way relay channel. Channel coding was jointly considered with network coding in [26]. The bit error rate (BER) of physical network coding for two-way relay channel was considered in [42]. A protocol for network coding for relay networks, COPE, [32] also has been proposed. Nodes broadcast a list of received packets to neighboring nodes. When a node overhears received packet lists from neighboring nodes, it broadcasts a network coded (exclusive-or) packet. With the network coded packet, each node can decode another packet which improves bandwidth efficiency. However, network coding approach for relay network does not consider the MAC overheads for the channel access.

There have been approaches to consider more realistic model for relay networks. One direction is to consider the relay selection. Because the performance of relay transmission depends on the channel states, choosing a good relay to cooperate is important for the performance improvement. In [7] selection cooperation that allows one best relay for each source node was proposed. However, it requires a priori knowledge of the channel state information between the source node and all relays. There have been various relay selection schemes proposed that do not require prior knowledge of the channel. These include the best relay selection schemes based on SNR [34], distance [49], best of the worst channel [9], and best harmonic mean [9]. Bletsas [9] proposed a relay selection scheme using a timer that depends on the channel state. Multiple relay selection schemes were proposed and analyzed in papers such as [31] and [44].

Another area of investigation for relay network is the MAC protocol. Because relay transmission requires multiple transmission, MAC protocols that support multiple transmission in one channel access are needed. Also, because the MAC operations can incur significant overhead (delay and energy), these should be accounted for in the performance analysis. Several MAC protocols has been proposed for relay networks. Harbinger [62] is a MAC protocol for the relay selection through a contention period between relays that decoded the information from the source. Among the relays that decoded received information, the relay closest to the destination acquires a chance to transmit to the destination. However, the protocol does not consider the procedure for the channel access for source node, but only consider the MAC operation for relays. The CoopMAC [41] is a MAC protocol for relay networks that involves the relay selection. In CoopMAC, each node maintains a list of potential help nodes and their channel condition to other nodes. When a node has a packet to send, it estimates the performance improvement from relaying based on the maintained list. When the relaying is more beneficial, the sender choose the best relay from the list and include the request for relaying in the request-to-send (RTS) packet. The relay broadcasts the Helper ready to send (HTS) packet as the response. After the reception of HTS packet, the destination broadcasts a CTS packet. After CTS packet from the destination, the source sends a packet to the relay at a proper rate that depends on the channel condition and the relay sends the received packet to the destination in a similar way. The CoopMAC requires a priori knowledge on channel condition between nodes and only supports one type of relaying. Also, the destination cannot combine the two received signal because they are encoded in different rate. Relay enabled distributed coordination function (rDCF) [63] is also a MAC protocol to support relaying in distributed wireless networks. In rDCF, each node overhears packet transmissions between neighboring nodes and determines whether relaying through itself can improve the throughput. If so, it includes those pairs in the relaying list and periodically advertise the list to neighbors. When a node has a packet to send, it searches the received list to check possible throughput improvement by relaying. When relaying achieves higher throughput, it operates three-way handshake that is the same with the Coopmac. However, it relies on the channel condition collected in advance, which can be changed in the meantime. Also, the advertisement can cause significant overhead, which was not considered. Space-time coding in Cooperative MAC (STiCMAC) [40] is a MAC protocol to support space-time coded relay networks. It also utilizes the three-way handshake between the source, relay, and destination. During the handshake, critical parameters such as packet transmission timing, space-time code that will be used, and transmission rate should be exchanged. At the first transmission timing, the source transmits the data packet and all relays transmit the received data packet simultaneously in the second transmission timing. The MAC protocol can improve throughput, but using all relays in the area can be energy inefficient. Also, precise time synchronization required for STiCMAC can incur significant overheads. A MAC protocol to support incremental relaying was proposed in [39]. The incremental relaying introduced previously involves only one relay, but this protocol allows multiple relays participate in incremental relaying if they have a channel condition over a threshold. To resolve collisions between relays, it proposes a random backoff based MAC protocol to select a relay to repeat the received packet. There have been several MAC protocols for relay networks. However, they have limitations such as requiring a priori channel information, incurring significant overhead to support relaying, or only supporting one type of relaying scheme.

As mobile devices battery operated devices are widespread, the energy consumption becomes a significant performance factor in these networks. There is a fundamental tradeoff between bandwidth efficiency and energy efficiency in a wireless communication systems. The fundamental energy-throughput tradeoff was considered in [57]. Rather than just considering the transmitted signal power for energy consumption, there has been practical approaches that incorporated the circuit energy consumption in the analysis. These research considered optimization in modulation [16], transmit power and transmit time [51], and routing, scheduling, and modulation [17]. However, they only minimized the energy consumption and did not consider the bandwidth efficiency. In multi-hop wireless networks, the energy-bandwidth tradeoff was investigated in [14], [47], [46], and [6]. However they did not consider the circuit energy consumption. There has been a multi-hop wireless network research that optimized the energy consumption including the circuit energy consumption [4]. However it did not consider the overheads from MAC operations.

We investigate the bandwidth efficiency (throughput), energy efficiency, and optimization of relay networks considering both the physical layer and the MAC layer. In the second chapter of this thesis, the energy-throughput tradeoff of a two hop relay network is analyzed and compared with direct transmission. We analyze the energy consumption and the throughput of relay networks as a function of the transmit power. Transmit power affects both the physical layer and the MAC layer. At the physical layer, it determines the rate that a packet can be transmitted and the power consumption for transmission. At the MAC layer, it determines the level of channel contention, which affects both the throughput and energy consumption. Based on the tradeoff, we find the optimal transmit power level that achieves the maximum throughput or minimum energy consumption for direct transmission and relay transmission. Contrary to popular belief, the transmit power level that achieves the maximum throughput is not the maximum transmit power and the transmit power level that achieves the minimum energy consumption is not the minimum transmit power when we consider both the physical layer and the MAC layer. We compare the performance of the optimal operating points of direct transmission and relay transmission for different source-destination distance and node densities. It is shown that relay transmission is more bandwidth efficient and energy efficient at longer source destination and higher node densities.

In the third chapter, we investigate a multihop scenario and determine the optimal number of hops and the optimal transmit power that achieves the minimum energy consumption or maximum throughput considering both the physical layer and MAC layer. When the source-destination distance is large, using small number of relays is inefficient because the one hop distance becomes too large. On the other hand, using too many relays decreases efficiency because it incurs unnecessarily many time of channel access. The transmit power and the number of hops are jointly optimized to maximize throughput or minimize energy consumption. It is shown when the source-destination distance is large the optimal transmit power and the optimal one hop distance approaches a constant. The optimal number of hops increases linearly as the source-destination distance increases.

In the fourth chapter, a simple relay enabled medium access (SRMAC) protocol that enables cooperative relay transmissions is proposed. Standard MAC protocols such as the IEEE 802.11 MAC protocols are not designed to support cooperative communication. When IEEE 802.11 MAC protocol is used for cooperative communication, packet transmission at each hop should undergo a separate channel access procedure, which is not efficient. The new protocol, SRMAC, is a cooperative MAC protocol that utilizes information from the physical layer for the MAC operation. The energy and bandwidth efficiency of SRMAC protocol considering both the physical layer and the MAC layer is identified. With SRMAC, cooperative transmission can be dynamically chosen when it is more beneficial than direct transmission. Different decision criteria for relaying can be adopted for the choice of relay transmission. It is shown that the SRMAC protocol improves both the bandwidth efficiency up to 20% and energy efficiency up to 40% compared to direct transmission. Compared to relay transmission with IEEE 802.11 MAC protocols, it achieves 88% higher throughput.

The proposed model, analysis, optimization, and design will be useful in the design of distributed wireless networks that use relays. Because the overhead from the physical layer and the MAC layer are accounted for in the analysis, the results provided here will give a realistic understanding of relay networks. For example, the proposed methods can be applied to the design of general distributed wireless networks, mobile device-to-device communication, or sensor networks.

CHAPTER II

Cross Layer Analysis of Energy-Throughput Tradeoff for Relay Networks

In this paper we study the bandwidth efficiency (throughput) and energy efficiency of relay networks considering both the physical layer and the medium access control (MAC) layer. Due to wireless signal power attenuation with transmission distance, using a relay for packet transmissions can lead to more energy efficient wireless networking at the expense of requiring multi-hop transmissions. To understand the potential benefits of using a relay, the energy-throughput tradeoff needs to be analyzed. In a decentralized wireless network, not only the physical layer but also the MAC layer should be considered. At the physical layer the transmit power determines the area which contains nodes that might be contending for channel access at the MAC layer. At the MAC layer, gaining access to the channel entails transmitting various signals at the physical layer. This uses energy and takes time which impacts the bandwidth efficiency. We analyze the energy consumption and the throughput of relay networks as a function of the transmit power. We determine the conditions in which wireless communication using a relay has better energy efficiency or bandwidth efficiency than direct transmission.

2.1 Introduction

There is a fundamental tradeoff between bandwidth efficiency and energy efficiency in wireless communication systems. In a single point-to-point link this tradeoff is embodied in the well known capacity of a communication system, which indicates the maximum achievable data rate in a given bandwidth as a function of the received signal-to-noise ratio. The use of a relay can improve both the energy efficiency and the bandwidth efficiency in distributed wireless networks. However, in a decentralized multi-hop wireless network, the tradeoff is not clearly understood. In the case of a multi-hop wireless network, the physical layer overhead and the overhead from channel access should be considered when analyzing the energy efficiency and the bandwidth efficiency.

To understand the issues involved in the energy-bandwidth tradeoff, consider a distributed network of nodes whereby a source node uses a relay node to reach a final destination node. Because the relay node reduces the distance for each transmission, the power level required for a given data rate can be drastically reduced or with the same transmission power the data rate can be significantly increased. This is because the propagation loss is generally at least proportional to the distance squared. However, use of a single relay means two transmissions: a transmission from the source to the relay and a transmission from the relay to the destination. This reduces the throughput. In addition, each time a node needs to access the channel overhead may be required (e.g. a request-to-send message and a clear-to-send message). This also reduces the bandwidth efficiency relative to a single hop transmission. A single hop transmission, however, would necessarily have to contend for channel access with a larger set of nodes and thus the time for a single channel access would be larger with a larger pool of nodes. The goal of this research topic is to analyze the performance (energy and throughput) of a distributed wireless network taking into consideration these effects. Furthermore, the effect of the power level used for transmission of information on the bandwidth efficiency and energy efficiency is investigated. Interestingly, increasing the power levels can actually decrease the energy used for relaying information because of the shorter transmission times and the duration of time a receiver must listen to a message.

Research on relay networks has its origin in van der Meulen's seminal work [55], [56] which studied the capacity of a three terminal channel. Since then much research has been done on the capacity of different relay schemes [15], [24], [61] and on the diversity-multiplexing tradeoff of cooperative relaying schemes [36], [37], [3]. However, these papers on distributive relay networks only considered the physical layer. Moreover, they only considered the bandwidth efficiency. The potential improvement in energy efficiency was not considered. The energy-throughput tradeoffs of cooperative relay networks was considered in [5], [4], and [30]. These papers considered both the energy efficiency and the bandwidth efficiency. However, they considered only the physical layer, which ignores the overhead due to channel access. Thus, while a significant amount of research has been done on relay networks, it does not provide the energy-bandwidth efficiency of relay networks talking into account both the physical and MAC layer.

For instance, Bianchi [8] analyzed the throughput performance of the IEEE 802.11 RTS/CTS MAC protocol. However, he analyzed the performance of a one hop wireless communication and did not consider the energy consumption. Feeney [22] investigated the energy consumption of wireless network by measuring the actual energy consumption of an IEEE 802.11 wireless LAN card, but did not consider the bandwidth efficiency. Carvalho [10] investigated the energy consumption for a single hop in an ad-hoc network. He considered energy consumption from the MAC layer operation, but did not consider the throughput-energy consumption relationship. Liaskovitis [38] studied the throughput and the energy consumption of multi-hop wireless networks with transmit power optimization. However, he simplified the physical layer by assuming only a fixed packet transmission rate is supported at the physical layer regardless of the transmit power level. He also did not consider the energy consumption from MAC layer control packet transmissions. Moreover, packets are assumed to be routed through the minimum hop. But the minimum number of hops does not guarantee the maximum throughput or the minimum energy consumption. Chang, Stark, and Anastasopoulos studied the energy-delay analysis of MAC protocols in [11]. They considered how the energy per coded bit and the codeword length affects the total energy consumption and the delay of the network by using the cutoff rate of the channel. However, their approach did not consider the effect of transmit power level on the number of contending nodes by assuming that there are $n-1$ contending nodes regardless of the energy per coded bit level.

In this research, we consider the energy-throughput relationship of relay networks taking into account both the physical layer and the MAC layer. The time consumption and the energy consumption from all of the packet transmissions, packet receptions, and the MAC operation are incorporated into the analysis. We show that the maximum throughput or the minimum energy consumption can be achieved by optimizing the transmit signal power for both the direct transmission scheme and the relay transmission scheme. We determine which of two transmission schemes (direct or relay) should be chosen using the energy-throughput tradeoff analysis for the optimum transmit signal power.

The outline of this chapter is as follows. In Section II, we introduce the system model. In Section III, we analyze the delay of a relay network. In Section IV, we analyze the energy consumption. In Section V, we discuss the energy-throughput relationship. In Section VI, we compare the direct transmission and the relay transmission. Conclusions are given in Section VII.

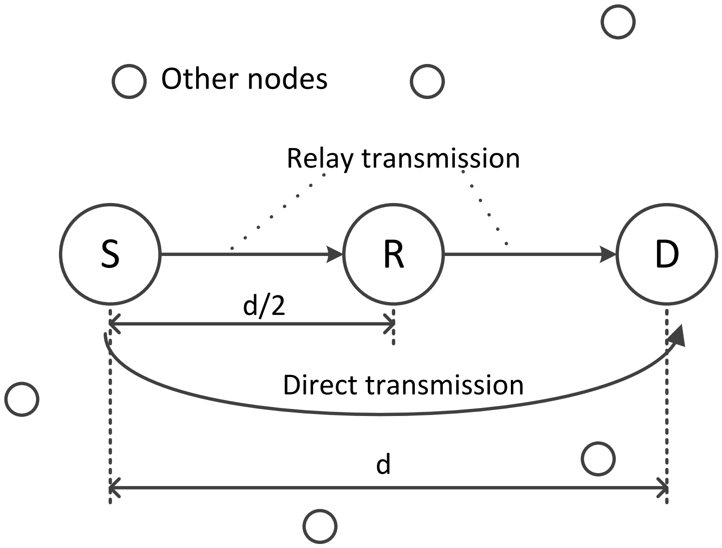

Figure 2.1: System model

2.2 System Model

As shown in Fig. 2.1 the system model we consider there is one source node, one relay node, and one destination node separated by the same distance $\frac{d}{2}$ on a straight line. There are also other nodes contending for channel access. In our model, the source node can send packets either directly to the destination or through the relay node. We assume all nodes in the network use the same transmit power and the same MAC protocol.

2.2.1 Physical Layer Model

At the physical layer, we assume the channel model is a Rayleigh fast fading channel with distance dependent path loss. The transmitter encodes data with a code of rate R information bits per coded bit. The encoded bits are transmitted with transmit power P_t. The average received signal power $\bar{P}_r$ is

$$\bar{P}_r = \left(\frac{k}{d}\right)^{\alpha} P_t \tag{2.1}$$

where α is the path loss exponent, which is usually between 2 and 4 [27] and k is number of hops for packet transmission. For the direct transmission, k is one, and for the relay transmission, k is two.

We assume that the data packet transmission achieves the capacity of the IID Rayleigh fading channel with coherent reception by using proper coding and modulation. The IEEE 802.11 RTS/CTS MAC operation can be used to inform the path loss measured at the receiver to the transmitter as in [28]. We also assume that the receiver can perfectly track the fading in the channel. The transmitter does not know the fading level in the channel but knows the distribution of fading. With these assumptions, the capacity for one hop transmission, S, in bits/second is expressed by [54]

$$S = W \cdot E\left[\log_2\left(1 + \frac{|h|^2 k^\alpha P_t}{N_0 W d^\alpha}\right)\right] \tag{2.2}$$

where h is the fading process, W is the channel bandwidth, and N_0 is the additive white Gaussian noise power spectral density. The expectation is with respect to h which is a Rayleigh distributed random variable. In (2.2), $\frac{k^\alpha P_t}{N_0 W d^\alpha}$ is the average received signal-to-noise-ratio (SNR). Because the packet length is not infinity, the assumption that the data packet transmission achieves capacity can be contradictory. However, when the code length is 2,000 bytes (16,000 bits), the required bit SNR penalty, $\frac{E_b}{N_0}$, to achieve the block error rate of 10^{-4} is less than 0.3dB when the rate same with the channel capacity is used with Turbo code [20]. As such, the assumption of the achieving capacity at the physical layer is a reasonable approximation. The assumption allows cross layer energy and throughput analysis. Those small SNR penalty and error rate might change the results in this research slightly, but the idea developed in this research will be still valid.

2.2.2 MAC Layer Model

In a wireless network, the MAC protocol controls the channel access. We adopt the IEEE 802.11 RTS/CTS protocol as the MAC protocol. For simplicity, we assume that all nodes in the network use the same power and the same transmission scheme. We assume that the control packets are transmitted at a fixed rate $R_{control}$ regardless of the transmit power level to enable reliable control packet communication. In the IEEE 802.11 RTS/CTS protocol, when the source obtains a channel access, other nodes in the area around the source and the area around the receiving node are blocked from transmitting. These other nodes in that area defer packet transmissions when it overhears an RTS packet or a CTS packet, or detects any packet transmission until the packet transmission from the source is finished. We make a heavy traffic assumption which means each node always has packets to transmit to other nodes. For more detailed description of IEEE 802.11 backoff mechanism and RTS/CTS protocol, see [8].

At the MAC layer, we consider the dynamic relationship between the transmit power and the number of contending nodes. We assume the minimum received signal power that overhearing nodes can detect a CTS or an RTS packet is P_{th}. Then the radius of channel reservation is

$$d_{resv} = \left(\frac{P_t}{P_{th}} \right)^{\frac{1}{\alpha}} . \tag{2.3}$$

Other nodes in the radius around the receiving node contend with the source for the channel access. We assume that other nodes are distributed with density ρ. Then the average number of contending nodes for the source node, n, is

$$n = \rho \pi d_{resv}^2 = \rho \pi \left(\frac{P_t}{P_{th}} \right)^{\frac{2}{\alpha}} . \tag{2.4}$$

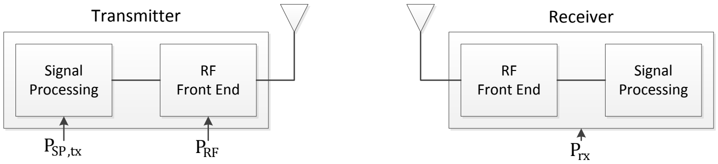

Figure 2.2: Wireless node model

Accordingly, the number of contending nodes increases as the transmit power increases.

2.2.3 Energy Consumption Model

In this section, we propose an energy consumption model. Figure 2.2 shows the wireless node model. A wireless node consists of an RF front end and a signal processing part. At the trasmitter RF front end amplifies and transmits signals. The signal processing part includes MAC operations, encoding, and modulation. When there are packet transmissions, both the RF front end part and the signal processing part are used. At the RF front end, the power consumption increases as the transmit signal power increases. The signal processing part consumes a fixed amount of power, $P_{SP,tx}$ regardless of the transmit signal power level. The RF front end converts the DC power P_{RF} to RF power, P_t with an efficiency η. Accordingly, the power consumption is

$$P_{tx} = P_{RF} + P_{SP,tx} = \frac{1}{\eta} P_t + P_{SP,tx}. \tag{2.5}$$

When a node is receiving, both the RF part and the signal processing part are actively consuming power. However, the amount of power consumed at the RF part of a receiver is small compared to that of a transmitter because a receiver does not use a power amplifier. We assume a fixed amount of power, P_{rx} for receiving a packet. The energy consumption is multiplication of power consumption and the duration of the power consumption. As such, packets with longer duration consume more energy than packets with shorter duration.

2.3 Delay Analysis

2.3.1 Data Packet Delay

We assume that the capacity is achieved for packet transmissions at the physical layer. When the rate supported by the physical layer is given by S bits/sec, the delay from the actual data packet transmission is simply the time consumed for the transmission. With the data packet size M bits, the delay from the data packet transmission, D_{data} is

$$D_{data} = \frac{M}{S}. \tag{2.6}$$

Previously the data packet transmission rate was assumed to be fixed [8]. We incorporate the dynamic relationship between the transmit power and the data packet transmission rate in this research.

2.3.2 MAC Protocol Delay

For the MAC layer delay analysis, we adopt and modify Bianchi's Markov chain analysis [8] and Boucouvalas' analysis [13]. We also extend the model to account for the connection between the physical layer and the MAC layer. In [8] and [13], the MAC layer performance was analyzed assuming that the physical layer is fixed. The physical layer was abstracted to support a fixed data transmission rate. However, the physical layer can be optimized and this affects the performance of the MAC layer. When a node increases the transmit power, the achievable transmission rate increases. At the same time, the signal reaches a farther distance and increases the number of nodes contending for channel access as in (2.4), which determines the performance of the MAC layer. We capture the effect of this connection between the physical layer and the MAC layer by extending Bianchi's model. As such, the transmit power control affects not only the physical layer performance but also the MAC layer performance. Also, only the overall network performance was considered in [8] and [13]. However, we consider the performance of individual packet transmissions between the source and destination by modifying their analysis.

In IEEE 802.11 RTS/CTS protocol, the four-way handshake of RTS-CTS-Data-ACK is used for channel access. When a source node has a packet to transmit, it listens to the channel and starts a random backoff when the channel is idle for a distributed interframe space (DIFS) time duration. When the backoff counter expires, the source transmits an RTS control packet. Upon correct reception of the RTS packet, the destination responds with a CTS packet. When the source node receives the CTS packet, it starts a data packet transmission. When the data packet is successfully received, the destination node transmits an ACK packet. Other nodes postpone packet transmission when they receive either an RTS or a CTS packet. The backoff counter is frozen when the channel is sensed busy and reactivated when the channel is idle for a DIFS duration. When there is collision between RTS packets, the process starts again with twice the contention window size from which the random backoff size is chosen.

We define two random variables to analyze the delay from MAC operations. Let X be a random variable representing the number of backoff counts consumed for the source node to gain the channel access. Let L be a random variable representing the length of time for a decrease of the backoff count. Define T_c as the time consumption from collision between RTS packets and p as the collision probability when a node transmits a packet. Define T_{RTS}, T_{CTS}, and T_{ACK} to be the time used to transmit RTS, CTS, and ACK control packets. These can be calculated by dividing the control packet size by control packet transmission rate, $R_{control}$. There are fixed time intervals that need to be accounted for, short interframe space (SIFS) and DIFS. The latter fixed time duration was explained previously. In 802.11 MAC protocol, there exists a short time duration between any packet transmission, SIFS. The time duration of those fixed intervals are denoted as T_{SIFS}, and T_{DIFS} in the analysis. There is also propagation delay δ. The average delay from the MAC protocol, D_{MAC}, when the IEEE 802.11 MAC protocol is adopted is

$$D_{MAC} = E[X] \cdot E[L] + \frac{pT_c}{1-p} + T_{RTS} + T_{CTS} + T_{ACK} + 4\delta + 3T_{SIFS} + T_{DIFS}. \quad (2.7)$$

Among the terms, $E[X]$, $E[L]$, and $\frac{pT_c}{1-p}$ are affected by the transmit power. As the transmit power increases, the average number of backoff counts, $E[X]$, and the average time consumption for unsuccessful transmissions of RTS packets, $\frac{pT_c}{1-p}$, increases due to the increased number of contending nodes, n. However, the average length of time for a decrease of the backoff count, $E[L]$ decreases as the transmit power increases because data packet transmissions between nodes become faster with higher SNR.

Let p_{tr} be the probability that there is at least one transmission at a randomly chosen time, and p_s be the conditional probability that a transmission occurring in the channel is successful given that there is at least one transmission in the channel. Successful transmission happens when only one node transmits over the channel. Then p_{tr} and p_s are [8]

$$p_{tr} = 1 - (1-\tau)^n \quad (2.8)$$

$$p_s = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n} \quad (2.9)$$

where τ is the probability that a node transmits a packet at a random time, which can be determined by a Markov chain analysis. Let p be the collision probability when a node transmits a packet. Then p and τ can be determined by following two nonlinear equations [8].

$$\tau = \frac{2(1-2p)}{(1-2p)(W+1) + pW(1-(2p)^m)} \quad (2.10)$$

$$p = 1 - (1 - \tau)^n \tag{2.11}$$

where W is the minimum contention window size and the maximum contention window size, $CW_{max} = 2^m W$.

When there is no transmission in the wireless network, the backoff counter is decreased by one after time duration σ. We define T_s as the time consumed to decrease the backoff counter by one when there is a successful packet transmission between other nodes and T_c as the time consumed to decrease the backoff counter by one when there is a collision between other nodes. These can be expressed as

$$T_s = T_{RTS} + T_{CTS} + T_{ACK} + T_H + T_D + 4\delta + 3T_{SIFS} + T_{DIFS} \tag{2.12}$$

$$T_c = T_{RTS} + \delta + T_{DIFS} \tag{2.13}$$

where T_H, T_D are time consumed to transmit the header part and data part of a packet.

With the probabilities defined above, the average length of time for a decrease of the backoff counter by one, $E[L]$, is [13]

$$E[L] = (1 - p_{tr})\sigma + p_{tr} p_s T_s + p_{tr}(1 - p_s)T_c. \tag{2.14}$$

The average number of backoff counts for one successful channel access, $E[X]$ is given by [13]

$$E[X] = \sum_{i=0}^{m-1} \left(p^i \frac{W_i - 1}{2} \right) + \frac{p^m}{1-p} \left(\frac{CW_{max} - 1}{2} \right) \tag{2.15}$$

where W_i is the size of backoff window after the ith collision, CW_{max} is the maximum size of the contention window, m is the exponent that satisfies $CW_{max} = 2^m CW_{min}$ and p is the collision probability when a node attempts channel access. The collision probability can be analyzed using Markov chain analysis [8]. Our contribution in

Parameter	Value
Payload (I) / Header (H)	2000 / 36 bytes
RTS / CTS / ACK	20 / 14 / 14 bytes
Slot time (σ) / DIFS / SIFS	9 / 34 / 16 μsec
CW_{min} / CW_{max}	16 / 1024 slots
Bandwidth	20 MHz
Path loss exponent (α)	4
$R_{control}$	20 Mbps
ρ (Node density)	0.00001 nodes/m^2
η (Amplifier efficiency)	50%
$P_{SP,tx}$	50mW
P_{rx}	55mW
P_{th}	- 100dBm

Table 2.1: Analysis parameters

delay analysis is to account for the influence of transmit power on delay and the number of contending nodes, which were not considered previously. This enables analysis that includes the physical layer and the MAC layer.

2.3.3 Overall Delay and Throughput

Delays from both the physical layer and the MAC layer should be considered when we evaluate the throughput. The total delay D_{total} is defined by

$$D_{total} = k(D_{Data} + D_{MAC}) \tag{2.16}$$

where $k = 1$ for the direct transmission and $k = 2$ for the relay transmission. We define the throughput T by

$$T = \frac{I}{D_{total}} \tag{2.17}$$

where I is the size of just the data part in a packet. The total size of a data packet is $M = I + H$, where H is the size of the header part in a packet. We list the parameters we assume including I and H in Table 1.

2.4 Energy Consumption Analysis

2.4.1 Data packet transmission energy consumption

In this section, we consider the energy consumed in order to transmit a data packet. Let P_{tx} be the transmit power consumption and P_{rx} be the power consumption necessary at the receiver to demodulate and decode a packet. Then the energy consumption for one data packet transmission E_{data} is

$$E_{data} = (P_{tx} + P_{rx})D_{data}. \tag{2.18}$$

Transmit power affects the energy consumption from data packet transmission in two ways. First, higher transmit power incurs more power consumption for the transmission, which increases the energy consumption. Second, higher transmit power achieves higher data packet transmission, which reduces the time used to transmit a packet. This reduces the energy consumption.

2.4.2 MAC Protocol Energy Consumption

The MAC protocol operations which include transmission and reception of control packets such as RTS, CTS, and ACK consume energy. The energy consumption from the MAC protocol can be divided into two categories. The first one is the energy consumption, E_{wait}, from listening to packets transmitted by other nodes while waiting for the backoff counter to expire. The second category is the energy consumption, E_{access}, for channel access trials. When the backoff counter expires, the source node tries to access the channel by transmitting an RTS frame to the receiving node. When there is a collision between RTS frames, the source node needs to try the channel access more than once.

2.4.2.1 Energy Consumption from Listening

When a node is in the backoff process, it listens to other nodes' channel access attempts. For other nodes' channel access, there are three possible cases, no transmission, successful transmission, and collision. Then the energy consumption from overhearing, E_{wait} is

$$\begin{aligned} E_{wait} &= ((1-p_{tr})P_{rx}\sigma + p_{tr}p_s P_{rx}T_{RTS} + p_{tr}(1-p_s)P_{rx}T_{RTS})E[X] \\ &= ((1-p_{tr})\sigma + p_{tr}T_{RTS})P_{rx}E[X] \qquad (2.19) \end{aligned}$$

where the first term represents no transmission. The second term and the third term represent the successful transmission between other nodes and the collision, repectively. Here again, the transmit power affects the energy consumption for listening. With higher transmit power, p_{tr} and $E[X]$ increase due to the increased number of contending nodes. Accordingly, higher transmit power incurs higher energy consumption from listening.

2.4.2.2 Energy Consumption from Channel Access Trials

A node transmits an RTS packet when the backoff counter expires. When there is a collision, the source node needs to retransmit an RTS frame after a new random backoff. Then the energy consumption for the channel access trials per packet transmission, E_{access} can be expressed as

$$E_{access} = \frac{p}{1-p}P_{tx}T_{RTS} + (P_{tx}+P_{rx})(T_{RTS}+T_{CTS}+T_{ACK}) \qquad (2.20)$$

where the first term is the energy consumption from unsuccessful RTS packet transmissions and the last term is the energy consumption for the final successful RTS/CTS handshake. Then the overall energy consumption from the MAC protocol operation

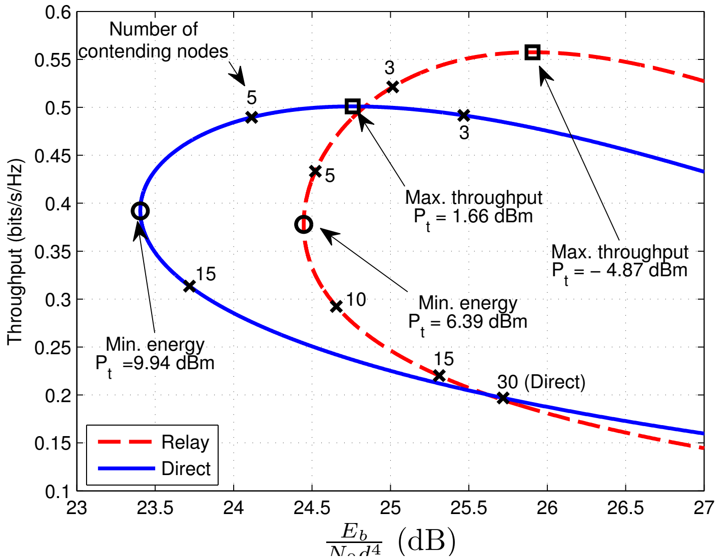

Figure 2.3: Energy-throughput relationship when the source-destination distance is 200m

combining (2.19) and (2.20) is

$$\begin{aligned} E_{MAC} &= E_{wait} + E_{access} \\ &= ((1 - p_{tr})\sigma + p_{tr} T_{RTS}) P_{rx} E[X] + \frac{p}{1-p} P_{tx} T_{RTS} \\ &+ (P_{tx} + P_{rx})(T_{RTS} + T_{CTS} + T_{ACK}). \end{aligned} \tag{2.21}$$

2.4.3 Overall Energy Consumption

The overall energy consumption, E_{total} includes the energy consumption from both the data packet transmission and control packet transmissions.

$$E_{total} = k(E_{data} + E_{MAC}) \tag{2.22}$$

where $k = 1$ for the direct transmission and $k = 2$ for a single relay transmission. Then the per bit energy consumption normalized by distance is

$$\frac{E_b}{N_0 d^4} = \frac{E_{total}}{I N_0 d^4} \tag{2.23}$$

where I is the number of information bits in the data part of a packet. We normalize the energy consumption per bit by d^4 in order to get an equaled received energy consumption.

2.5 Energy-Throughput Tradeoff

As pointed out, the transmit power plays an important role in a wireless network. Transmit power affects the number of contending nodes, capacity and energy consumption. As the transmit power increases, the rate supported by the physical layer increases. At low received power levels, the capacity increases linearly with received power. At high power levels the capacity only increases logarithmically. The transmission range increases as the transmit power increases, which results in the number of contending nodes increasing. With more contending nodes, more time and energy are consumed to access the channel. As a result, the transmit power level also determines the delay and energy consumption. Because the energy consumption and the throughput are coupled by the transmit power, a tradeoff between bandwidth efficiency and energy efficiency is obtained by varying the transmit power. In this section, we analyze the energy-throughput tradeoff using the parameters in Table 1. We assume a density of 0.00001 $nodes/m^2$. While this density may seem low, because the nodes always have packets to transmit the density of active nodes with packets to transmit of 0.00001 is quite reasonable.

Figure 2.3 shows an example of the energy-throughput tradeoff when the source-destination distance is 200m. The y-axis represents the throughput and the x-axis represents the energy consumption per bit normalized by the fourth power of the source-destination distance. The top right end of the graph represents the low transmit power range and the bottom right end of the graph represents the high transmit power range. As the transmit power increases, the corresponding points on the graph moves counterclockwise on each graph. The numbers labeled on the graph stand for the expected number of contending nodes at the marked points. We can see that as the transmit power increases the expected number of contending nodes increases. The points marked with the square represent the maximum throughput operating points for direct transmission and the relay transmission. The corresponding transmit signal power is labeled with the operating points. The points marked with the circle represents the minimum energy consumption operating points for the direct transmission and the relay transmission. We can choose an operating point on the energy-throughput tradeoff graph by adjusting transmit power. Each point on the graph identifies the throughput and the energy consumption achievable by choosing the corresponding transmit power. Accordingly, we can choose between the maximum throughput operating point and the minimum energy consumption operation point by choosing corresponding transmit power level. .

We can compare the direct transmission and the relay transmission from the figure. The direct transmission achieves better energy efficiency than the relay transmission at this distance. However, the relay transmission achieves higher bandwidth efficiency. Accordingly, direct transmission is a better choice when the system requirement is the energy efficiency at this distance. As the source-destination distance varies, the energy-bandwidth characteristic changes, which also changes the choice between direct transmission and relay transmission. The comparison between direct transmission and relay transmission for different source-destination distances will be presented in the next section.

We also consider the throughput characteristic in Figure 2.3. We first notice

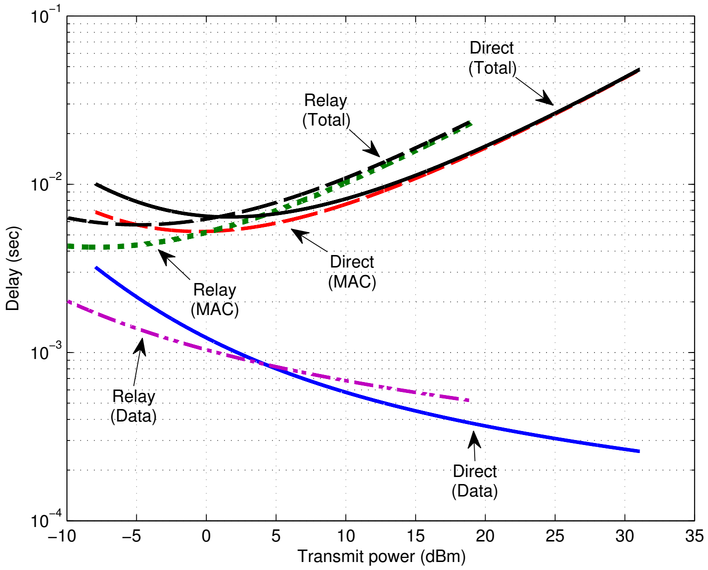

Figure 2.4: Delay components when the source-destination distance is 200m

that the throughput is low compared to the capacity at the physical layer. The maximum throughput of direct transmission in this case is about 0.5 bps/Hz when the transmitted signal strength is -1.66 dBm. When we only consider the physical layer, the channel capacity when the same transmit power is used is 2.66 bps/Hz. When we considered both the physical layer and the MAC layer, the throughput went down by less than 1/5. The low effective throughput is because of the large delay from MAC operations. Because we assume that all nodes in the area always have a packet to transmit, having many contending nodes can increase the MAC delay significantly. Control packet transmissions also increases delay potentially because the control packet transmission is transmitted at a fixed rate that is lower than the channel capacity to ensure the reliable control packet reception at neighboring nodes.

Now we investigate the energy-throughput tradeoff in more detail by considering the components of the delay and the energy consumption. Figure 2.4 shows the delay components when the source-destination distance is 200m. The delay components are separated into two categories, the delay from data packet transmission and the delay from the MAC operation. By comparing the data packet transmission delay and the MAC operation delay, we can see that the MAC operation delay dominates and becomes more profound as the transmit power increases. The data packet transmission delay decreases with higher transmission rate as the transmit power increases and the MAC operation delay increases due to the increased number of relays with an increase in transmit power. The delay from data packet transmission does not significantly affect total delay. We plot the components of delay in Figure 2.4. The total delay is slightly larger than the delay from MAC operations. The transmit power level affects the MAC operation delay in two ways. First, the transmit power level determines the number of contending nodes for the channel access, which is shown in (2.4). With more contending nodes, the collision probability, p, increases. Then the average number of backoff counts $E[X]$ increases as seen in (2.15), which results in an increase in MAC operation delay in (2.7). Second, the transmit power level determines data packet transmission rates on the network. With higher transmit power, the data packet transmission between nodes in the network, T_s in (2.12), decreases, which reduces the time consumption during the backoff process, which is represented by $E[L]$ in (2.14). At low transmit power levels, the delay from data packet transmission comparable to the MAC operations delay. Also, the effect of an increase in the transmit power at low transmit power levels is significant as seen in delay from data packet transmission in Figure 2.4. As such, higher transmit power can reduce the delay due to the MAC protocol at low transmit power levels. Figure 2.4 shows both of these effects. As the transmit power increases, the MAC protocol delay decreases initially due to the faster data packet transmissions between other nodes in the network. Also, the delay from data packet transmission from the source decreases when the transmit power is increased. However, as the delay increases at higher transmit power levels because the increased number of contending nodes dominates over the higher rate among the other nodes.

When we consider the delay from the data packet transmission, we can see that the

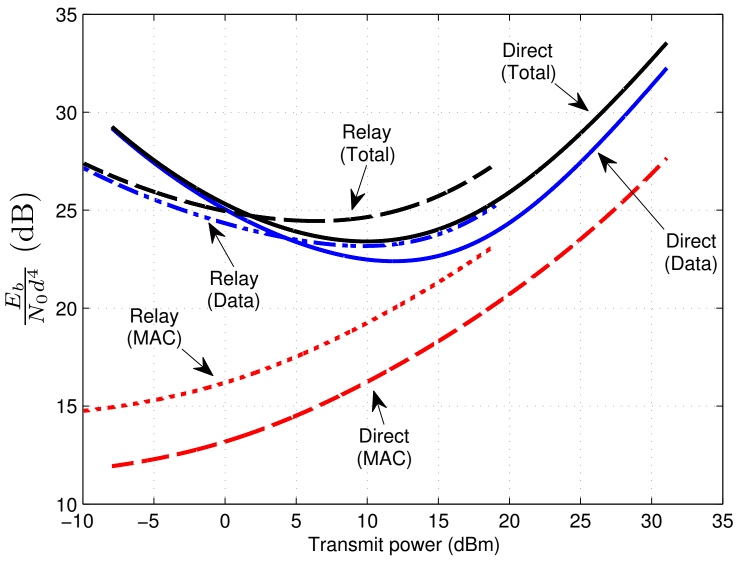

Figure 2.5: Energy components when the source-destination distance is 200m

actual data packet transmission consumes decreasing delay as the transmit power increases. This is because the data packet transmission rate increases with the transmit power. Combining (2.6) and (2.2) the data packet transmission delay is

$$D_{data} = \frac{kM}{W \cdot E\left[\log\left(1 + \frac{|h|^2 k^\alpha P_t}{N_0 W d^\alpha}\right)\right]}. \tag{2.24}$$

We can see that the data packet delay decreases monotonically in transmit power in Figure 2.4. There exists an optimal transmit power that minimizes the delay and maximizes the throughput. The optimal transmit power that achieves the minimum delay is lower for relay transmission compared to direct transmission. As such, in relay transmission lower transmit power should be used than direct transmission. When we compare the total delay, relay transmission achieves lower total delay and higher throughput than direct transmission when the source-destination distance is 200m. However, direct transmission achieves higher throughput than relay transmission when the source-destination distance is short, which will be shown in next section.

Figure 2.5 shows the energy consumption components when the source-destination distance is 200m. By comparing data packet transmission and the MAC operation, we can see that the data packet transmission dominates over the MAC operation at low transmit power levels. At low transmit power levels, the number of contending nodes is small and the channel contention is small. As such, the energy consumption for transmitting and receiving much bigger data packets consumes more energy. However, the MAC operation energy consumption gets larger than the data packet transmission energy consumption as the transmit power increases due to the increased channel contention. At high transmit power levels, the MAC operation energy consumption increases due to the increased channel contention. From (2.21) we can see that increasing the transmit power increases p_{tr}, $E[X]$, P_{tx}, and p while T_{RTS}, T_{CTS}, and T_{ACK} are constants. Accordingly, the energy consumption from MAC operations increases as the transmit power increases.

For both direct transmission and relay transmission, there is an optimal transmit power that minimizes the data packet transmission energy consumption. At higher transmit power levels, the energy consumption for data packet transmission and reception increases. Combining (2.18) and (2.2), the energy consumption for data packet delivery is

$$E_{data} = \frac{k(P_{tx} + P_{rx})M}{W \cdot E\left[\log\left(1 + \frac{|h|^2 k^\alpha P_t}{N_0 W d^\alpha}\right)\right]}. \tag{2.25}$$

The energy consumption is the multiplication of power and the time the power is used. So, the energy consumption decreases as long as the time consumed to transmit a packet decreases faster than the transmit power consumption increment. However, the capacity increases linearly at low transmit power levels and only logarithmically at high transmit power levels. Accordingly, at high transmit power levels, the power consumption increases faster than the time consumption reduction, which results in increased energy consumption for data packet transmission.

We compare the energy consumption components of the direct transmission and the relay transmission in Figure 2.5. It shows the energy consumption components versus the transmitted signal power, P_t. When we compare the energy consumption from MAC operations, we can see that relay transmission consumes more energy than direct transmission when the same transmit power is used. This is because relay transmission requires channel access twice with the same number of nodes as the case of direct transmission contending for access. When we compare the energy consumption from data packet transmission, relay transmission consumes less energy than direct transmission at low transmission power levels. However the gap between relay transmission and direct transmission decreases as the transmit power increases. At high transmit power levels, direct transmission consumes less energy in data packet transmission than relay transmission. When we compare the total energy consumption, the transmit power level that achieves the minimum energy consumption for relay transmission is lower than the transmit power level that achieves the minimum energy consumption for direct transmission. With lower transmit power, the transmission range for relay transmission is lower than the range for direct transmission, which reduces the number of contending nodes. The relay transmission requires only $\frac{1}{16}$ of transmit power to achieve the same average received SNR level compared with direct transmission when the path loss exponent is 4. In Figure 2.5, the minimum energy consumption for direct transmission is lower than the minimum energy consumption for relay transmission. However, relay transmission achieves lower minimum energy consumption than direct transmission for longer source-destination distances, which will be shown in following section.

2.6 Direct transmission vs Relay Transmission

In the previous section, we analyzed the energy consumption and the throughput when the source-destination distance is 200m. Direct transmission achieved better

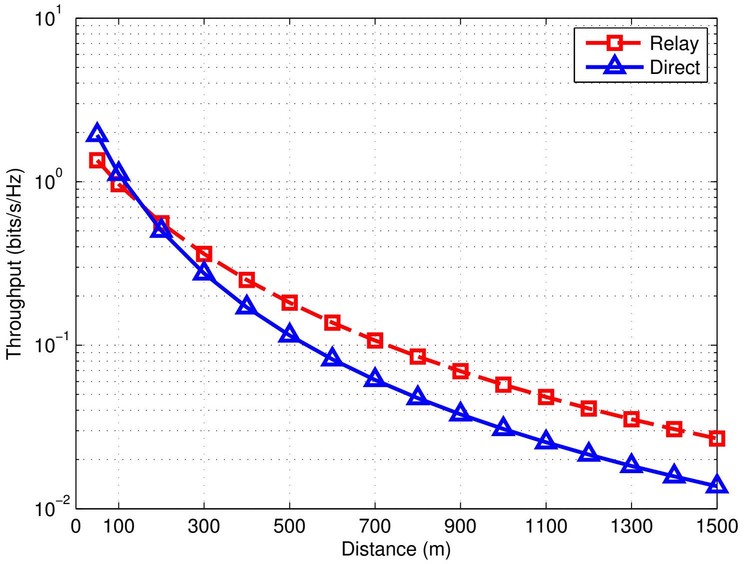

Figure 2.6: Direct transmission and relay transmission comparison - maximum throughput scheme

energy efficiency and relay transmission achieved better bandwidth efficiency. However, which scheme is a more efficient transmission scheme can vary as the source-destination distance changes. Figure 2.6 shows the maximum achievable throughput for both the direct transmission and the relay transmission as the source-destination distance varies. It is seen that the direct transmission achieves higher throughput than the relay transmission when the source-destination distance is 50m or 100m. But the relay transmission achieves higher throughput at larger source-destination distances. When the source-destination distance is short, the penalty of two transmissions and two channel contentions for the relay transmission outweighs the benefit of the shorter one hop packet transmission.

Figure 2.7 shows the achievable minimum energy consumption as the source-destination distance changes. It is seen that the direct transmission achieves better energy efficiency than the relay transmission when the source-destination distance is less than 400m. Again the penalty of the more energy consumption for two packet transmissions and the two channel contentions outweighs the benefit of less energy

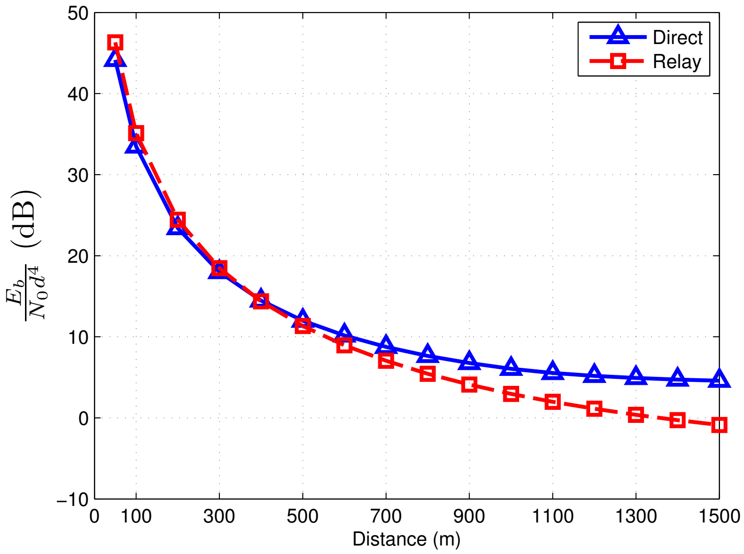

Figure 2.7: Direct transmission and relay transmission comparison - minimum energy consumption scheme

consumption from shorter one hop packet transmission for the relay transmission scheme. Between 100m and 300m, the direct transmission achieves higher energy efficiency and relay transmission achieves higher bandwidth efficiency. From Figure 2.7, the energy consumption per bit normalized by d^4 decreases as the source-destination distance increases. However the actual energy consumption increases with distance.

The node density can affect the energy efficiency and the bandwidth efficiency, which will result in change of the source-destination distance at which either direct transmission or relay transmission becomes more bandwidth efficient or energy efficient. We also investigate how the node density affects the direct transmission scheme and the relay transmission scheme. Figure 2.8 shows the threshold source-destination distance above which the relay transmission becomes more efficient than the direct transmission. The figure includes both criteria of the maximum throughput and the minimum energy consumption. For example, when the node density is 2×10^{-5} nodes/m^2, relay transmission achieves higher throughput than direct transmission if the source-destination distance is more than 160m, and less energy consumption if

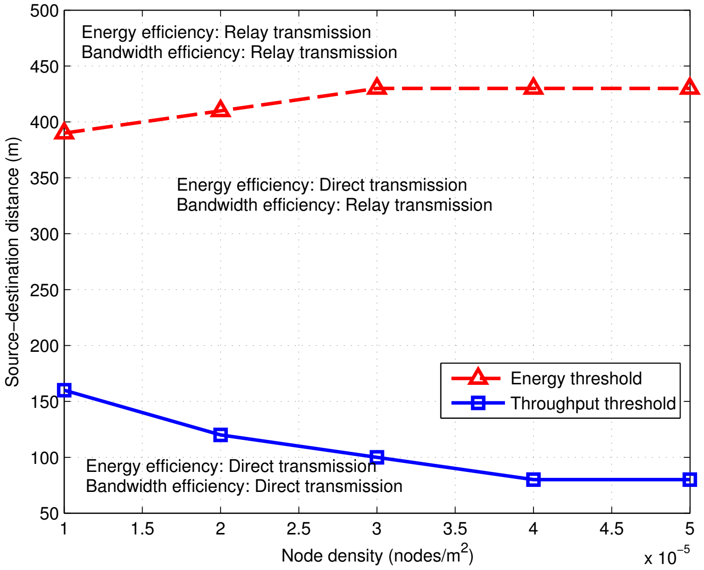

Figure 2.8: Threshold source-destination distance that the relay transmission becomes more efficient

the source-destination distance is more than 390m. Figure 2.8 shows that as the node density increases relay transmission becomes more bandwidth efficient than direct transmission at shorter distances. However, for the energy efficiency, the threshold distance that relay transmission becomes more efficient at slightly longer distances.

As the node density increases, the longer distance packet transmission is penalized in delay both at the physical layer and the MAC layer because it requires higher transmit power than the shorter distance packet transmission. With higher node density, ρ, the number of contending nodes, n, in (2.4) and the collision probability p gets larger, which leads to an increase in the average number of backoff counts in (2.15). This leads to an increase in the MAC operation delay in (2.7), which dominates the overall delay as shown in Figure 2.4. For the same reason, using a higher transmit power incurs more penalty when the node density is higher, which is seen in (2.4). As a result, relay transmission which requires shorter hop and lower transmit power achieves higher bandwidth efficiency.

The node density increase also degrades the energy efficiency. As the node density increases, the MAC operation increases, which leads to higher energy consumption from MAC operations. When the same transmit power is used, the energy consumption from data packet transmission remains the same. In Figure 2.5, it is seen that the energy consumption from data packet transmission dominates over the energy consumption from MAC operations. However, the rate of increases in the energy consumption from MAC operations is faster than the energy consumption from data packet transmission as the node density increases. As such, relay transmission is penalized more from the node density increase than direct transmission from node density increase. The transmit power that achieves the minimum energy consumption for relay transmission decreases faster than direct transmission as the node density increases. As a result, the energy consumption from data packet transmission, which only depends on the transmit power level, increases more for relay transmission case than direct transmission as node density increases. As such, the threshold distance that relay transmission becomes more energy efficient than direct transmission slightly increases as the node density increases. However, this tendency can be different when energy consumption parameters are different. With higher P_{rx} and P_{sp}, both the threshold distances for bandwidth efficiency and energy efficiency decrease as the node density increases. As such, the relay transmission scheme has advantages of shorter one hop distance and less transmit power level, which becomes more critical as the node density increases.

2.7 General system model

2.7.1 General topology

We have considered a simple relay network model in which the source, relay, and destination are placed in a straight line with equal distances. Now we generalize the

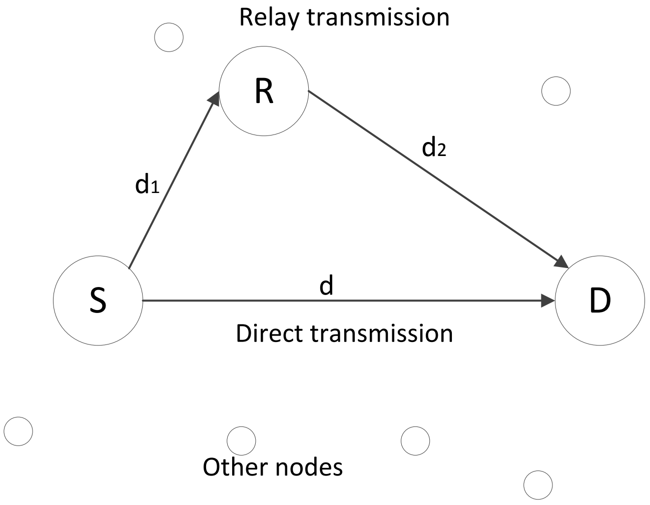

Figure 2.9: General system model

topology. The source and the relay are still separated by a distance d but the relay can be placed anywhere between the source and the destination. Figure 2.9 shows the general topology. Depending on the location of the relay node, the distance between the source and the relay, d_1, and the distance between the relay and the destination d_2 changes.

The previous analysis can be easily adapted to the new topology. We find the region where relay transmission performs better than direct transmission. Figure 2.10 shows the area where the relaying achieves higher throughput when the source-destination distance is 200m. The solid line indicates the border line of the area where the relay transmission achieves the same throughput as direct transmission. When a relay is positioned in the circular region, it achieves higher throughput than the direct transmission.

2.7.2 Randomly placed neighboring nodes

In the analysis up to now, we assumed that the number of contending nodes is fixed and determined by the transmit power level. We also assumed that the

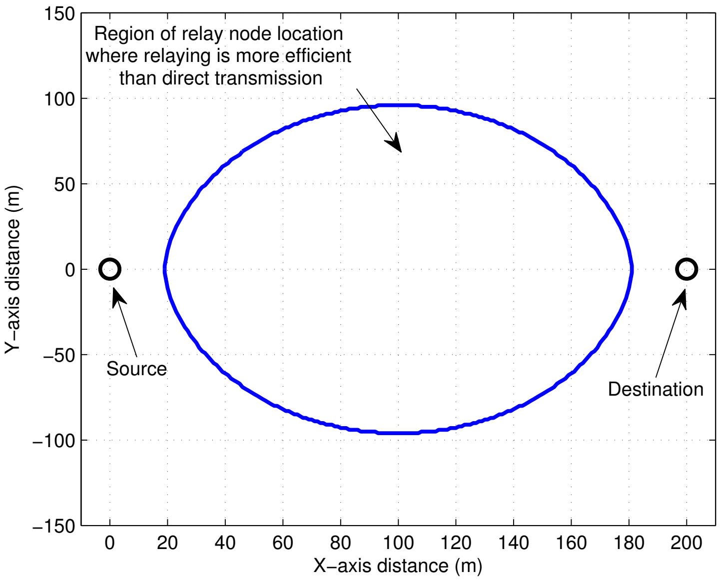

Figure 2.10: Area where the relay performs better than direct transmission

number of contending nodes is at least one. When a transmit power is given, the number of contending nodes is determined by (2.4) with the given node distribution, ρ. However, there can be variation in the number of contending nodes in reality even when the same transmit power is used. Also, there can be cases that no other node contends for the channel access. In this section, we consider how the performance changes as we account for the randomness in the number of contending nodes. We define a d_{area}^2 rectangular region, which includes transmission range of source, relay, and destination. We assume that the nodes are randomly (uniformly) placed in this region. When a neighboring node is located in the transmission range, d_{resv}, of the source node, it is contending with the source node for channel access. Let the area of the region be $A_{region} = d_{area} \times d_{area}$. The transmission range is determined by the transmit power level as in (2.3). Then the area in the transmission range is $A_{tran} = \pi d_{resv}^2$. When the node density is given as ρ, the total number of neighboring nodes in the area is $N = \rho A_{region}$. Then the probability that each node is located in the area that contends with the source node is

$$p_{cont} = \frac{A_{tran}}{A_{region}} = \frac{\pi d^2_{resv}(P_t)}{A_{region}}. \tag{2.26}$$

We can see that the probability that a neighboring node is located in the area that it should contend with the source node depends on the transmit power because the transmission range d_{resv} is dependent on the transmit power P_t. The probability that n nodes are contending with the source node for channel access is

$$P(n = k) = \binom{N}{k} p^k_{cont}(1 - p_{cont})^{N-k}. \tag{2.27}$$

Let $G(P_t, k)$ be the a performance when the transmit power is P_t and the number of contending nodes is k. The performance measure can be either delay or energy consumption. Then the average performance with a given transmit power, $G(P_t)$ which accounts for the randomness in the number of contending nodes can be obtained by

$$G(P_t) = \sum_{k=0}^{k=N} G(P_t, k)P(n = k). \tag{2.28}$$

Figure 2.11 illustrates the performance comparison between the case of fixed number of contending nodes and the case of random number of contending nodes. We assume the area is a 4km by 4km rectangular region and the source-destination distance as 200m. It is seen that the performance of the random number of contending nodes case differs from the case of fixed number of contending nodes at low transmit power levels. This is because we considered the case of no contending nodes for the performance analysis of the random number of contending nodes case. When the transmit power level is low, the probability of no contending nodes case is high. When there is no contending nodes, the delay and the energy consumption is low because the MAC operation requires only the random backoff without contention. For both

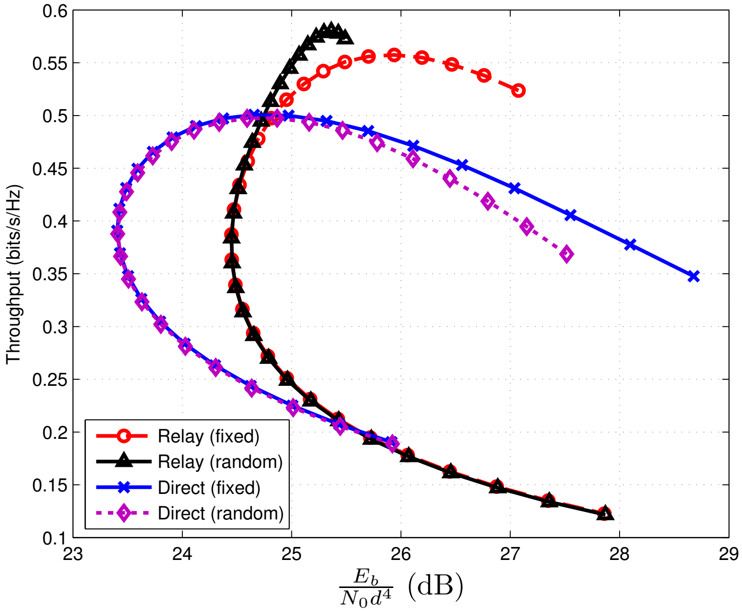

Figure 2.11: Performance comparison between the case of fixed number of contending nodes and the case of random number of contending nodes

relay transmission and direct transmission, we can see that the performance of the case of random number of contending nodes achieves higher throughput and lower energy consumption than the case of fixed number of contending nodes. It is also seen that the performance gap between the fixed and random case is larger for relay transmission. It is because relay transmission requires channel access twice, which amplifies the effect of no contending nodes case. At higher transmit power levels, the performance of fixed and random number of contending nodes cases are almost the same. At high transmit power levels, the probability of no contending nodes case is very small, which minimally affect on the performance. Also, the performance gap at low transmit power level decreases as the source-destination distance increases because a higher transmit power is used. This performance comparison justifies a simpler analysis based on the assumption that the number of contending nodes is fixed as determined by (2.4) when the transmit power level is high.

2.8 Conclusion

In this research we investigated the energy-throughput relationship for relay networks considering both the physical layer and the MAC layer. We also studied the effect of transmit power control on both the physical layer and the MAC layer. As the transmit power increases, the rate that can be supported at the physical layer increases, but delay to access the channel also increases due to an increase in the number of contending nodes. We found that we can achieve the minimum energy consumption or the maximum throughput by choosing the proper transmit power level. Transmit power levels that achieve those optimal points were neither the maximum transmit power nor the minimum transmit power. Based on the energy-throughput relationship we compared direct transmission and relay transmission. When the source-destination distance is short, the direct transmission achieves higher bandwidth efficiency and energy efficiency. However, relay transmission showed better performance in both the energy efficiency and bandwidth efficiency when the source-destination distance is long. We also investigated how the node density affects two packet transmission schemes. When the node density is low, the source-destination distance range such that direct transmission achieves better bandwidth efficiency or energy efficiency increases. As the node density increases, the relay transmission achieves better efficiency for shorter source-destination distances. We also analyzed the performance with a more general system model. We analyzed the performance in a general topology where a relay node can placed in any location. We found a region where relay transmission achieves higher efficiency for packet transmissions. We also analyzed the performance when the number of contending nodes is random. The performance was very close to the case when the number of contending nodes is fixed at the average determined by the transmit power level, which justifies a simpler analysis based on the assumption that the number of contending nodes is determined as a fixed average number.

CHAPTER III

On the Optimal Number of Hops in Relay Networks

We investigate the optimal number of relays that achieves minimum energy consumption and maximum throughput considering both the physical layer and the medium access control (MAC) layer in distributed multi-hop wireless networks with a decode-and-forward relaying scheme. Energy consumption and delay incurred by actual data packet transmission and MAC layer operations are analyzed to understand the energy-throughput relationship that takes into account both layers. Based on the analysis, it is shown that the number of relays and the transmit power can be jointly optimized when the source-destination distance is given. We consider two different optimizations, the minimum energy consumption and the maximum throughput. We also show that the optimal number of relays that achieves the minimum energy consumption or maximum throughput increases linearly with the source-destination distance.

3.1 Introduction

Using relays for packet transmissions can improve both the energy efficiency and bandwidth efficiency in wireless networks compared to the direct transmission which delivers packet directly from the source to the destination. As more relays are used for a packet transmission, one hop distance decreases, which leads to the increased received signal strength. Higher capacity is achievable at the physical layer with the higher received signal strength. However, the number of hops that a packet need to undergo increases with the number of relays. As such, it is not straightforward to understand what is the optimal number of hops to make a packet transmission most efficient. When we also consider the MAC layer, it becomes more complex. When more relays are used, lower transmit power can be used because one hop distance is shorter. When a lower transmit power is used by users in the network, channel contention decreases, which improves efficiency. At the same time, more channel access is required as more relays are used because each hop packet transmission requires channel access. Accordingly, bandwidth efficiency and energy efficiency can be improved by optimizing the transmit power and the number of relays for packet transmissions.

Significant research has been directed toward the performance of wireless networks. Bianchi [8] analyzed the performance of the distributed coordination function (DCF) used in IEEE 802.11 MAC layer. However, he only considered the performance at the MAC layer. The interaction between the physical layer and the MAC layer was not considered in his research by assuming that the physical layer supports a fixed packet transmission rate. Feeney [22] and Ebert and Wolisz [21] studied energy consumption characteristics of wireless networks. However, they only considered power and energy consumption characteristic for point-to-point communication, which does not consider the energy consumption from MAC operations. Also, they did not consider the interaction between the energy efficiency and the bandwidth efficiency. Bae and Stark in [5] and [4] investigated the energy-throughput tradeoff for wireless multi-hop networks at the physical layer. However they did not consider the MAC layer. Dawy and Leelapornchai [19] studied the optimal number of relay nodes which achieves least power consumption with a guaranteed rate. Florea and Yanikomeroglu [23] studied the optimal number of hops in relay networks, which achieves the highest rate. Sikora et. al., [52] studied the number of hops that achieves the desired end-to-end rate with the least transmission power. However, they all limited their research to infrastructure based multi-hop networks and considered only the physical layer [5, 4, 19, 23, 52].

In this paper, we analyze the energy and bandwidth performance of multi-hop relay networks. We consider both the physical layer and the MAC layer for performance analysis where the energy and bandwidth used to transmit, to receive, and to access the channel are incorporated. From the analysis we identify the tradeoff between the bandwidth efficiency and the energy efficiency. Based on the energy-throughput tradeoff, we optimize the transmit power and the number of relays to maximize throughput or minimize the energy consumption. Also, we find the optimal transmit power and the optimal number of relays when the transmit power is constrained. We show that the optimal number of relays increases linearly as the source-destination distance increases. Also, it is shown that the optimal transmit power and the optimal one hop distance is determined by the characteristic of the physical layer and the MAC layer, not by the source-destination distance.

The outline of this chapter is as follows. In Section II, we introduce the system model. In Section III, we analyze the delay of a multi-hop wireless network. In Section IV, we discuss the energy consumption analysis. In Section V we discuss the energy-throughput relationship. In Section VI, we consider the optimal number of hops for relay networks. Conclusion are given in Section VII.

3.2 System model

We consider a linear multi-hop wireless connection consisting of a source node, $k-1$ decode-and-forward (DF) relay nodes, and a destination where each hop is separated by the same distance, $\frac{d}{k}$. The source-destination distance is d. There are other nodes in the area, which have packets to transmit. They also contend for channel access to send their own packet. We assume saturated traffic, which means that all nodes always have a packet to send. We assume that all nodes use the same MAC protocol. We consider transmit power control to optimize the performance and assume that all nodes change the transmit power accordingly.

3.2.1 Physical layer model

At the physical layer, we assume the channel model is Rayleigh fading channel with distance dependant path loss. The transmitter encodes data with a code of rate R information bits per coded bit. The encoded bits are modulated and the modulated signal with power P_t is transmitted. When we use k hop transmission to deliver a packet from the source to the destination, each hop distance is $\frac{d}{k}$. The average received signal power $\bar{P}_r$ at the receiver is given by

$$\bar{P}_r = \beta(\frac{k}{d})^{\alpha} P_t \tag{3.1}$$

where α is the path loss exponent, and β is a constant that represents the antenna characteristic.

We assume that the wireless communication scheme achieves the capacity of the channel. The capacity achievable for a specific channel model depends on the average received SNR

$$\Gamma = \frac{\bar{P}_r}{N_0 W} = \frac{\beta k^{\alpha} P_t}{N_0 W d^{\alpha}} \tag{3.2}$$

where W is the channel bandwidth, and N_0 is the additive white Gaussian noise power spectral density. In case of the AWGN channel, it is clear that the capacity is expressed in the form of (3.4). For fading channels, the realization of fading should be accounted for the capacity. We assume that the channel state information (CSI) is known at the receiver only. Then the fading channel capacity is

$$C = \frac{1}{2} E\left[\log_2\left(1 + |h|^2\Gamma\right)\right] \text{ bits/dimension} \tag{3.3}$$

where h is the fading process. For different fading channels, different distributions are used for $|h|^2$. Accordingly, we can express the general capacity as a function of the transmit power, P_t, the inverse of one hop distance, $\frac{k}{d}$, the path loss exponent, α, and the noise power spectral density N_0.

$$C = f\left(\left(\frac{k}{d}\right)^{\alpha} \frac{P_t}{N_0}\right) \text{ bits/dimension.} \tag{3.4}$$

3.2.2 MAC layer model

In a wireless network the MAC protocol controls the wireless channel access. The process of channel access delays the transmission of a packet from a node. We assume that the IEEE 802.11 RTS/CTS protocol is used as the MAC protocol. We also assume that the channel access is required for each hop packet transmission when relaying is used. In RTS/CTS when a node has packets to transmit, the node monitors the channel. If the channel is busy, the node waits until it observes the channel idle for a period of time, which is called the distributed interframe space (DIFS). After an idle of time, DIFS, the node generates a random backoff counter value uniformly in the range $(0, w-1)$. Initially, the contention window size w is set as CW_{min}, which is minimum size of the contention window. The random backoff counter decreases the possibility of collision with other nodes. If the channel is idle for a slot time, σ, the backoff counter value is decreased by one. When the counter reaches zero, the node transmits a request-to-send (RTS) packet. When more than two nodes transmit RTS packets at the same time a collision occurs. If there is a collision, the value of w is doubled, and the backoff counter value is chosen again.

Parameter	Value
Payload / Header	1000 / 36 bytes
RTS / CTS / ACK	20 / 14 / 14 bytes
Slot time (σ) / DIFS / SIFS	20 / 50 / 10 μsec
CW_{min} / CW_{max}	32 / 1024 slots
Bandwidth	20 MHz
Distance(source-destination)	3000m
P_{rx}	10mW
Number of contending nodes	3 nodes
Path loss exponent (α)	4
Antenna Characteristic (β)	1

Table 3.1: Analysis parameters

Contention window size increases up to the maximum contention window size as collisions continues. The maximum contention window size is $CW_{max} = 2^m CW_{min}$. When a node gains a channel access successfully, the contention window size returns to the minimum size. When a node senses other on-going transmissions while the backoff counter is counting down, the backoff counter is frozen and reactivated when the channel is sensed idle for DIFS.

When the receiving node correctly detects an RTS packet, it responds with a clear-to-send (CTS) packet after a short time period, which is called the short inter-frame space (SIFS). The transmitting node can transmit its data packet only if a CTS packet is received. The time duration of data packet transmission is included in the RTS and CTS packets, which are also heard by other nodes in the neighborhood. The neighboring nodes update a network allocation vector (NAV) with the information, and defer transmission according to the NAV, by which they can avoid collisions.

We assume that there exists a fixed number of contending nodes for every channel access. We also assume that each node knows the one hop distance for the packet transmission originating from itself. [1] We use a saturated traffic model in which all nodes in the network always have packets to send.

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[1] We investigate the best possible maximum throughput and minimum energy consumption by assuming this. If it is not known, the performance would degrade than when it is known.

3.2.3 Energy consumption model

For the energy consumption analysis, we define power consumption model in this section. Energy consumption is the multiplication of power consumption with the duration of the power consumption. We account for the energy consumption both from transmitting and receiving packets. We define P_{tx} as the power consumed during a packet transmission. When the transmitted signal power is P_t, the transmit power consumption is

$$P_{tx} = \frac{1}{\eta} P_t \tag{3.5}$$

where η is the power efficiency of the transmitter. As the transmitted signal power increases, the power consumption increases accordingly. We assume that a fixed power P_{rx} is consumed at the receiver during a packet transmission.

3.3 Delay analysis

3.3.1 Data packet transmission delay

When the rate supported by the physical layer is given by R bits/second, the delay from one hop data packet transmission is simply the time consumed for the transmission. With the packet size M bits, the physical layer delay for one hop packet transmission is

$$D_{data} = \frac{M}{R}. \tag{3.6}$$

We assume that the physical layer achieves the capacity for data packet transmissions between the source and the destination. As such, the rate, R, is dependent on the transmitted signal power P_t. For a fixed source-destination distance, as the number of hops increases the distance between relays decreases. A decreased distance between relays increases the signal-to-noise at each hop. At low signal-to-noise ratios the achievable rate increases quickly with a higher signal-to-noise ratio while at high signal-to-noise ratios the achievable rate only increases slowly with an increase in signal-to-noise ratio [23]. At the same time, the number of hops that a data packet should undergo increases as the number of relays increases. As such, increasing the number of relays can increase the overall delay. Thus the number of relays should be optimized to maximize bandwidth efficiency and energy efficiency.

3.3.2 MAC layer operations delay

MAC layer operations consumes time and energy for coordinating the channel access between nodes by control packet exchange. In this section, we analyze the delay from the MAC layer operations. We modify Bianchi's [8], and Boucouvalas' [12] framework. They analyzed delays from MAC operations for one hop packet transmission assuming a fixed rate is supported at the physical layer for both control packet transmissions and data packet transmissions. Our contribution is to account for the effect of the transmit power control and the number of relays on the delay from MAC operations. As the transmit power increases, the control packets can be transmitted with higher rate. We assume that both data packets and control packets are transmitted at the rate of the channel capacity. As such, the delay from the MAC layer decreases as the transmit power increases. We optimize both transmit power and the number of relays between the source and the destination. The number of relays also affects the delay performance. When more relays are used for packet transmissions between the source and the destination, the one hop distance between nodes decreases, which increases the received signal strength with the same transmit power and capacity of the channel as in (3.1) and (3.3). At the same time, adopting more relays can increase MAC delay. Each packet transmission requires channel access and the increasing number of relays increases number of channel access and corresponding delay until a packet reaches the destination. In summary, we need to account for the transmit power and the number of relays for the analysis of the MAC layer delay performance. Based on the analysis, we optimize the transmit power and the number of relays.

Let X be the number of backoff counts consumed for the source node to gain the channel access. Let L be the length of time for a decrease of the backoff count. Define T_c as the time consumption from collision between RTS packets and p as the collision probability when a node transmits a packet. We define T_{RTS}, T_{CTS}, and T_{ACK} to be the time used to transmit RTS, CTS, and ACK packets. Then the average delay from the MAC layer for one hop transmission can be expressed as

$$D_{MAC} = E[X] \cdot E[L] + T_{RTS} + T_{CTS} + T_{ACK} \tag{3.7}$$

where $E[X]$ is the average number of backoff counts consumed for the source node to gain a channel access and make a successful transmission, and $E[L]$ is the average length of time for a decrease of the backoff count. The last three terms are the time used to transmit RTS, CTS, and ACK packets for the last successful RTS/CTS handshake. In the remainder of this section, we analyze $E[X]$ and $E[L]$.

Let p be the collision probability for a node for each trial to access the channel when there are n contending nodes in the network, and τ be the transmit probability which is the probability of each node transmitting at a randomly chosen time. By Markov chain analysis [8], the collision probability, and the transmit probability can be expressed as

$$p = 1 - (1 - \tau)^n \tag{3.8}$$

$$\tau = \frac{2(1 - 2p)}{(1 - 2p)(CW_{min} + 1) + CW_{min}(1 - (2p)^m)p}. \tag{3.9}$$

where m is the exponent that determines the maximum contention window size by $CW_{max} = 2^m CW_{min}$. The nonlinear system of equations (3.8), (3.9) in the two unknowns can be solved by numerical techniques.

Let p_{tr} be the probability that there is at least one transmission at a randomly chosen time, and p_s be the probability that a transmission occurring in the channel is successful given that there is at least one transmission in the channel. A successful transmission happens when only one node transmits over the channel. Then p_{tr} and p_s are expressed as

$$p_{tr} = 1 - (1 - \tau)^n \tag{3.10}$$

$$p_s = \frac{n\tau(1-\tau)^{n-1}}{p_{tr}} = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n}. \tag{3.11}$$

We can see that these probabilities depend on the number of contending nodes. As the number of contending node increases, p_{tr} increases and p_s decreases. With the probabilities defined above the average time for the backoff counter to decrease by one, $E[L]$, can be analyzed. During the backoff process, the source node can not transmit a packet. It listens to the channel to decrease or freeze the backoff counter. As such, the average time for the backoff counter decrease by one is governed by packet transmission activities between other nodes in the network. There are three cases for a decrease of the backoff count. The first case is that there is no transmission in the network. Then after the time duration σ, the backoff counter is decreased by one. The probability of the first case is (1-p_{tr}).

The second case is successful transmission where only one of other nodes transmits in the network. During the other node's transmission, the source node freezes its backoff counter, and reactivates when the transmission is finished and the channel is idle for DIFS duration. We define the time to transmit the header and data part of a packet as T_H and T_D. The propagation delay, and the time durations of DIFS and SIFS are represented by δ, T_{DIFS}, and T_{SIFS} respectively. The time duration for each packet transmission can be calculated by dividing the respective frame size by the rate supported for the corresponding type of packet transmissions. For the successful packet transmission case, RTS, CTS, Data, and ACK packets are exchanged with a SIFS duration between packet transmissions. When the packet transmission between other nodes is finished, the source node listens to the channel and restarts the backoff counter if the channel is idle for a DIFS duration. Once the backoff counter is reactivated, the backoff counter decreases by one after a slot time, σ. Then the time consumed to decrease the backoff counter by one in the second case is

$$T_s = T_{RTS}+\delta+T_{SIFS}+T_{CTS}+\delta+T_{SIFS}+T_H+T_D+\delta+T_{SIFS}+T_{ACK}+\delta+T_{DIFS}. \tag{3.12}$$

The control frames, RTS, CTS, and ACK are short, nevertheless we assume for simplicity that these packets also achieve the capacity of the channel. The effect of this assumption on the throughput and energy consumption is slight. The probability that the second case happens is $p_{tr}p_s$.

The third case is that several other nodes transmit RTS packets simultaneously, which causes a collision. The transmitting node sends an RTS packet, which takes time duration of $T_{RTS}+\delta$ including propagation delay, but no CTS packet is sent back by the receiving node because it cannot decode the RTS packet due to the collision. The transmitting node waits for DIFS duration which is longer than SIFS duration and decides there was a collision. Once they recognize the occurrence of a collision, they restart the backoff counter with an increased contention window size. In this case, the destination senses activities in channel by the signal strength it receives, but can not decode the control packet due to the collision. As such, the source node reactivates the backoff counter after a DIFS duration. Then the time passed to decrease the backoff counter of the source node by one in third case is

$$T_c = T_{RTS} + \delta + T_{DIFS}. \tag{3.13}$$

The probability that the third case happens is $p_{tr}(1 - p_s)$. Then the average time of the backoff counter to decrease by one, $E[L]$ is given by

$$E[L] = (1 - p_{tr})\sigma + p_{tr}p_sT_s + p_{tr}(1 - p_s)T_c \tag{3.14}$$

Previous work on MAC layer performance [8], [12] assumed that a fixed rate is supported by the physical layer. However, we assume that packet transmissions achieve the channel capacity. Then the transmission rate changes with the transmit power level and number of relays. The varied rate at the physical layer affects the MAC layer delay through the time factors such as T_{RTS}, T_{CTS}, T_H, T_D, and T_{ACK}. The average number of backoff counts for one successful transmission, $E[X]$ is given by

$$E[X] = \sum_{i=0}^{m-1}(p^i\frac{W_i + 1}{2}) + \frac{p^m}{1-p}\frac{CW_{max} + 1}{2} \tag{3.15}$$

where W_i is the size of backoff window after ith collision, and CW_{max} is the maximum size of contention window. We can see that the collision probability, p is included in (3.15), which accounts for the backoff counts when an RTS packet transmitted from the source collides with an RTS packet from other nodes.

3.3.3 Overall delay and throughput analysis

Delays from both layers should be considered when we evaluate the throughput. The total delay D_{total} is defined by

$$D_{total} = k(D_{Data} + D_{MAC}) \tag{3.16}$$

where k is the number of hops between the source and the destination. When the number of relays increases, delay components, D_{Data} and D_{MAC} decreases, but the overall delay D_{total} can increase with more hops, k. Then, we define throughput S_T

by

$$S_T = \frac{I}{D_{total}} \tag{3.17}$$

where I is the size of a data in a packet, which is different from the size of a packet, M, that also includes headers.

3.4 Energy consumption analysis

3.4.1 Energy consumption from data packet transmission

In this section, we analyze the energy consumption from data packet transmission and reception at the physical layer. Let P_t be the transmitted signal power, P_{tx} be the transmit power consumption, and P_{rx} be the power consumption when a node is receiving a packet. Then, the energy consumption for one hop packet transmission at the physical layer, E_{Data} is

$$E_{Data} = (P_{tx} + P_{rx})D_{Data} = (\frac{1}{\eta}P_t + P_{rx})D_{Data}. \tag{3.18}$$

where D_{Data} is the duration of data packet transmission.

3.4.2 MAC layer energy consumption

In this section, we analyze the energy consumption for MAC operations. The source node needs to listen to the channel to check whether the channel is busy, which consumes energy. Transmitting and receiving control packets such as RTS, CTS, and ACK also consume energy. We account for all those energy consumptions for MAC operations. The energy consumption at the MAC layer, E_{MAC} can be divided into two categories. The first category is the energy consumption while waiting for the backoff counter expiration, E_{wait}. While the backoff counter decreases, the node listens to the idle channel or RTS frames transmitted from other nodes, which consumes energy.

The second category is the energy consumed for channel access trials, E_{access}. When the backoff counter expires, the source node tries to access channel by transmitting an RTS packet to the destination node. When there are collisions between RTS packets, a node needs to try more than once until it obtains channel access.

3.4.2.1 Energy consumption of MAC backoff process

To calculate the average energy consumption while waiting for the backoff counter expiration, a method similar to the method used to analyze the MAC layer delay is used. The energy consumed waiting for access E_{wait} is

$$E_{wait} = (p_{tr} p_s T_{RTS} + p_{tr}(1 - p_s) T_{RTS})\, P_{rx} E[X]. \tag{3.19}$$

where the first term corresponds to the successful packet transmission and the second term corresponds to the collision. Accordingly, $(p_{tr} p_s T_{RTS} + p_{tr}(1 - p_s) T_{RTS}) P_{rx}$ represents the energy consumption per unit backoff counter decrease. The source node undergoes $E[X]$ slot times until it gains the channel access on average.

3.4.2.2 Energy consumption for channel access trials

A node transmits an RTS packet when the backoff counter expires. When there is a collision, the source node needs to retransmit an RTS frame after a new random backoff. Then, the energy consumption for channel access trials per packet transmission, E_{access}, can be expressed as:

$$E_{access} = \frac{p}{1-p} P_{tx} T_{RTS} + (P_{tx} + P_{rx})(T_{RTS} + T_{CTS} + T_{ACK}) \tag{3.20}$$

where the first term accounts for the RTS packet transmissions until a successful channel access. The last term represents the energy consumptions for a final successful RTS/CTS handshake. Then, the overall energy consumption in the MAC layer per

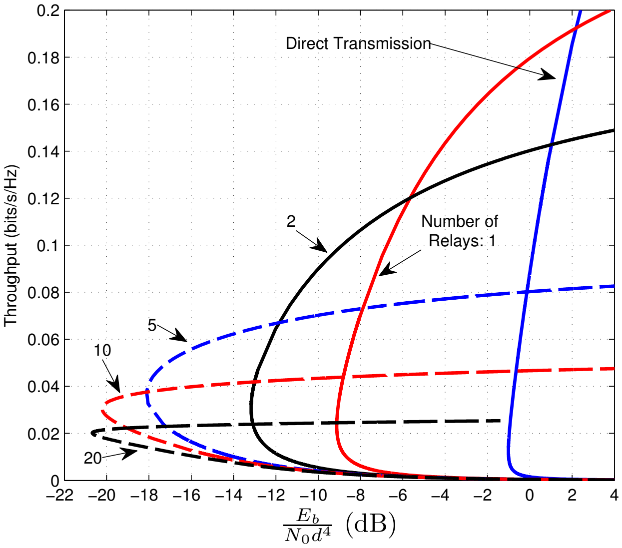

Figure 3.1: Energy-throughput relationship for source-destination distance 3km

one hop transmission is the sum of two energy consumptions in the MAC layer.

$$E_{MAC} = E_{wait} + E_{access}. \tag{3.21}$$

3.4.2.3 Overall energy consumption

When $k-1$ relays are used, a packet undergoes k hop packet transmissions until it reaches the destination. Then the overall energy consumption per packet transmission is

$$E_{total} = k\left(E_{Data} + E_{MAC}\right). \tag{3.22}$$

3.5 Energy-throughput relationship

We analyze the delay and energy consumption of multihop wireless network. When the number of relays used between the source and the destination is given, the delay and the energy consumption are coupled by the transmit power, which enables us to analyze the energy-throughput tradeoffs. Figure 3.1 shows the energy-throughput relationship of a relay network using parameter values in Table 1. The x-axis represents the energy per info bit normalized by the distance and noise power, $\frac{E_b}{N_0 d^\alpha}$, where E_b is the energy per bit, N_0 is noise power, and $d = 3000m$ is the distance between the source and destination. The energy per bit is defined by

$$E_b = \frac{E_{total}}{I} \tag{3.23}$$

where I is number of data bits in the packet. Also, we normalize by the distance to the power of $\alpha = 4$, to obtain the normalized average received energy per bit.

For each energy-throughput curve, the lower part of the graph corresponds to low transmit power, and the upper part of the graph corresponds to high transmit power. As the transmit power increases, the corresponding point on the graph moves clockwise. As seen in Figure 3.1 there is a reasonably good operating point where the energy per bit is minimized for the curves with a large number of relays. At this point the throughput is not maximized but increases in throughput are at the expense of a large increase in the energy per bit. We define this good operating point as the practical operating point. When few relays are used or for direct transmission, the energy-throughput curves show that the throughput can be increased without large increase of energy consumption. However, due to the large distances, the upper part of those two cases require very high transmit power that might exceed the limitation imposed by IEEE 802.11 regulation. Accordingly, in the reasonable transmit power range, we define the practical operating point as the point with minimum energy consumption. Merging (3.6), (3.18), (3.19), (3.20), and (3.22), the overall energy consumption is expressed as

$$\begin{aligned} E_{total} = \frac{k}{R}\Bigg[\bigg(RTS\frac{1}{1-p} + CTS + ACK + M\bigg)P_t \\ + \big(RTS(1 + E[X]p_{tr}) + CTS + ACK + M\big)P_{rx}\Bigg] \end{aligned} \quad (3.24)$$

which can be simplified as

$$E_{total} = \frac{k}{R}[C_1 P_t + C_2] \quad (3.25)$$

where $C_1 = \frac{RTS}{1-p} + CTS + ACK + M$ and $C_2 = [RTS(1 + E[X]p_{tr}) + CTS + ACK + M]P_{rx}$. Both C_1 and C_2 positive numbers which are independent on the transmitted signal power, P_t. We concentrate our analysis on source-destination distance, number of hops, and transmit power. Then we can use the representation in (3.4) for the rate supported at the physical layer. Then overall energy consumption can be simplified as

$$E_{total} = \frac{k(C_1 P_t + C_2)}{f\left(\left(\frac{k}{d}\right)^{\alpha} \frac{P_t}{N_0}\right)}. \quad (3.26)$$

3.6 Optimization

3.6.1 Optimization for Minimum Energy Consumption

As the first optimization, we consider the optimization for minimum energy consumption. As we can see in Figure 3.1, there exists an optimal transmit power that minimizes the energy consumption for each number of relays. We want to optimize both the transmit power and the number of relays to minimize the energy consumption.

The overall energy consumption is given in (3.26). As the first step, we check the convexity condition of energy consumption on the number of hops, k, by checking when the second derivative is positive.

$$\frac{\partial^2 E_{total}}{\partial k^2} = \frac{\partial^2}{\partial k^2}\left(\frac{k\left(C_1 P_t + C_2\right)}{f\left(\left(\frac{k}{d}\right)^{\alpha}\frac{P_t}{N_0}\right)}\right) > 0 \tag{3.27}$$

After some algebraic manupulations, the convexity condition can be simplified to

$$f(X) < \frac{2\alpha X f'(X)}{2 + (\alpha - 1)f'(X) + \alpha X f''(X)} \tag{3.28}$$

where $X = (\frac{k}{d})^{\alpha}\frac{P_t}{N_0}$, $f' = \frac{\partial f(X)}{\partial k}$, and $f'' = \frac{\partial^2 f(X)}{\partial k^2}$.

Given the convexity of the energy consumption in the number of hops, k, we can find the optimal number of hops that achieves the minimum energy consumption for a given transmit power.

$$\frac{\partial E_{total}}{\partial k} = \frac{(C_1 P_t + C_2) f\left(\left(\frac{k}{d}\right)^{\alpha}\frac{P_t}{N_0}\right) - k(C_1 P_t + C_2) f'\left(\left(\frac{k}{d}\right)^{\alpha}\frac{P_t}{N_0}\right)\left(\frac{P_t}{d^{\alpha}}\alpha k^{\alpha-1}\right)}{f^2\left(\left(\frac{k}{d}\right)^{\alpha}\frac{P_t}{N_0}\right)} = 0. \tag{3.29}$$

The optimality condition can be simplified as

$$f(X) = \alpha X f'(X). \tag{3.30}$$

By solving the equation numerically, we can find out the optimal X^*. Because $X = \left(\frac{k}{d}\right)^{\alpha}\frac{P_t}{N_0}$, we can get the optimal number of hops k^* as

$$k^* = d\left(\frac{N_0 X^*}{P_t \alpha}\right)^{\frac{1}{\alpha}}. \tag{3.31}$$

We can see that the optimal number of hops k increases linearly as the source-destination distance d increases.

As an example, we consider a communication system operating at a high SNR in a fading channel. At high SNR, the capacity in (3.4) can be approximated as (using

$\log(1 + x) \approx \log(x)$ for large x)

$$S = WE\left[\log_2(1 + |h|^2\Gamma)\right] \simeq WE\left[\log_2(|h|^2\Gamma)\right] = W\left(\log_2(\Gamma) + E[\log_2(|h|^2)]\right). \tag{3.32}$$

For example,

$$\frac{\partial^2 E_{total}}{\partial k^2} = \frac{(C_1 P_t + C_2)(\frac{\alpha}{\ln 2})\frac{1}{k}}{(\log(P_t(\frac{k}{d})^\alpha) + C_3)^2}\left[\frac{2\frac{\alpha}{\ln 2}}{\log P_t(\frac{k}{d})^\alpha + C_3} - 1\right] \tag{3.33}$$

The total energy consumption is a convex function on the number of hops, k, when (3.33) is positive. The condition is satisfied when

$$\frac{2\alpha}{\ln 2}\frac{1}{R} > 1 \tag{3.34}$$

Based on the analysis parameter in Table 1, the condition is satisfied when

$$R < \frac{2\alpha}{\ln 2} = \frac{8}{\ln 2} = 11.5416\ bits/sec/Hz \tag{3.35}$$

which is satisfied in normal operating ranges. When the one hop distance is 150m, more than 200mW transmit power is required to support more than 11.5 bits/sec/Hz, which can be obtained by (3.3). A typical IEEE 802.11 system transmits less than 15dBm (100mW), which will satisfy the convexity of the overall delay over the number of hops. Accordingly, we can say that the total energy consumption E_{total} is convex in the number of hops, k.

Given the convexity in the number of hops, we can find the optimal number of hops that achieves the minimum energy consumption for a given transmit power.

$$\frac{\partial E_{total}}{\partial k} = \frac{C_1 P_t + C_2}{\log(P_t(\frac{k}{d})^\alpha) + C_3} - \frac{(C_1 P_t + C_2)\frac{\alpha}{\ln 2}}{(\log(P_t(\frac{k}{d})^\alpha) + C_3)^2} = 0 \tag{3.36}$$

which is simplified as

$$\log(P_t(\frac{k}{d})^{\alpha}) + C_3 = \frac{\alpha}{\ln 2}. \tag{3.37}$$

We can find the optimal number of hops from the equation.

$$k = d\left[\frac{2^{\left(\frac{\alpha}{\ln 2} - C_3\right)}}{P_t}\right]^{1/\alpha}. \tag{3.38}$$

Then we can apply the result on k to the total energy, E_{total}. By pluggin in $k = d\left[\frac{A}{P_t}\right]$ where $A = 2^{(\frac{\alpha}{\ln 2} - C_3)}$.

$$E_{total} = \frac{d[\frac{A}{P_t}]^{1/\alpha}(C_1 P_t + C_2)}{\frac{\alpha}{\ln 2}}. \tag{3.39}$$

We also optimize the transmit power to achieve minimum energy consumption. We check the convexity of the overall energy consumption according to the transmit power P_t. We use the energy consumption with the optimized number of hops in (3.39). Then the energy consumption convexity in the transmit power can be checked by

$$\begin{aligned} \frac{\partial^2 E_{total}}{\partial P_t^2} &= \frac{(\ln 2) d A^{1/\alpha}}{\alpha}\left[C_1\left(\frac{1}{\alpha} - 1\right)\left(\frac{1}{\alpha}\right)P_t^{(-1-\frac{1}{\alpha})} + C_2\left(\frac{1}{\alpha}\right)\left(1 + \frac{1}{\alpha}\right)P_t^{(-2-\frac{1}{\alpha})}\right] \\ &> 0 \end{aligned} \tag{3.40}$$

The convexity condition can be simplified as

$$C_2(1 + \frac{1}{\alpha}) > C_1(1 - \frac{1}{\alpha})P_t. \tag{3.41}$$

The overall energy consumption E_{total} is convex if

$$P_t < \frac{C_2(1 + \frac{1}{\alpha})}{C_1(1 - \frac{1}{\alpha})} = 0.0183W = -17.4dBW \tag{3.42}$$

The convexity condition for the energy consumption to the transmit power seems to be too strict. The transmit power should be smaller than -17.4dBW, which is far smaller than the maximum transmit power level of IEEE 802.11 system. However, it is shown in our numerical analysis that the optimal transmit power that minimizes the energy consumption is much smaller than the convexity requirement. For the mathematical analysis, we assume that the optimal transmit power is convex and analyze the optimal transmit power that minimizes the energy consumption. When the optimal transmit power lies in the power level that maintains the convexity of the energy consumption function, the assumption can be justified.

Given the total energy consumption is convex in the the transmit power, we can find the optimal transmit power that minimizes the energy consumption.

$$\frac{\partial E_{total}}{\partial P_t} = d\frac{A^{\frac{1}{\alpha}}\ln 2}{\alpha}\left[P_t^{\frac{1}{\alpha}}C_1 - \frac{1}{\alpha}P_t^{(-1-\frac{1}{\alpha})}(C_1P_t + C_2)\right] = 0 \tag{3.43}$$

Then the energy consumption is minimized if

$$\frac{1}{\alpha}P_t^{-1}(C_1P_t + C_2) = C_1 \tag{3.44}$$

With parameters in Table 1, the optimal transmit power is

$$\hat{P}_t = \frac{C_2}{C_1(\alpha - 1)} = 0.0037W = -24.4dBW \tag{3.45}$$

We can see that the optimal transmit power is in the range that the overall energy consumption is convex to transmit power, P_t. Now we substitute in the optimal transmit power to (3.38) to find the optimal number of hops that minimizes the energy consumption.

Then the optimal number of hops is

$$k = d\left[\frac{2^{(\frac{\alpha}{\ln 2} - C_3)}(C_1(\alpha - 1))}{C_2}\right]^{1/\alpha} \tag{3.46}$$

and the optimal one hop distance is

$$\frac{d}{k} = \left[\frac{C_2}{2^{(\frac{\alpha}{\ln 2} - C_3)} (C_1(\alpha - 1))} \right]^{1/\alpha}. \tag{3.47}$$

We find two important results from this analysis. First, the optimal number of hops increases linearly with the source-destination distance. Accordingly, the optimal one hop distance is fixed regardless of the source-destination distance. Second, the optimal transmit power is fixed regardless of the source-destination distance. The optimal number of hops and the optimal transmit power is determined by the MAC protocol characteristic and the channel characteristic. The coefficients C_1, C_2 are determined by the MAC protocol (RTS/CTS) parameters and α is the path loss exponent of the channel.

The energy consumption characteristic with the optimal transmit power and the optimal number of hops can be found by substituting (3.45) into (3.39). Then the energy consumption is

$$E_{total} = \frac{d \left[\frac{AC_1(\alpha-1)}{C_2} \right]^{1/\alpha} \left(\frac{C_2}{\alpha-1} + C_2 \right)}{\frac{\alpha}{\ln 2}}. \tag{3.48}$$

In the energy consumption, we also find an interesting trend. When the number of hops and the transmit power are optimized to minimize the energy consumption, the energy consumption increases linearly with the source-destination distance. As the source-destination distance increases, the total energy consumption to deliver packet from the source to the destination increases linearly.

Next we investigate the delay characteristic of a relay network when the transmit power and the number of hops are optimized to minimize the energy consumption.

The overall delay which was analyzed in previous section can be simplified as

$$D_{total} = k \left(C_4 + \frac{C_5}{R} + C_6 \left(\frac{d}{k} \right) \right) \tag{3.49}$$

where $C_4 = E[X][(1 - p_{tr})\sigma + 3p_{tr}p_sT_{SIFS} + p_{tr}T_{DIFS}]$, $C_5 = M + RTS + CTS + ACK + E[X](p_{tr}RTS + p_{tr}p_s(CTS + M + ACK))$, and $C_6 = E[X](\frac{4p_{tr}p_s+p_{tr}(1-p_s)}{3\cdot 10^8})$. All coefficients, C_4, C_5, and C_6 are determined by the MAC protocol characteristics.

With the optimal transmit power, $\hat{P}_t$ in (3.45) and the optimal number of hops, k in (3.38), the overall delay is

$$D_{total} = d \left(\left[\frac{2^{(\frac{\alpha}{\ln 2} - C_3)} C_1(\alpha - 1)}{C_2} \right] \left(C_4 + \frac{C_5 \ln 2}{\alpha} \right) + C_6 \right) \tag{3.50}$$

When multi-hop relay networks operated with the optimal number of hops and the optimal transmit power that minimizes the energy consumption, the overall delay increases linearly with the source-destination distance. As the asymptotic case, we consider the case when the source-destination distance is infinity. When the source-destination distance d is infinity, both the energy consumption and the overall delay become infinity. All other coefficients except for the source-destination distance are fixed. As a result, the throughput becomes zero as the source-destination distance goes to infinity. The throughput is

$$S_T = \frac{I}{D_{total}} = \frac{I/d}{\left(\left[\frac{2^{(\frac{\alpha}{\ln 2} - C_3)} C_1(\alpha - 1)}{C_2} \right] \left(C_4 + \frac{C_5 \ln 2}{\alpha} \right) + C_6 \right)} \tag{3.51}$$

which shows that the throughput is inversely linear with the source-destination distance.

3.6.2 Optimization for Minimum Energy Consumption with Transmit Power Constraint

In the previous section, we considered minimum energy consuming configuration without transmit power constraints. However, in many wireless systems, transmit power is constrained. We want to minimize the energy consumption with the transmit power constraints, which can be formulated as

$$\begin{aligned} &\min_{k,P_t} E_{total} \\ &\text{subject to } P_t - P_{max} \leq 0 \end{aligned} \tag{3.52}$$

From previous section, we have shown that the energy consumption is minimized in terms of the number of hops by

$$E_{total} = \frac{(\ln 2) d A^{1/\alpha}}{\alpha} [C_1 P_t^{(1-1/\alpha)} + C_2 P_t^{(-1/\alpha)}]. \tag{3.53}$$

Then the minimization problem becomes

$$\begin{aligned} &\min_{P_t} E_{total} \\ &\text{subject to } P_t - P_{max} \leq 0. \end{aligned} \tag{3.54}$$

Then the Lagrangian equation is

$$L(P_t, \lambda) = \frac{(\ln 2) d A^{1/\alpha}}{\alpha} [C_1 P_t^{(1-1/\alpha)} + C_2 P_t^{(-1/\alpha)}] + \lambda (P_t - P_{max}). \tag{3.55}$$

The Kuhn-Tucker condition for the optimality of transmit power is

$$\frac{\partial L(P_t, \lambda)}{\partial P_t} = 0 \text{ (Optimality condition)} \tag{3.56}$$

$$P_t - P_{max} \leq 0 \text{ (Feasibility)} \tag{3.57}$$

$$\lambda(P_t - P_{max}) = 0 \text{ (Complementary slackness condition)} \tag{3.58}$$

$$\lambda \geq 0 \text{ (Non-negativity)} \tag{3.59}$$

From the complementary slackness condition, we can see that either $\lambda = 0$ or $P_t = P_{max}$. When we take derivative with respect to P_t, then by the optimality condition,

$$\frac{\partial L(P_t, \lambda)}{\partial P_t} = \frac{(\ln 2) d A^{(1/\alpha)}}{\alpha} \left[C_1 (1 - \frac{1}{\alpha}) P_t^{-1/\alpha} + C_2 (-\frac{1}{\alpha}) P_t^{(-1-1/\alpha)} \right] + \lambda = 0 \tag{3.60}$$

When we consider the case of $\lambda = 0$, optimality is achieved if

$$C_1 (1 - \frac{1}{\alpha}) P_t^{-1/\alpha} + C_2 (-\frac{1}{\alpha}) P_t^{(-1-1/\alpha)} = 0. \tag{3.61}$$

Then the optimal transmit power that minimizes the energy consumption is

$$\hat{P}_t = \frac{C_2}{C_1(\alpha - 1)}. \tag{3.62}$$

But the solution should satisfy the feasibility condition, which is the maximum transmit power allowed in nodes.

$$\hat{P}_t = \frac{C_2}{C_1(\alpha - 1)} \leq P_{max} \tag{3.63}$$

In case the obtained transmit power does not satisfy the feasibility condition, $\frac{C_2}{C_1(\alpha-1)} \geq P_{max}$, there is no solution compatible with $\lambda = 0$. In that case, we should consider other case, $P_t = P_{max}$.

When $P_t = P_{max}$, then

$$\lambda = -\frac{(\ln 2) d A^{(1/\alpha)}}{\alpha} \left[C_1 (1 - \frac{1}{\alpha}) P_{max}^{-1/\alpha} + C_2 (-\frac{1}{\alpha}) P_{max}^{(-1-1/\alpha)} \right] \tag{3.64}$$

This should satisfy the non-negativity condition of λ. Then

$$C_1(1-\frac{1}{\alpha})P_{max} - C_2\frac{1}{\alpha} \leq 0 \tag{3.65}$$

which leads to

$$P_{max} \leq \frac{C_2}{C_1(\alpha-1)} \tag{3.66}$$

As a result, we can see that the optimal transmit power that minimizes the energy consumption is

$$\hat{P}_t = \begin{array}{ll} \frac{C_2}{C_1(\alpha-1)} & \text{if} \frac{C_2}{C_1(\alpha-1)} \leq P_{max}, \\ P_{max} & \text{if} \frac{C_2}{C_1(\alpha-1)} \geq P_{max}. \end{array}$$

However, the Kuhn-Tucker condition minimizes the overall energy consumption when the objective function E_{total} is a convex function or a quasi-convex function. From (3.42), we have shown a condition that the overall energy consumption is convex. Accordingly, the Lagrangian analysis above holds only when the transmit power is below the threshold. The threshold is determined by parameters of the MAC layer and the physical layer.

When the maximum transmit power is larger than the convex condition in (3.42), the energy consumption function is convex in low transmit power range and concave in high transmit power range. In this case, the optimal transmit power that achieves the minimum energy consumption can be chosen by comparing the energy consumption of three transmit power, the threshold transmit power given in (3.42), the maximum transmit power, and the estimated optimal transmit power given in (3.45). The transmit power that achieve the minimum energy consumption among the three cases is the optimal transmit power when the energy consumption function is not convex in transmit power range.

Let the chosen optimal transmit power be denoted by $\hat{P}_t$. Then the optimal number of hops is

$$k = d \left[\frac{2^{(\frac{\alpha}{\ln 2} - C_3)}}{\hat{P}_t} \right]^{\frac{1}{\alpha}}. \tag{3.67}$$

We can see that the optimal number of hops increases linearly with the source-destination distance. Also, optimal one hop distance is constant regardless of the source-destination distance once the system parameters in Table 1 and the transmit power are given. The energy consumption with the chosen transmit power is

$$E_{total} = \frac{d[\frac{A}{\hat{P}_t}]^{\frac{1}{\alpha}}(C_1\hat{P}_t + C_2)}{\frac{\alpha}{\ln 2}} \tag{3.68}$$

where $A = 2^{(\frac{\alpha}{\ln 2} - C_3)}$. Here again, we can see that the energy consumption increases linearly with the source-destination distance. The overall delay with the chosen transmit power is

$$D_{total} = d \left[\left(\frac{2^{(\frac{\alpha}{\ln 2} - C_3)}}{\hat{P}_t} \right)^{\frac{1}{\alpha}} \left(C_4 + \frac{C_5 \ln 2}{\alpha} \right) + C_6 \right]. \tag{3.69}$$

We can see that the overall delay also increases linearly with the source-destination distance. As a result, the throughput is inverse linear related to the source-destination distance. The energy-throughput relationship can be expressed as

$$S_T = \frac{1}{E_b \frac{\frac{\alpha C_4}{\ln 2} + C_5}{C_1\hat{P}_t + C_2} + E_b \frac{C_6 \frac{\alpha}{\ln 2}}{(\frac{A}{P_t})^{\frac{1}{\alpha}}(C_1\hat{P}_t + C_2)}} = \frac{1}{E_b K_1} \tag{3.70}$$

where $K_1 = \frac{\frac{\alpha C_4}{\ln 2} + C_5}{C_1\hat{P}_t + C_2} + \frac{C_6 \frac{\alpha}{\ln 2}}{(\frac{A}{P_t})^{\frac{1}{\alpha}}(C_1\hat{P}_t + C_2)}$, E_b is the energy per bit, and I is the number of data bits in a packet. We can see the inverse linear relationship between the energy per bit and the throughput. We also see the inverse linear relationship between the energy per bit and the throughput when the transmit power and the number of hops are optimized.

3.6.3 Optimization for Maximum Throughput

Next we optimize the number of relays and the transmit power to achieve the maximum throughput. We reorganize the overall delay in (3.49) as

$$D_{MAC} = kD_1 + \frac{k}{R}D_2 + D_3 \tag{3.71}$$

where $D_1 = E[X](1-p_{tr})\sigma + p_{tr}p_s(4\delta + 3T_{SIFS} + T_{DIFS}) + p_{tr}(1-p_s)(\delta + T_{DIFS})$, $D_2 = E[X][p_{tr}p_s(RTS+CTS+ACK+M)+p_{tr}(1-p_s)RTS]+M+RTS+CTS+ACK$, and $D_3 = E[X](\frac{4p_{tr}p_s+p_{tr}(1-p_s)}{3\cdot 10^8})d$.

The packet transmission rate can be approximated as

$$\begin{aligned} R &= E\left[\log\left(1 + |h|^2 \frac{\beta P_t}{N_0 W}\left(\frac{k}{d}\right)^{\alpha}\right)\right] \\ &\simeq E[\log(|h|^2)] + \log\left(\frac{\beta P_t}{N_0 W}\left(\frac{k}{d}\right)^{\alpha}\right) = \log(P_t(\frac{k}{d})^{\alpha}) + C_3. \end{aligned} \tag{3.72}$$

We check the convexity of the overall delay on the number of hops between the source and the destination.

$$\frac{\partial^2 D_{total}}{\partial k^2} = \frac{-D_2 \frac{\alpha}{\ln 2}\frac{1}{k}}{(\log_2(P_t(\frac{k}{d})^{\alpha}) + C_3)^2} + \frac{2D_2 \frac{\alpha}{\ln 2}\frac{1}{k}}{(\log_2(P_t(\frac{k}{d})^{\alpha}) + C_3)^3} > 0. \tag{3.73}$$

Then, the overall delay is a convex function in the number of hops k when the condition below is satisfied.

$$R < \frac{2\alpha}{\ln 2} = 11.5416\text{bits/sec/Hz} \tag{3.74}$$

which is satisfied in normal operation range. When the one hop distance is 150m, more than 200mW transmit power is required to support more than 11.5 bits/sec/Hz, which can be obtained by (3.3). A typical IEEE 802.11 system transmits less than 15dBm (100mW), which will satisfy the convexity of the overall delay over the number of hops.

Then the minimum delay is achieved when

$$\frac{\partial D_{total}}{\partial k} = D_1 + \frac{D_2}{\log_2(P_t(\frac{k}{d})^{\alpha}) + C_3} - \frac{\frac{\alpha}{\ln 2} D_2}{(\log_2(P_t(\frac{k}{d})^{\alpha}) + C_3)^2} = 0. \tag{3.75}$$

However, as $D_1 \ll D_2$ and D_1 is close to zero, the equation can be approximated as

$$\frac{D_2}{\log_2(P_t(\frac{k}{d})^{\alpha}) + C_3} - \frac{\frac{\alpha}{\ln 2} D_2}{(\log_2(P_t(\frac{k}{d})^{\alpha}) + C_3)^2} = 0. \tag{3.76}$$

Then the equality is achieved when

$$\log_2(P_t(\frac{k}{d})^{\alpha}) + C_3 = \frac{\alpha}{\ln 2}. \tag{3.77}$$

Then the optimal number of hops is

$$k = d \left(\frac{2^{\left(\frac{\alpha}{\ln 2} - C_3\right)}}{P_t} \right)^{\frac{1}{\alpha}}. \tag{3.78}$$

It is shown that the optimal number of hops is determined by the channel characteristics, α and C_3. We can see that the optimal number of relays that maximized with a given power is linearly dependent on the source-destination distance.

We need to optimize the transmit power to minimize the overall delay. From (3.71), we find that the delay decreases as the rate supported at the physical layer, R, increases. Accordingly, maximizing the rate minimizes the overall delay. The rate is maximized when the maximum transmit power, P_{max} is used. Then the optimal number of relays can be optimized on the transmit power as

$$k = d \left(\frac{2^{\left(\frac{\alpha}{\ln 2} - C_3\right)}}{P_{max}} \right)^{\frac{1}{\alpha}}. \tag{3.79}$$

The analysis can be understood by the energy-throughput relationship in Figure 3.1. As we can see from Figure 1, the throughput increases as the transmit power increases for every graphs that corresponds to different number of relays between the source and the destination. For each graph, the lower part of the graph represents the low transmit power and the higher part of the graph represents the high transmit power. Accordingly, for all cases of number of relays, maximum throughput is achieved when the maximum transmit power is used. We can also see that the number of relays that yield the achievable maximum throughput. There exist the optimal number of relays that achieves the highest throughput. We can see that the optimal number of hops increases linearly with the source-destination distance and the optimal one hop distance is fixed regardless of the source-destination distance.

The energy consumption and overall delay are

$$E_{total} = \frac{d[\frac{2^{(\frac{\alpha}{\ln 2} - C_3)}}{P_{max}}]^{\frac{1}{\alpha}}(C_1 P_{max} + C_2)}{\frac{\alpha}{\ln 2}} \tag{3.80}$$

$$D_{total} = d\left[\left(\frac{2^{(\frac{\alpha}{\ln 2} - C_3)}}{P_{max}}\right)^{\frac{1}{\alpha}}\left(C_4 + \frac{C_5 \ln 2}{\alpha}\right) + C_6\right]. \tag{3.81}$$

We can see that both the energy consumption and the overall delay increases linearly as the source-destination increases. As the asymptotic case, we consider what happens when the source-destination distance goes to infinity. When the source-destination distance, both the energy consumption and the overall delay becomes infinity, which can be seen in (3.80) and (3.81). As a result, the throughput converges to zero as the source-destination distance even when we use the maximum throughput configuration. The energy-throughput relationship can be expressed as

$$S_T = \frac{1}{E_b \frac{\frac{\alpha C_4}{\ln 2} + C_5}{C_1 P_{max} + C_2} + E_b(\frac{\alpha}{\ln 2})\frac{C_6}{\left[\frac{2^{(\frac{\alpha}{\ln 2} - C_3)}}{P_{max}}\right]^{\frac{1}{\alpha}}(C_1 P_{max} + C_2)}} = \frac{1}{E_b K_2} \tag{3.82}$$

where

$$K_2 = \frac{\frac{\alpha C_4}{\ln 2} + C_5}{C_1 P_{max} + C_2} + (\frac{\alpha}{\ln 2}) \frac{C_6}{\left[\frac{2^{(\frac{\alpha}{\ln 2} - C_3)}}{P_{max}}\right]^{\frac{1}{\alpha}} (C_1 P_{max} + C_2)}, \tag{3.83}$$

E_b is the energy consumption per bit, and I is the number of data bits in a packet. Here, P_{max} and all other parameters in K_2 are fixed regardless of the source-destination distance. As a result, we can find that the throughput is inversely linear to the energy per bit in the case of the maximum throughput configuration.

3.7 Numerical Analysis

In this section, we analyze the throughput and energy consumption numerically. In mathematical analysis, the optimal number of hops, the energy consumption, and the overall delay increases linearly with the source-destination distance. However, in actual relay networks, the number of hops should be integer, which does not allow perfect linear relationship. Figure 3.2 shows the optimal number of relays that minimizes the energy consumption according to respective source-destination distance when only integer number of relays are allowed. It follows linear trend, but shows integer increments. For the comparison, we also allowed noninteger number of relays. Figure 3.3 shows the optimal number of relays that achieves the minimum energy consumption when the noninteger number of relays is allowed. We can see clear linearity between the optimal number of relays and the source-destination distance for minimum energy configuration in the figure. Figure 3.4 shows the comparison of the energy-throughput relationship when the optimal number of relays are adopted to achieve the minimum energy consumption. Each data point in Figure 3.4 represents the energy consumption and the throughput of one source-destination distance. The top data point of each graph is 500m source-destination distance case and the bottom data point of each graph is 5000m source-destination case. We varied the source-destination distance between them in 100m scale. For each source-destination

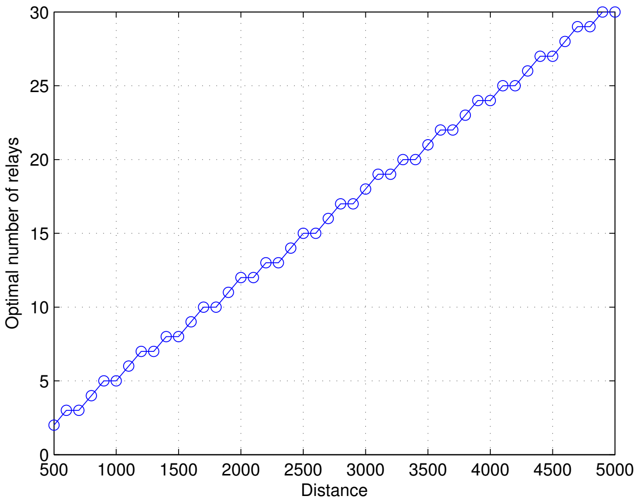

Figure 3.2: Optimal number of relays (integer) that minimizes the energy consumption

distance, the optimal number of relays is used and corresponding energy consumption and throughput are analyzed.

Figure 3.5 shows the optimal number of relays to achieve the maximum throughput when only integer number of relays is allowed. Figure 3.6 shows the optimal number of relays when noninteger number of relays is allowed. Clear linearity between the optimal number of relays and the source-destination distance for the maximum throughput configuration is shown in the Figure. Figure 3.7 shows comparison of the energy-throughput relationship of integer number of relays and noninteger number of relays. Each data point in Figure 3.7 represents one source-destination distance and corresponding energy consumption and throughput. The top data point represents 500m source-destination distance and the bottom data point represents 5000m.

By the last figure, we compare energy-throughput relationships of minimum energy configuration and maximum throughput configuration. Each data point in the graph represents the optimized performance for the corresponding source-destination distance. We varied the source-destination distance between 500m and 5000m. For each point on the graph, the optimal number of relays and the optimal transmit power

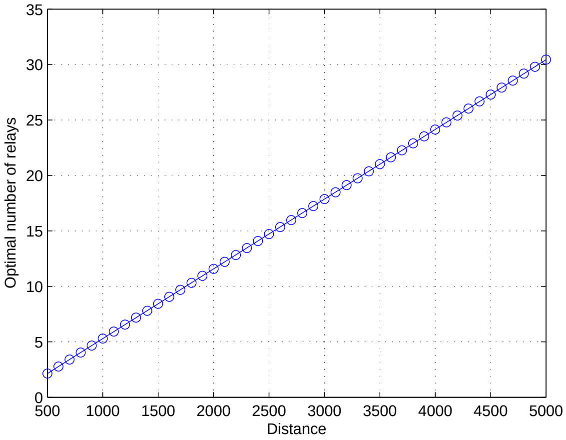

Figure 3.3: Number of relays of minimum energy configuration with noninteger number of relays

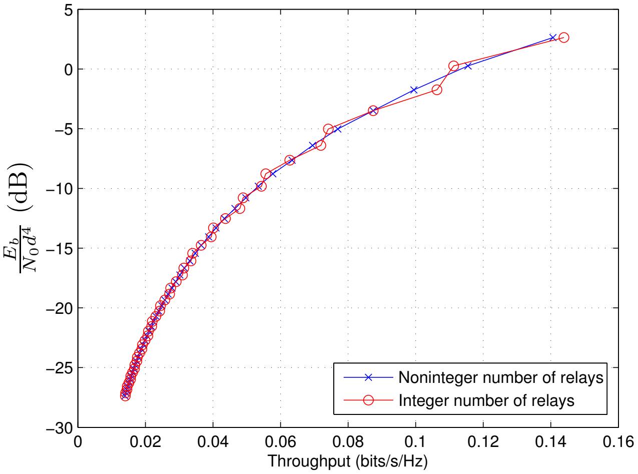

Figure 3.4: Comparison of energy-throughput relationship of minimum energy configuration between the integer number of relays case and noninteger number of relays case.

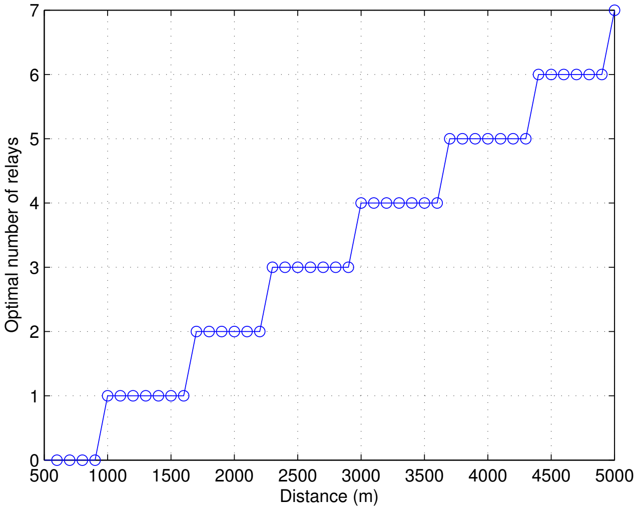

Figure 3.5: Optimal number of relays when the maximum throughput configuration is used. Integer number of relays

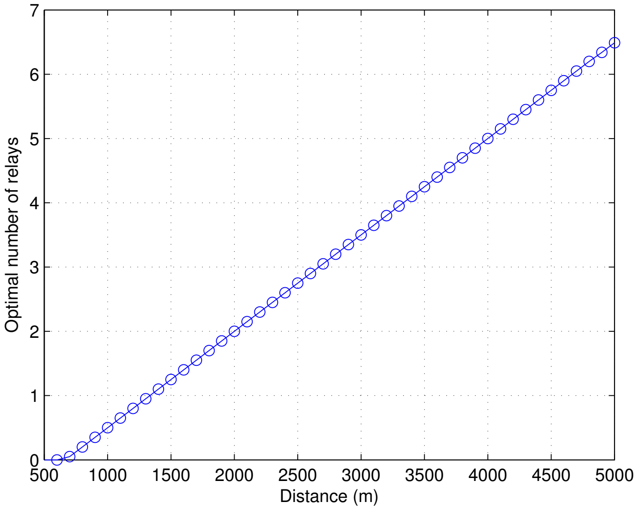

Figure 3.6: Number of relays of minimum energy configuration with noninteger number of relays

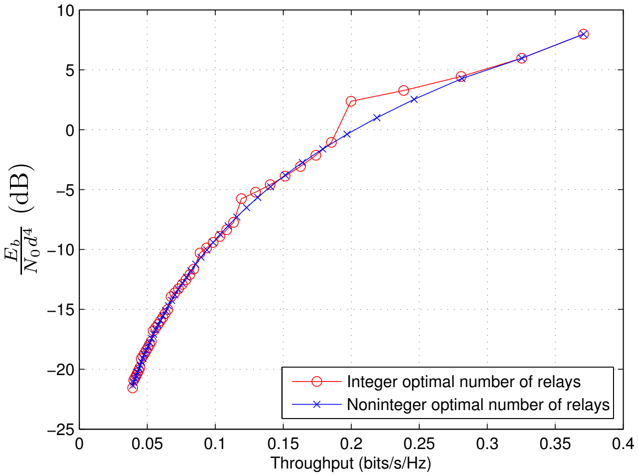

Figure 3.7: Comparison of energy-throughput relationship of maximum throughput configuration between the integer number of relays case and noninteger number of relays case.

that achieves either the minimum energy consumption or the maximum throughput for given source-destination distance is chosen. The top data point from each graph is 500m case, and the bottom data point from each graph is 5000m case. It is shown that the maximum throughput configuration achieves higher throughput with higher energy consumption compared to the minimum energy consumption configuration of corresponding source-destination distance.

3.8 Conclusion

In this paper we analyzed the energy-throughput relationship for multi-hop relay networks. Based on the relationship we found that there exists optimal number of relays and the optimal transmit power that achieves the minimum energy consumption or maximum throughput. It is also shown that the optimal number of relays for both the minimum energy configuration and the maximum throughput configuration increases linearly with the source-destination distance. When the optimal number of hops and optimal transmit power are adopted, resulting energy consumption and

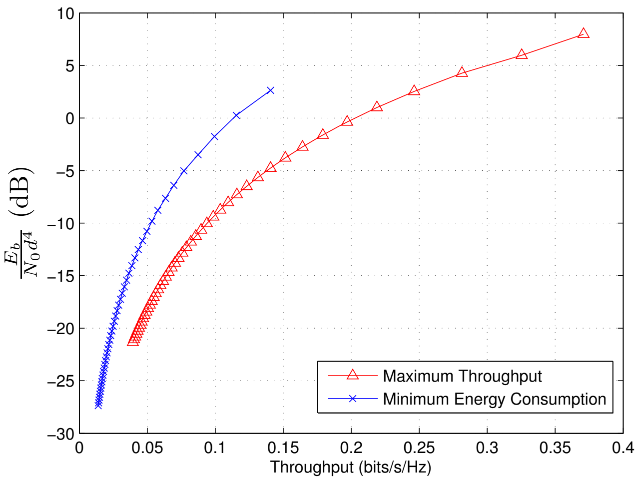

Figure 3.8: Energy-throughput relationship comparison between the minimum energy configuration and maximum throughput configuration. In case of maximum throughput configuration we assumed that the maximum transmit power allowed is 100mW. The number of relays was increased by noninteger amounts

overall delay increased linearly with the source-destination distance. From our analysis, the optimal number of hops and the optimal transmit power can be chosen based on the physical layer and MAC layer parameters for each configuration.

CHAPTER IV

Simple Relay Enabled MAC (SRMAC) Protocol for Cooperative Communication

In this paper we propose a simple relay enabled medium access (SRMAC) protocol that enables cooperative relay transmissions. Due to the wireless signal power attenuation with transmission distance, using relays in a wireless network can make wireless networking more bandwidth and energy efficient at the expense of requiring multiple transmissions for a single packet. Because cooperative relay transmission requires two transmissions, a proper medium access control (MAC) protocol that supports two hop transmission is needed. Standard MAC protocols such as the IEEE 802.11 MAC protocols are not designed to support cooperative communication. When IEEE 802.11 MAC protocol is used for cooperative communication, each hop packet transmission should undergo separate channel access procedure, which is not efficient. As such, cooperative communication schemes have been studied mainly in the context of the physical layer with the assumption that channel access is given. There has been little work on the MAC layer which controls the channel access. The new protocol, SRMAC, is a cooperative MAC protocol that utilizes information from the physical layer for the MAC operation of relay networks. We consider the energy and bandwidth efficiency of SRMAC protocol considering both the physical layer and the MAC layer. The SRMAC protocol includes the possibility of both cooperative transmission and the direct transmission. With SRMAC, cooperative transmission can be dynamically chosen when it is beneficial than direct transmission. The SRMAC improves the throughput up to 20% and energy consumption up to 40% by using cooperative transmission when it is more beneficial.

4.1 Introduction

The use of cooperative relaying schemes can improve the bandwidth and energy efficiency in distributed wireless networks. Compared to direct transmission in which packets are sent directly from the source to the destination, cooperative relaying of packets has the advantage of one hop transmission distances that are much shorter than the direct transmission distance, which leads to higher received signal-to-noise ratio (SNR) when the relaying node is closer to the destination than the source. The higher received SNR can improve the bandwidth efficiency. On the other hand, cooperative relaying has a disadvantage of involving two transmissions for a packet delivery. Moreover, the channel access overhead from a conventional MAC protocol can significantly degrade the performance of cooperative relaying because each hop requires a channel access. In decentralized wireless networks the bandwidth efficiency and throughput are critically dependent on the MAC protocol overhead. As such, a proper design of a new MAC protocols for cooperative communications becomes important. As such new MAC protocols for cooperative communications are needed minimize the MAC overheads of cooperative relaying in wireless networks.

In a decentralized multi-hop wireless network, time is consumed for MAC operations as well as for actual data communications. Thus to understand the throughput performance, both the physical layer and MAC layer should be incorporated into the analysis. The transmit power level affects the throughput performance in both layers. As the transmit power increases, the rate supported at the physical layer increases. In addition, contention for the channel access at the MAC layer increases because the number of contending nodes increases as the transmit power level increases. As such, there is an optimal transmit power that maximizes the throughput. As the number of available relays increases, it is more probable that there are relays in good positions that can improve the throughput performance significantly by cooperative relaying. We suggest a new MAC protocol that supports cooperative relaying with minimal MAC overhead and investigate the associated throughput according to the transmit power levels and the number of available relays. We also find the optimal transmit power to maximize the throughput.

Energy is also consumed for MAC operations as well as for actual data communications. We consider energy consumption from both transmitting and receiving packets. At the MAC layer, energy is consumed when control packets such as RTS, CTS, and ACK packets are transmitted and received. Also, when a node listens to the channel according to the MAC protocol procedures, the same amount of power is consumed with the packet reception. We investigate the energy consumption of the new MAC protocol as a function of the transmitted signal power.

There has been considerable past research devoted to relay networks. Though some of the past research was mentioned in previous chapters, I also discuss them here in as well. After van der Meulen's seminal work [56], there have been investigations into relay networks including the capacity of relay networks [15], [24], and [25] and on diversity-multiplexing tradeoff of cooperative relaying schemes [36] and [3]. However, these papers did not account for the MAC layer and only considered the physical layer.

There has been various papers on the bandwidth performance of distributed wireless networks. Bianchi [8] investigated the throughput performance of IEEE 802.11 RTS/CTS MAC protocol. However, he considered only the MAC layer performance with a simple model of the physical layer. He assumed that the physical layer supports only a fixed data transmission rate. The energy-throughput tradeoff for cooperative relay networks considering both the physical layer and the MAC layer was investigated in [33]. However, the IEEE 802.11 protocol was adopted as the MAC protocol.

There have been several MAC protocols proposed for relay communication. The rDCF [63] and CoopMAC [41] were proposed to enable the use of relays when it can provide faster packet transmissions. However, they did not consider cooperative communication. The destination received the packet only through the relay node. Here we assume that both packet transmissions from the source and the relay are utilized at the destination. In [63] and [41], the source knows the relay's channel state in advance. We will assume it is not known to the source.

In this paper, we propose a simple and adaptive MAC protocol that can support diverse cooperative relaying. We analyze the bandwidth efficiency and energy efficiency considering both the physical layer and the MAC layer. The MAC layer protocol chooses to use relay transmissions only when it improves the throughput. The decision criteria between the cooperative packet transmission and the direct packet transmission is proposed. We show that the simple decode and forward cooperative relaying scheme with SRMAC can improve the bandwidth efficiency.

The outline of this chapter is as follows. In Section II we introduce the system model. In Section III we introduce simple relay enabled MAC (SRMAC) protocols. In Section IV we analyze the throughput of SRMAC. In Section V we analyze the energy consumption. In Section VI we compare the performance of SRMAC with direct transmission by numerical analysis. Conclusion is given in Section VII.

4.2 System Model

4.2.1 Physical layer model

At the physical layer, the propagation model includes fast fading and distance dependent path loss. We model the fast fading as independent and identically distributed (IID) Rayleigh fading. We assume the path loss follows an inverse power law. The received signal power $\bar{P}_r$ when packets are transmitted through a distance d with a transmit power P_t is

$$P_r = \frac{|h|^2 P_t}{d^\alpha} \tag{4.1}$$

where h captures the Rayleigh fading, α is a path loss exponent. We assume that the transmitter does not know the fast fading level in the channel but it knows the distribution of fast fading. We also assume that the receiver knows fast fading level. We assume that the wireless communication scheme achieves the capacity of the Rayleigh fading channel with coherent reception by using appropriate coding and modulation.

Then the capacity, S, for this model wireless of the channel using a bandwidth W is

$$S = W \cdot E_h \left[\log_2 \left(1 + \frac{|h|^2 P_t}{N_0 W d^\alpha} \right) \right] \; bits/sec \tag{4.2}$$

where N_0 is the noise power spectral density, and $N_0 W$ is the noise power when bandwidth W is used.

4.2.2 MAC layer model

We suggest a protocol, called SRMAC, to control the channel access for cooperative relay networks. Our MAC protocol is a modification of IEEE 802.11 RTS/CTS MAC protocol. We assume that all nodes in the network use the same power. The following model captures the effect of transmit power control for the MAC layer. We assume that a transmitted control packet can be successfully decoded by other nodes when the received power is over a threshold, P_{th}. We define transmission radius as the radius where the transmitted control packets can be successfully decoded. Nodes that are separated by less than the transmission radius contend for access to the channel.

Then the transmission radius, d_t is

$$d_t = \left(\frac{P_t}{P_{th}}\right)^{\frac{1}{\alpha}}. \tag{4.3}$$

As the transmit power increases, the transmission radius increases, which results in an increase in the channel contention. Then the number of contending nodes, n is

$$n = \rho\pi d_t^2 = \rho\pi\left(\frac{P_t}{P_{th}}\right)^{\frac{2}{\alpha}}. \tag{4.4}$$

where ρ is the density of nodes in the network. We assume all nodes in the area always has a packet to send, which is a saturated traffic model. At the MAC layer, we assume that the control packets for the MAC protocol are transmitted at a fixed rate, R_{MAC}, even though the same transmit power is used for data packet and control packets. The assumption is needed for reliable control packet decoding at the neighboring nodes.

4.2.3 Energy consumption model

We consider energy consumption for both transmitting and receiving packets. A wireless node consists of RF front end and signal processing part. At the transmitter the RF front end has a power amplifier which amplifies the signal which is then transmitted. At the receiver the RF front end has a low noise amplifier which amplifies the received signal. The energy consumption for signal processing part includes baseband operations such as encoding, decoding, modulation and demodulation as well as MAC operations. When a wireless node transmits a packet, both the RF front end and signal processing part are utilized. The power consumption at the RF front end increases as the transmit signal power increases. We assume the RF front end converts the DC power P_{RF} into the signal power P_t with an efficiency η. We assume the signal processing part consumes a fixed amount of power, P_{SP}, regardless the packet transmission rate. The power consumption for packet transmissions is

$$P_{tx} = P_{RF} + P_{SP} = \frac{1}{\eta} P_t + P_{SP}. \tag{4.5}$$

When a wireless node receives a packet, both the RF front end and signal processing part are utilized. However, the power amplifier, which consumes large portion of power at the RF front end is not involved. Moreover, the power consumption variation at the receiver due to the received signal power variation is small. As such, we assume that a fixed amount of power, P_{rx} is consumed when a wireless node is receiving a packet regardless of the transmitted power or data rate.

4.2.4 Topology models

We assume that the location of the source and the destination is fixed. We assume k dedicated relays are randomly placed in an area. There are other nodes that have packets to send and contend for the channel access. We assume that the other nodes are distributed uniformly with a density ρ over the network. We assume those other nodes use the IEEE 802.11 RTS/CTS protocol. We assume all nodes in the area use the same transmit power. As such, when we consider different transmit power levels, we assume all nodes use the transmit power level we consider. The number of contending nodes increases with the transmit power level increase. However, the number of relays is fixed regardless of transmit power level. This model can be appropriate for the case that either user mobile devices are used as relays or dedicated mobile relays are adopted. Dedicated mobile relays can be implemented by using vehicles or balloons that equipped with a relaying system.

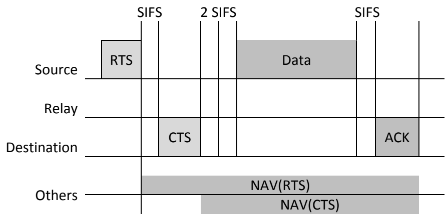

Figure 4.1: SRMAC with direct transmission

4.3 Simple Relay Enabled MAC (SRMAC) Protocol

4.3.1 Simple Relay Enabled MAC (SRMAC)

We now describe the SRMAC protocol that supports cooperative relaying. When the source node has a packet to transmit to the destination, it transmits an RTS packet. Upon the detection of the RTS packet transmission, the destination node responds with a CTS packet to the source. The destination estimates the received signal power and includes it in the RSS field of CTS packet. After receiving the CTS packet, the source waits for up to twice SIFS duration for an rCTS packet from a potential relay node. We name the duration as the rCTS wait time. When there is no relay node offering help during that duration, the source transmits the packet to the destination directly. A relay node can overhear both the RTS and CTS packets and estimate the channel condition, source-relay and destination-relay propagation loss. It also learns the channel condition between the source and the destination from the CTS packet (RSS). Based on the channel conditions, the relay node determines whether cooperative communication improves the throughput. When it improves the throughput, an rCTS control packet is transmitted from the relay. The relay node includes the achievable capacity of cooperative packet transmission and destination address in the rCTS packet.

However, when multiple relays respond with rCTS packets, they may collide with each other. As such, there should be a mechanism to minimize the collisions. We adopt a fast random backoff scheme to avoid a collision. For the fast backoff scheme,

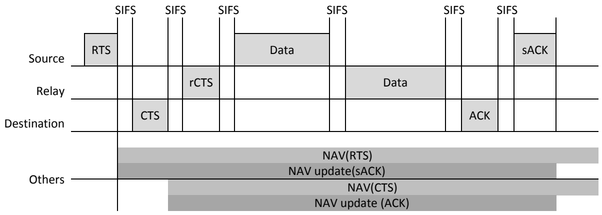

Figure 4.2: SRMAC with cooperative transmission

we adopt shorter slot time. In an IEEE 802.11 system, a random backoff scheme is used based on the slot time, which is a discrete time backoff scale (9μs). For the collision avoidance between rCTS packets, a shorter slot time (2μs) can be adopted. When a relay node decides to send an rCTS packet, a backoff time is uniformly chosen in 2 SIFS duration (18 shorter slot time). When the backoff time reaches zero, the relay node transmits an rCTS packet. By the random backoff scheme, SRMAC can avoid or reduce collisions between rCTS packets. When there is a collision even after the random backoff, the source node sends the packet directly to the destination. After exchanging the RTS and CTS packets, the source waits for 2 SIFS duration for possible rCTS packet. When there is no rCTS packet transmission during the 2 SIFS duration, the direct packet transmission is chosen and it is indicated in the MAC header fields as described in the next section. By using a shorter slot time, the overhead from waiting for an rCTS packet is minimized. Because only the relays that can improve the performance participate in the backoff process for rCTS transmission, the 2 SIFS duration will be enough to avoid collisions between rCTS packets from different nodes. The feasibility of using shorter slot time was explored and verified to be achievable in a study on the improvement of IEEE 802.11 standard MAC protocol by using shorter time slots [43].

When the destination node receives the rCTS packet from the relay, it learns whether or not the packet will be transmitted cooperatively from the destination address field of the rCTS packet. When direct transmission is chosen due to collisions between rCTS packets, the destination can determine this from the Address 4 filed of the received data packet sent from the source. In this paper, we assume that the source node adopts cooperative transmission once a relay node sends an rCTS packet successfully. However, other decision criteria can be also implemented at the source node to determine whether to accept a relay's proposal. When the source node decides not to use cooperative packet transmission, it can include the destination address in the Address 4 field in the MAC header. Both the relay and the destination can know the source node's decision from this field in that case. If relaying is used, the source node transmits the packet with the higher rate as informed by the relay in the rate field of the rCTS packet. The relaying scheme will be presented in the next section.

When cooperative packet transmission is used, the packet transmission occupies the channel a shorter time than RTS/CTS control packets would otherwise indicate. Because other nodes in the network set the NAV based on the information in the RTS/CTS packets, we need to clear the neighboring nodes' NAVs. To do that, upon reception of the ACK packet from the destination, the source transmits an sACK informing neighboring nodes to clear their NAVs. Neighboring nodes in the range of the ACK or sACK packet clear their NAVs to enable channel access when they have a packet to send.

SRMAC can be easily integrated into the IEEE 802.11 RTS/CTS protocol. Diverse types of cooperative communication schemes can also be easily integrated with SRMAC. Once channel access is given for packet transmission, cooperative communication schemes can access channel without worrying about additional channel access overhead for relaying. We assume that the packet transmission is attempted only when a control packet can reach between the source and the destination. With SRMAC, the source node does not have to know relay information in advance. Also, cooperative communication can be used dynamically and efficiently because cooperative packet transmission is chosen only when it's beneficial.

The SRMAC protocol can be improved by adopting different criteria than the standard SRMAC protocol for different environments. For example, in (4.3.4) a relay decides it can participate in relaying when it reduces overall delay. In (4.3.4), the threshold for the decision is zero. However, when there are many relays it can be beneficial to increase the threshold for decision to relay. By changing the threshold, we can allow only relays that can reduce the overall delay over a certain level to participate in relaying. In SRMAC, a relay is chosen randomly among the relays that improve the throughput. As such, by allowing only relays that improve throughput above certain level, the throughput of SRMAC can increase when there are many relays.

4.3.2 Frame Formats

SRMAC builds on the IEEE 802.11 protocol with some modifications to some control packets and a method of determining which relay should transmit and some additional control packets sent by the relay. To support the SRMAC protocol, additional information is added to the standard IEEE 802.11 frame formats. Figure 4.2 shows the timing of control and data packets of SRMAC. The RTS frame format need not to be modified. The format of the CTS frame, transmitted by the destination, should be changed to include the received signal strength (RSS) which indicates the realization of propagation loss which is estimated by receiving an RTS packet from the source. The relay node learns the achievable direct packet transmission rate by knowing the RSS value in the CTS packet. When the relay node determines that the cooperative packet transmission is beneficial, it transmits an rCTS packet to the source after a short random backoff process to avoid a collision with rCTS packets sent by other nodes, which is described in detail in the previous section. The back off algorithm for transmitting an rCTS packet is the same as the algorithm for transmitting the RTS packets except that the slot time for the backoff process is much shorter and the maximum duration of backoff process is twice SIFS duration. The timing of the rCTS packet transmission from different nodes can be different due to the random backoff process. But on average, the timing will be one SIFS duration after the CTS packet transmission as shown in Figure 4.2. To inform the source and the destination about the cooperative packet transmission, the rCTS packet includes the rate for cooperative packet transmission and the destination address in the MAC header. The destination understands the packet will be delivered through cooperative transmission by overhearing the rCTS packet. The modified ACK frame format is used for both the ACK and sACK packets. These packets includes a clear network allocation vection (clear NAV) field that indicates the end of packet transmission to the overhearing neighbor nodes. The NAV fields in neighboring nodes are set with information in either RTS packet or CTS packet, which was set with the assumption of direct transmission. When cooperative packet transmission is used, the packet transmission is maybe finished earlier than the reserved duration because the cooperative transmission is used only when it increases the throughput. To allow other nodes to access the channel earlier, the sACK packet is transmitted from the source for neighboring nodes in the transmission range of the source.

When a data packet is transmitted using cooperative packet transmission, the relay node should be able to determine if the packet transmission from the source is intended for the cooperative packet transmission or not. We can utilize an unused field in the data packet MAC header for this purpose. When a packet is interchanged between nodes in an independent basic service set (IBSS), the 'To DS' and 'From DS' field are set as 1, and the Address 4 field in the MAC header is filled with the destination address [1]. We modify the procedure to fill in Address 4 field with the relay node address when the cooperative packet transmission is used. When direct transmission is used, the Address 4 field is filled with the destination address. The relay node can determine whether a packet from the source should be relayed by checking the 'To DS', 'From DS', and 'Address 4' fields. The destination node can also learn whether the packet transmission is cooperative packet transmission or direct transmission using the Address 4 field.

4.3.3 Decode and Froward Cooperative Relaying Scheme

The cooperative relaying scheme we consider is decode and forward relaying in which full decoding is done at the relay. This cooperative relaying scheme consists of two phases. In the first phase, the source transmits a packet to the relay. The relay fully decodes the received packet. During the first phase, the destination overhears the packet transmission. In the second phase, the relay transmits the correctly decoded packet to the destination. With the received signal from the first phase and the second phase, the destination decodes the packet. We assume that proper coding and modulation were adopted at the physical layer to achieve the capacity. We also assume that a proper combining technique is used at the destination. Other cooperative relaying schemes can also be used easily with the SRMAC protocol.

4.3.4 Decision Criteria for the Relay Node

In the SRMAC protocol, the relay node decides whether to help a packet transmission or not. When cooperative communication achieves higher throughput, the relay decides to participate in cooperative communication. From the average received SNR of an RTS packet, CTS packet, and the RSS information of the CTS packet, the relay node can calculate the capacity of the cooperative packet transmission and the direct packet transmission. The capacity of the cooperative packet transmission, R_{coop}, is [35]

$$\begin{aligned} R_{coop} = W \cdot \min \Bigg\{ & E\left[\log_2\left(1 + |h_{sr}|^2 \frac{P_t}{N_0 W d_{sr}^{\alpha}}\right)\right], \\ & E\left[\log_2\left(1 + |h_{sd}|^2 \frac{P_t}{N_0 W d_{sd}^{\alpha}} + |h_{rd}|^2 \frac{P_t}{N_0 W d_{rd}^{\alpha}}\right)\right]\Bigg\} \end{aligned} \quad (4.6)$$

where d_{sr}, d_{rd}, and d_{sd} are source-relay distance, relay-destination distance, and source-destination distance, respectively. The average is over Rayleigh fading, h_{sr}, h_{rd}, and h_{sd}. The capacity for direct packet transmission, R_{direct} is

$$R_{direct} = W \cdot E\left[\log_2\left(1 + |h_{sd}|^2 \frac{P_t}{N_0 W d_{sd}^{\alpha}}\right)\right]. \tag{4.7}$$

where the average is over the Rayleigh fading h_{sd}. Then the relay node calculates the difference of the time consumption between the cooperative packet transmission and the direct packet transmission, D_{diff}, as

$$D_{\text{diff}} = \frac{2M}{R_{coop}} + T_{rCTS} + T_{sACK} + 2T_{SIFS} + 3\delta - \frac{M}{R_{direct}} \tag{4.8}$$

where M is the total number of bits in the data packet, T_{rCTS} and T_{sACK} are the time consumed for rCTS packet transmission and sACK packet transmission. If the time consumption difference is negative, the cooperative packet transmission improves the throughput. When the time consumption difference is positive, the relay decides the direct transmission achieves better throughput. When the time consumption difference is negative, the relay sends out an rCTS packet. We should comment that the decision criterion of SRMAC involves factors from both the physical layer and the MAC layer. For the following analysis, we define an indicator function for the decision.

$$I(D_{\text{diff}}) = \begin{cases} 1 & \text{if} \quad D_{\text{diff}} \leq 0, \\ 0 & \text{if} \quad D_{\text{diff}} > 0. \end{cases}$$

In this case, the threshold for the relaying decision is zero. We can also use different threshold for the relaying decision. For example, allowing only relays with certain level of throughput improvement is also possible. It can be implemented by using negative number as the threshold instead of using zero as the threshold. Then a relay is chosen among better performing relays. When there are many relays in the area, it will improve the bandwidth efficiency. However, it can reduce the throughput when there are not many relays in the area. The analysis can also be done for other measures of the rate. For example, R_{coop} and R_{direct} can be replaced by a set of rates supported by practical wireless network systems according to the received SNR when the system only supports fixed set of rates.

4.4 Throughput Analysis

We define the throughput T as

$$T = \frac{I}{D_{\text{total}}} \tag{4.9}$$

where I is number of data bits contained in a packet, which excludes header part in the packet and D_{total} is the total delay for the packet transmission. The total delay consists of two parts, the delay from the MAC protocol operations and the delay from actual data packet transmission.

4.4.1 Delay from the MAC layer operation

For the MAC layer delay analysis, we adopt the throughput analysis of IEEE 802.11 RTS/CTS MAC protocol by Bianchi [8]. However, we extend the model to account for the dynamic relationship between the physical layer and the MAC layer as discussed in the previous section. Previous research assumed that the physical layer only supports a fixed rate. The effect of the transmit power control on the physical layer and the MAC layer are shown in (4.2) and (4.4). As such our analysis accounts for the performance change at both the physical layer and the MAC layer according to the transmit power control, which were not considered previously [8], [10].

Let X be the number of backoff counts consumed for the source node to gain channel access and B be the average length of time for a decrease of the backoff count.

Define T_c as the time consumption from collision between RTS packets and p as the collision probability when a node transmits a packet. We define T_{RTS}, T_{CTS}, and T_{ACK} to be the time used to transmit RTS, CTS, and ACK control packets, which are transmitted with a fixed rate, R_{MAC}. There are fixed time intervals between control packet transmissions, T_{SIFS} and before starting the backoff count, T_{DIFS}. There is also propagation delay, δ. Then the average delay from the MAC protocol operation, D_{MAC}, for SRMAC when the cooperative packet transmission is used is

$$D_{MAC,coop} = E[X] \cdot E[B] + \frac{pT_c}{1-p} + T_{RTS} + T_{CTS} + T_{rCTS} + 2T_{ACK} + 7\delta + 6T_{SIFS} + T_{DIFS} \tag{4.10}$$

where the first term is the time consumed while the backoff counter decreases, the second term accounts for the time consumption for unsuccessful RTS packet transmissions, and other terms are the time consumed for the last successful SRMAC control packets exchange. The time to transmit control packets is the size of control packet divided by the control packet transmission rate, R_{MAC}. If direct packet transmission is chosen by the SRMAC protocol, the average delay from the MAC protocol operation is

$$D_{MAC,direct} = E[X] \cdot E[B] + \frac{pT_c}{1-p} + T_{RTS} + T_{CTS} + T_{ACK} + 4\delta + 4T_{SIFS} + T_{DIFS}. \tag{4.11}$$

Note that the transmit power levels affects the delay from the MAC protocol. The number of contending nodes, which increases with the transmit power level affects the delay from the MAC protocol through $E[X]$ and $E[B]$. The analysis for $E[X]$ and $E[B]$ can be found in [33].

4.4.2 Delay from data packet transmission

Once the channel access is granted to the source and the cooperative packet transmission is used, we use decode and forward cooperative relaying scheme to transmit

Parameter	Value
Payload / Header	2000 / 36 bytes
RTS / CTS / rCTS / ACK / sACK	20 / 16 / 22 / 15 / 15 bytes
Slot time (σ) / DIFS / SIFS	20 / 50 / 10 μsec
CW_{min} / CW_{max}	16 / 1024 slots
Bandwidth	20 MHz
Node density	0.000001 nodes/m^2
Path loss exponent (α)	4
P_{rx} / P_{sp} / P_{th}	50mW / 50mW / 10^{-13}W
R_{MAC}	20 Mbps

Table 4.1: Analysis parameters

the data packet. During the fist phase, the source transmits a packet to the relay and the destination overhears the packet transmission. During the second phase, the relay transmits the received packet to the destination. The capacity for cooperative packet transmission is R_{coop} is in (4.6) and for the direct transmission is R_{direct} is in (4.7). The average delay for data packet transmission for cooperative packet transmission is $\frac{2M}{R_{coop}}$ and for direct transmission is $\frac{M}{R_{direct}}$. The overall delay of SRMAC is

$$D_{total} = I(D_{\text{diff}})(D_{MAC,coop} + \frac{2M}{R_{coop}}) + (1 - I(D_{\text{diff}}))(D_{MAC,direct} + \frac{M}{R_{direct}}). \quad (4.12)$$

Then the throughput, T is given by (4.9).

4.5 Energy Consumption Analysis

For the energy consumption analysis, we use the energy consumption model in Section II. We assume that the same power is used for data packet transmission and control packet transmission. We consider energy consumption from the data packet transmission and the MAC operations. The energy consumption for data packet transmission in cooperative transmission scheme is

$$E_{data,coop} = (2P_{tx} + 3P_{rx})\frac{M}{R_{coop}} \quad (4.13)$$

and the energy consumption for data packet transmission in direct transmission scheme is

$$E_{data,direct} = (P_{tx} + P_{rx})\frac{M}{R_{direct}}. \tag{4.14}$$

The energy consumption from the MAC operation is be divided into two parts. The first part is the energy consumption from overhearing packet transmissions between other nodes while the source node undergoes the random backoff process, E_{wait}. The second part is the energy consumption from transmitting and receiving control packets to reserve the channel for packet transmissions, E_{trial}. Then the energy consumption for overhearing other nodes is

$$E_{wait} = (p_{tr}T_{RTS} + (1 - p_{tr})\sigma)P_{listen}E[X] \tag{4.15}$$

where the first term represent the energy consumption from overhearing RTS control packet transmission between other nodes for both successful packet transmission and collision. The second term accounts for the energy consumption from listening to the channel when there is no packet transmission. When there is no packet transmission, the backoff counter is decreased by when after a slot time σ.

A node transmits an RTS packet when the backoff counter expires. When there is a collision between RTS packets, the channel reservation is not successful and the source node needs to retransmit an RTS packet after a new random backoff. Then the energy consumption from transmitting control packets to reserve the channel for packet transmission, E_{access}, is

$$\begin{aligned} E_{access,coop} =& \frac{p}{(1-p)}P_{tx}T_{RTS} + P_{tx}(T_{RTS} + T_{CTS} + T_{rCTS} + T_{ACK} + T_{sACK}) \\ &+ P_{rx}(2T_{RTS} + 2T_{CTS} + 2T_{rCTS} + T_{ACK}). \end{aligned} \tag{4.16}$$

The energy for direct packet transmission, E_{access}, is

$$E_{access,direct} = \frac{p}{(1-p)} P_{tx} T_{RTS} + (P_{tx} + P_{rx})(T_{RTS} + T_{CTS} + T_{ACK}). \tag{4.17}$$

Thus, the energy consumption difference between cooperative transmission and direct transmission is

$$\begin{aligned} E_{\text{diff}} =& (2P_{tx} + 3P_{rx})\frac{M}{R_{coop}} - (P_{tx} + P_{rx})\frac{M}{R_{direct}} \\ & + P_{tx}(T_{rCTS} + T_{sACK}) + P_{rx}(T_{RTS} + T_{CTS} + 2T_{rCTS}) \end{aligned} \tag{4.18}$$

Then the average total energy consumption of SRMAC, E_{total}, which includes energy consumption from data packet transmission and MAC operations is

$$\begin{aligned} E_{total} = E\big[& I(D_{\text{diff}})(E_{access,coop} + E_{wait} + E_{data,coop}) \\ & + (1 - I(D_{\text{diff}}))(E_{acceess,direct} + E_{wait} + E_{data,direct})\big]. \end{aligned} \tag{4.19}$$

4.6 Numerical Analysis

In this section, we analyze the energy-throughput tradeoff considering both the physical layer and the MAC layer. By analyzing the tradeoff for SRMAC, we can find the optimal transmit power that finds the appropriate operating point. Also, the tradeoff of relay transmission can be compared to the direct transmission. It helps to understand when the relay transmission performs better than the direct transmission according to the relay location. For the comparison, we place relays in several locations. As the first case, we assume that the relay is placed in between the source and destination. The source, relay, and destination are separated by the same distance $\frac{d}{2}$ on a straight line. As the second case, we locate the relay close to the source, one fourth of the source-destination distance from the source in a straight line between

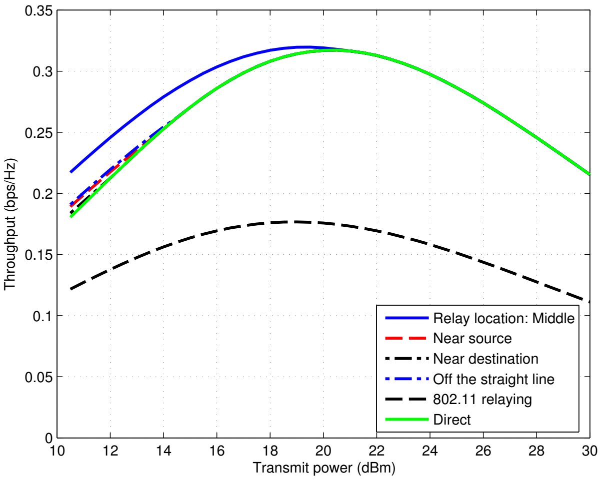

Figure 4.3: Throughput comparison between different relay locations with IID Rayleigh channel

the source and the destination. As the third case, we place the relay close to the destination, three fourth of the source-destination distance from the source node. As the fourth case, we place the relay off the straight line between the source and the destination, at a point where the distance from the source and the destination is $\frac{1}{\sqrt{2}}$ of the source-destination distance. Figure 4.3 compares the throughput of different relay locations in IID Rayleigh fading channel. Parameters for the analysis is given in Table 1. The case of a relay placed outside the straight line is labeled as "Off the straight line". When a relay is located at the middle point between the source and destination, SRMAC achieves the highest throughput. At low transmit power levels, SRMAC protocol improves the throughput by up to 20%. When we compare the maximum throughput of SRMAC when a relay is located in the middle and direct transmission, SRMAC achieves higher maximum throughput than direct transmission. However, at higher transmit power levels, SRMAC protocol achieves the same throughput with direct transmission. At high transmit power levels, relay transmission achieves less throughput than direct transmission and SRMAC choose to transmit packets by direct transmission. For all other relay locations, the throughput is slightly higher than direct transmission at low transmit power levels. Among relay locations not in the middle of the source and the destination, the highest throughput is obtained by "Off the straight line case", followed by "Near the source case", followed by "Near the destination case". The near the source case achieves higher throughput than the near the destination case because the capacity of cooperative packet transmission is higher when a relay is near the source than when a relay is near the destination as in (4.6). Though the off the straight line case achieved slightly higher throughput than those two cases, but it depends on the distance from the source and destination. When those distances are longer, it achieves lower throughput than two previous cases. For the comparison, the throughput of relay transmission using the standard IEEE 802.11 MAC protocol is also shown in Figure 4.3. The IEEE 802.11 protocol achieves much lower throughput than direct transmission and relay transmission using SRMAC protocol because it requires the two channel contentions while SRMAC protocol requires only one. Because the delay from MAC operations dominates the total delay, doubling MAC operation decreases the throughput significantly. However, SRMAC takes advantage of cooperative communication with minimal additional overhead from MAC operations.

As analyzed in the previous sections, the throughput and the energy consumption are dependent on the transmit power level and coupled by it. From the energy-throughput relationship, we can understand how the transmit power affects the throughput and the energy consumption considering both the physical layer and the MAC layer. When we choose a transmit power, corresponding energy consumption and throughput can be achieved. Figure 4.4 shows the energy-throughput tradeoff when the source-destination distance is 500m. For each graph, the left lower ends corresponds to the low transmit power and the right lower end corresponds to the high transmit power. As the transmit power increases, the corresponding point on the graph moves clockwise. In each graph, we can find an optimal operating point that

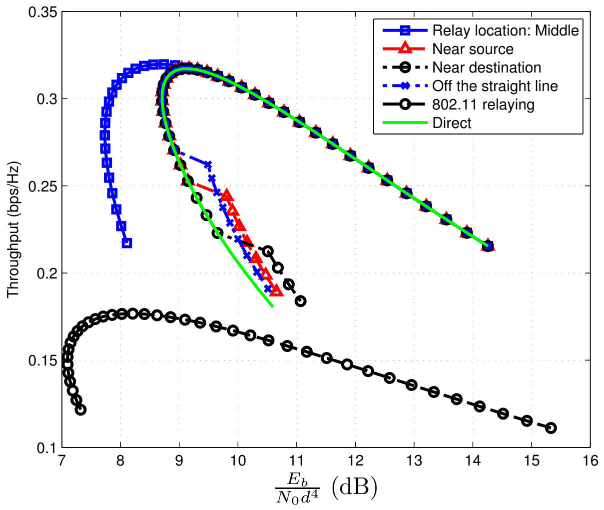

Figure 4.4: Energy-throughput tradeoff of different relay locations with IID Rayleigh fading channel channel

achieves the maximum throughput or an optimal operating point that achieves the minimum energy consumption. Depending on the purpose of the wireless network, either the maximum throughput configuration or the minimum energy consumption configuration can be chosen.

It is seen that the SRMAC achieves higher throughput with less energy consumption (up to 40%) than direct transmission when a relay is located in the middle of the source and destination. At low transmit power levels both energy efficiency and bandwidth efficiency improvement is large while there is no improvement over direct transmission at high transmit power level. It is because the SRMAC protocol uses direct transmission at high transmit power levels. At low transmit power range, an increment of the transmit power achieves big return in the capacity. The capacity increases almost linearly as the transmit power increases at low transmit power levels. With increased capacity, the energy consumption from data packet transmission decreases because it takes less time to transmit data packets. As the side effect, the transmit power increment also incurs more contention for the channel access. However, the good effects dominates over the side effect because the data packet size is much bigger that the control packet size. As a result, both the energy efficiency and the throughput improves as the transmit power increases at low transmit power range. At high transmit power range, the return from increasing the transmit power diminishes. The capacity increases logarithmically as the transmit power increases at high transmit power levels. At high transmit power range, the delay from MAC operations dominates over the data packet transmission time as the transmit power increases. As a result, both the energy consumption and the throughput degrades as the transmit power increases. At moderate power levels optimal operating points appear which achieve either the maximum throughput or the minimum energy consumption as the energy consumption. In Figure 4.4, the two optimal operating points are different, but there can be cases that the two optimal operating points are the same. When we consider other relay locations, it is seen that there are slight bandwidth efficiency improvements compared to direct transmission at the expense of higher energy consumption at low transmit power levels. It is because using relay increases the capacity slightly at those locations and the energy consumption increases from additional control packet transmissions and receptions. For the comparison, energy-throughput tradeoff of relay transmission using IEEE 802.11 protocol is shown in Figure 4.4. It achieves lower energy consumption than relay transmission with SRMAC at low transmit power levels because SRMAC requires the destination to listen to the both the first hop transmission and second hop transmission. It consumes more energy than other transmission schemes at high transmit power levels due to the increased MAC contentions.

We also investigate the average performance of SRMAC when the relays are randomly placed in the area. We average the throughput performance of different relay placement realizations. In some cases relays are placed in good locations that can improve the throughput such as the middle point between the source and destination. In other cases, relays are placed in bad locations that does not improve the through-

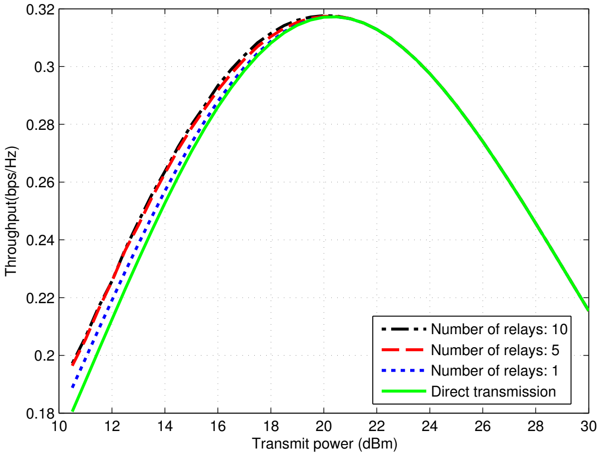

Figure 4.5: SRMAC average throughput comparison for different number of relays in IID Rayleigh fading channel channel

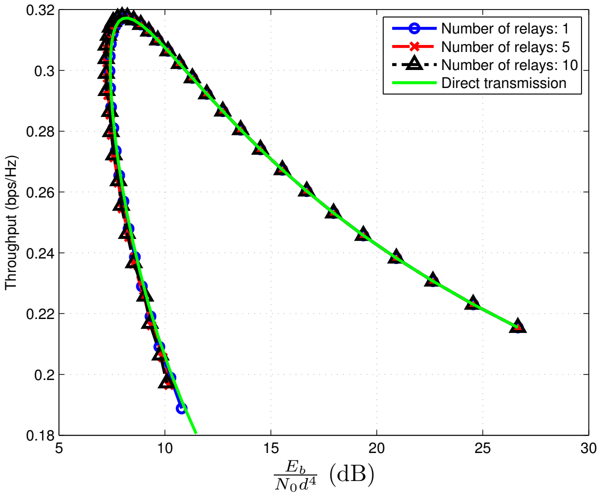

Figure 4.6: Average energy-throughput tradeoff of different number of relays in IID Rayleigh fading channel channel

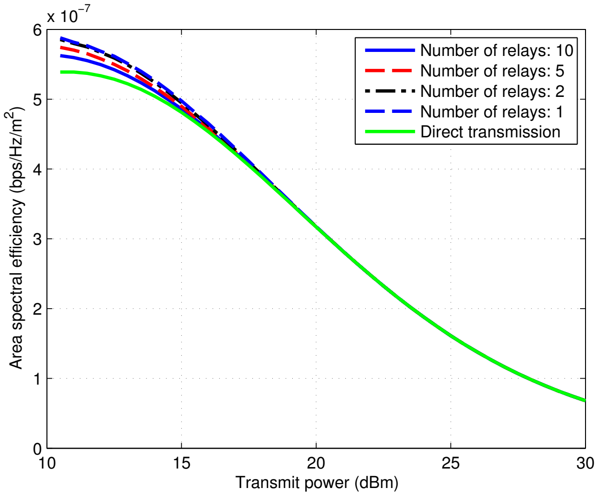

Figure 4.7: SRMAC average area spectral efficiency comparison for different number of relays in IID Rayleigh fading channel channel

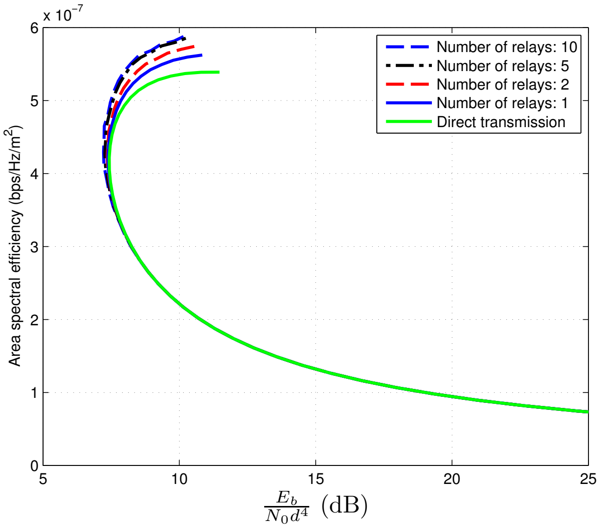

Figure 4.8: Average energy-area spectral efficiency tradeoff of different number of relays in IID Rayleigh fading channel channel

put. According to SRMAC protocol, only relays that can improve the throughput attempts to aid the data packet transmission between the source and destination. Figure 4.5 compares the throughput performance for different number of relays. It is seen that SRMAC protocol improves the throughput at low transmit power levels. As the number of relays increases, the throughput increases. When there is one relay, the throughput is increased by SRMAC protocol up to 5% at low transmit power level. With five relays, the throughput is increased up to 10% at low transmit power. We also investigated the average energy-throughput tradeoff of SRMAC protocol. Figure 4.6 shows the average energy-throughput tradeoff for different number of relays. The SRMAC improves the energy efficiency up to 25% at low transmit power levels when there are 10 relays in the area.

Figure 4.7 compares the area spectral efficiency for different number of relays. Area spectral efficiency is throughput per unit bandwidth and unit area. When the area spectral efficiency is higher, more sum throughput can be supported in the area. It is seen that SRMAC protocol achieves about 10% higher area spectral efficiency than direct transmission when there are 10 relays in the area. Figure 4.8 shows the energy-area spectral efficiency tradeoff of SRMAC protocol. It is seen that SRMAC protocol achieves that higher area spectral efficiency with much less energy consumption at low transmit power levels.

For the comparison, we investigate the performance of SRMAC when the best relay is selected for cooperative communication. Figure 4.9 shows the average throughput performance of SRMAC when the best relay is selected. For each realization, we randomly placed relays in the area and chose the best relay to deliver a data packet to the destination using decode and forward cooperative communication. We averaged the best relay performance of many relay placement realizations. It is seen that the best relay choice among 50 relays increases the throughput up to 19% compared to direct transmission when the same transmit power is used. When there are 10

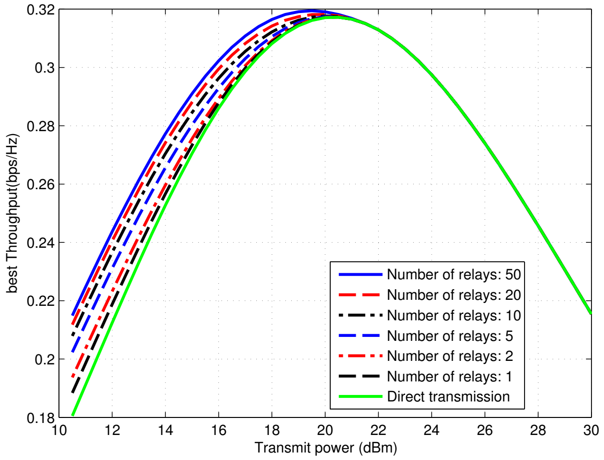

Figure 4.9: Average throughput performance of the best relay in IID Rayleigh fading channel channel

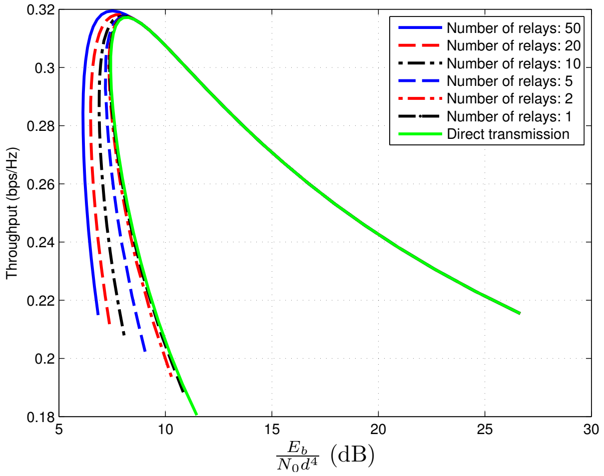

Figure 4.10: Average energy-throughput tradeoff of the best relay in IID Rayleigh fading channel channel

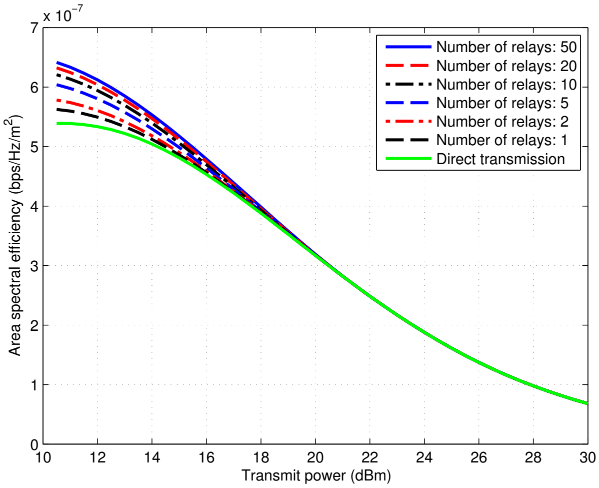

Figure 4.11: Average area spectral efficiency of the best relay in IID Rayleigh fading channel channel

relays in the area, the throughput is increased up to 15% at low transmit power level. Figure 4.10 shows the average energy-throughput tradeoff of SRMAC when the best relay is selected for cooperative communication. It is seen that SRMAC with the best relay achieves higher throughput with much less energy consumption than direct transmission. When there are 10 relays in the area, SRMAC with the best relay reduces the energy consumption more than 50%. When there are 50 relays in the area, the energy consumption is reduced more than 70%.

Figure 4.11 compares the area spectral efficiency of SRMAC protocol with the best relay choice. It is shown the area spectral efficiency of the best relay is increased by 15% when there are 10 relays and 19% when there are 50 relays. Figure 4.12 shows the energy-area spectral efficiency tradeoff for the best relay choice. It is seen that SRMAC with the best relay choice improves the area spectral efficiency with significantly improved energy efficiency.

When we compare the performance of basic SRMAC which chooses a relay in a random manner and SRMAC with the best relay, there is a big performance gap between them. The random choice of a relay incurs this gap. As such, it is rea-

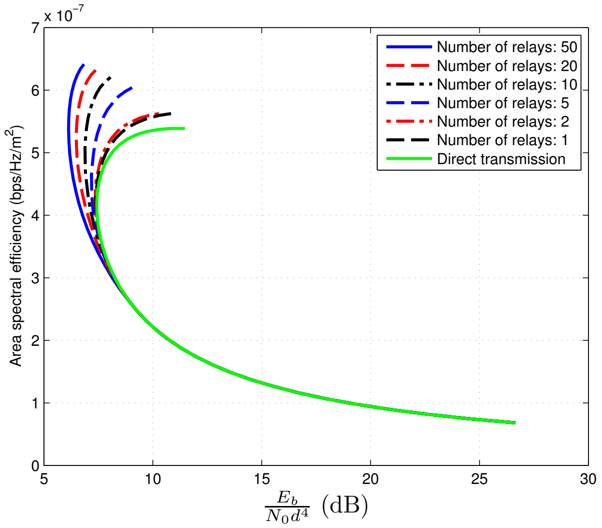

Figure 4.12: Average energy-area spectral efficiency tradeoff of the best relay in IID Rayleigh fading channel channel

sonable to consider different threshold for (4.3.4). We changed the threshold for the decision of relaying to -0.0001 and -0.0002, which allows only good relays to be a candidate for relaying a data packet. From Figure 4.13 and Figure 4.14, it is seen that a new threshold of -0.0001 improved both the bandwidth and energy efficiency. With 10 relays, SRMAC with a new threshold improved the throughput 10% and energy consumption more than 10% at low transmit power levels. However, as the transmit power increases, the performance of SRMAC with a new threshold merges to the performance of direct transmission earlier than the standard SRMAC protocol performance shown in Figure 4.5 and Figure 4.6. At higher transmit power level, the performance improvement from relaying gets smaller. When the decision threshold for relaying gets higher than zero as in (4.3.4), relays does not participate in relaying at higher transmit power levels because the performance improvement is less than the new threshold. Figure 4.15 and Figure 4.16 shows the area spectral efficiency and energy consumption with a new decision threshold of -0.0001. It is seen that SRMAC improves the area spectral efficiency significantly at low transmit power levels.

Figure 4.17, Figure 4.18, Figure 4.19, and Figure 4.20 shows the performance

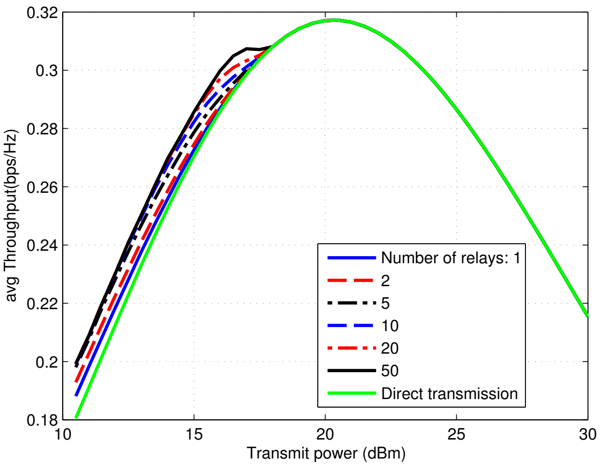

Figure 4.13: SRMAC average throughput comparison with a new threshold of -0.0001

of SRMAC with a new threshold of -0.0002. With higher threshold, the SRMAC protocol achieves higher throughput and less energy consumption at low transmit power levels. However, the performance merges to direct transmission performance at lower transmit power levels.

4.7 Conclusion

In this paper, we suggested a simple relay enabled MAC (SRMAC) protocol for cooperative relay networks. The SRMAC protocol provides two critical services for cooperative communications, channel reservation suitable for cooperative communication and the decision mechanism to decide between the relay transmission and direct transmission. We analyzed the throughput of SRMAC protocol considering both the physical layer and the MAC layer, and compared the performance with other packet transmission schemes. The SRMAC protocol showed better performance than direct packet transmission and relaying with IEEE 802.11 MAC protocol. The SRMAC is flexible and many other cooperative communication schemes can be easily integrated. Different decision criteria can be adopted for the better performance where there are many relays in the area.

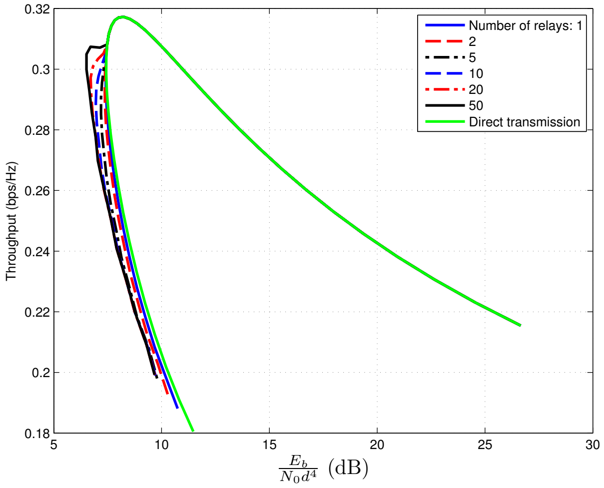

Figure 4.14: SRMAC average energy-throughput tradeoff with a new threshold of -0.0001

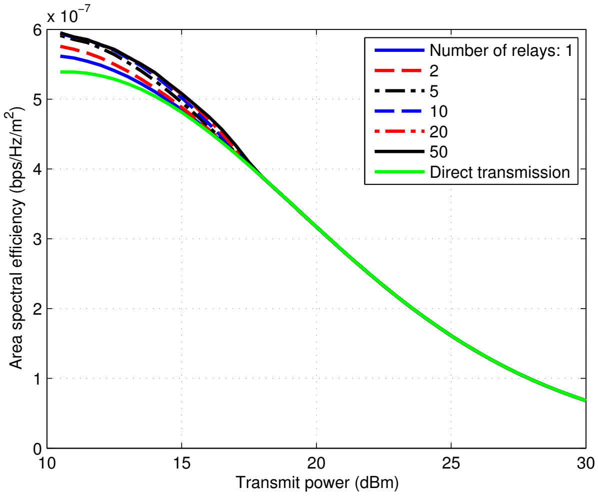

Figure 4.15: SRMAC average area spectral efficiency comparison with a new threshold of -0.0001

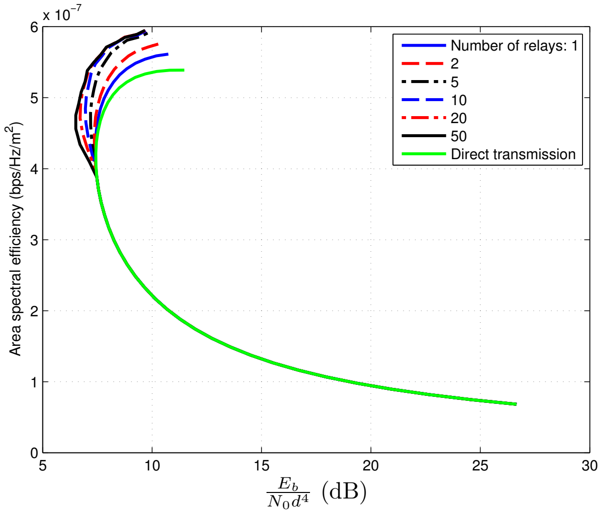

Figure 4.16: SRMAC average energy-area spectral efficiency with a new threshold of -0.0001

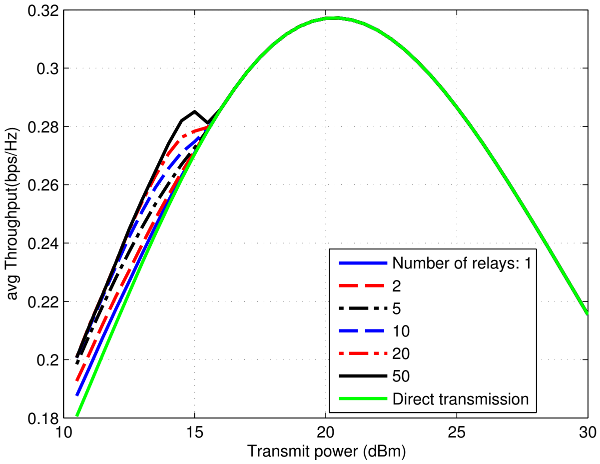

Figure 4.17: SRMAC average throughput with a new threshold of -0.0002

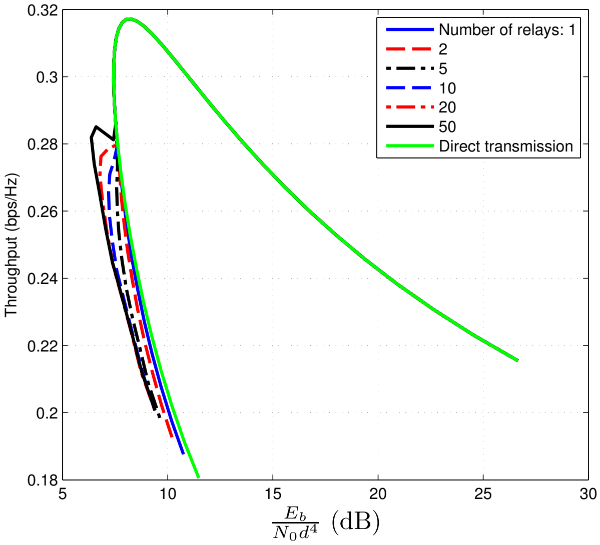

Figure 4.18: SRMAC average energy-throughput tradeoff with a new threshold of -0.0002

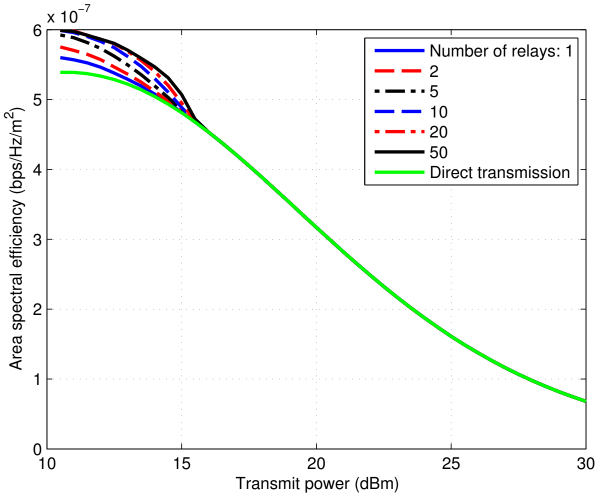

Figure 4.19: SRMAC average area spectral efficiency with a new threshold of -0.0002

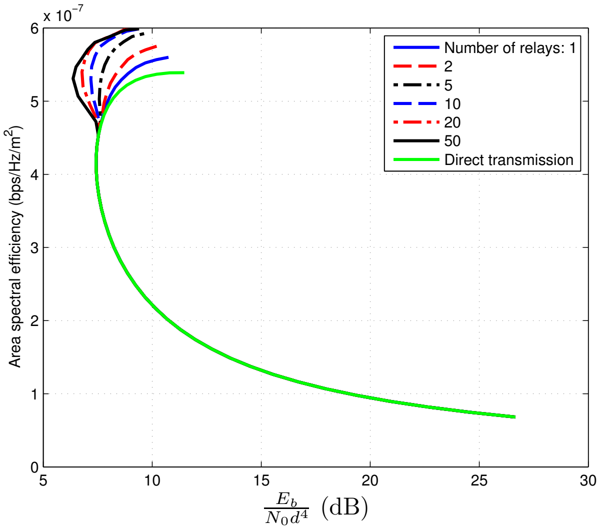

Figure 4.20: SRMAC average energy-area spectral efficiency with a new threshold of -0.0002

CHAPTER V

Conclusions and Future Work

In this thesis, we concentrate on analysis and optimization of relay networks considering both the physical layer and MAC layer. In Chapter II, we propose a model for the performance analysis of relay network considering both the physical layer and the MAC layer. Previous research on relay networks assumed the channel access is granted for the cooperative transmission schemes. However, in reality, multiple transmission requires multiple channel access grants. Because the MAC operations can incur significant overhead in distributed wireless networks, the MAC layer should be accounted for the performance analysis. The energy-throughput tradeoff was investigated considering both the physical layer and the MAC layer. By the tradeoff, it was shown how the transmit power level affect the energy and bandwidth efficiency. Also, the time and energy consumption from the physical layer and the MAC layer was investigated and compared. It was shown that there exists optimal operating points that achieves the maximum throughput or the minimum energy consumption. The optimal operating points can be achieved by using the optimal transmit power levels. Contrary to widely perceived idea, the optimal transmit power levels were neither the minimum transmit power level nor the maximum transmit power level. The better choice between direct transmission and relay transmission depends on the source-destination distance. When the distance is large, relay transmission performs better than direct transmission. Compared to the throughput, the energy efficiency is less sensitive to the source-destination distance. At larger source-destination distance, relay transmission consumes less time and energy than direct transmission compared to the threshold distance for throughput. When the source-destination distance is 1000m, relay transmission achieves more than 100% improvement in throughput and 100% improvement in energy efficiency.

There are several interesting future research direction related to the energy-throughput tradeoff for relay networks. In Chapter II, we used a saturated traffic model which assumes all nodes always have packets to send. However, an unsaturated traffic model can be more realistic. However, the analysis for unsaturated traffic model is not well established while saturated traffic model is well established and widely used. There has been some research activities on unsaturated traffic model such as [18]. Investigation on relay networks with unsaturated traffic model might be an interesting direction to pursue. We also consider an analysis for heterogeneous relay networks. In Chapter II, we assumed that all nodes use the same transmit power. Modeling an analysis framework for relay networks that nodes can use different power level will be an interesting and fruitful research topic.

In Chapter III, we considered the performance analysis and optimization of multi-hop relay transmission. When the source-destination distance is large, using relay transmission performs better than direct transmission. However, increasing the number of hops does not always improve the performance because the number of required transmission and MAC overheads increase accordingly. The energy-throughput tradeoff for different number of hops considering both the physical layer and the MAC layer was compared. For each number of hop case, there were two optimal operating points where the throughput is maximized and the energy consumption is minimized. It was shown that keep increasing the number of hops degrades both the bandwidth and energy efficiency. By theoretical analysis, the transmit power level and the number of hops were jointly optimized for bandwidth efficiency and energy efficiency. Given the assumption that the source-destination distance is very large, it was shown that the optimal transmit power is fixed regardless the source-destination distance. The optimal transmit power level and the optimal one hop distance depends on the physical layer and the MAC layer parameters. Also, it is shown that the optimal number of hops increases linearly with the source-destination distance and the optimal one hop distance is fixed regardless of the source-destination distance. Our numerical analysis confirms this theoretical analysis results.

There are several interesting future research direction for multi-hop relay networks. The MAC protocol and relaying strategy for multi-hop relay network can be an interesting research topic to pursue. In Chapter III, it was assumed that IEEE 802.11 RTS/CTS MAC protocol is used for each hop channel access. However, it requires channel access procedure for each hop. Also, it is assumed that only one packet goes through the relay network rather than spatial reuse strategy. If spatial reuse strategy and multi-hop MAC protocol is jointly designed, it can improve the relay network throughput. Routing can also be combined with relaying strategies. In Chapter III, it was assumed that the relays are located on a straight line with equal distance for each hop. When relays are randomly located, the routing should be accounted for the performance analysis. Also, routing protocol can be optimized to achieve energy efficiency or bandwidth efficiency considering the time consumption and the energy consumption from both the physical layer and the MAC layer.

In Chapter IV, we proposed a new MAC protocol, SRMAC, for cooperative relay communication. There has been no MAC protocol that could support various type of cooperative communication schemes dynamically. Previous MAC protocol for relay networks such as CoopMAC [41] or rDCF [63] assumed that the channel condition between the source, relay, and destination is known to the source from previous communication activities. The source node determines whether relaying is more beneficial than direct transmission using a priori knowledge. However, those assumptions are not realistic in mobile environments. The SRMAC protocol consists of two parts. The first part is the relaying decision. In SRMAC relays decide whether to participate in relaying using the instantaneous channel condition between source, relay, and destination. By overhearing the control packet exchange between the source and destination, relays can estimate the channel from itself to the source and destination. Also, the channel condition information between the source and destination is included in the control packets. Based on the channel conditions, a relay determines whether relaying through itself is more beneficial. The second part is the collision avoidance between control packets from relays. When relaying is beneficial, a relay sends a control packet indicating the fact. However, there can be collisions when there are several relays that improves the performance. The SRMAC employs the random backoff procedure to avoid the collision, which choose a relay for cooperation at random. When there are many relays in the region, a higher threshold for relaying can be adopted. Only relays that can improve the bandwidth efficiency over a certain threshold can participate in relaying. It was shown that the SRMAC improves both the energy efficiency (up to 40%) and bandwidth efficiency (up to 20%).

There are several interesting future research topics related to MAC protocols for relay networks. Because MAC protocol requires signaling for channel reservation, other signaling for relay selection can be combined with the MAC protocols. We assumed random choice of relay in SRMAC. However, as shown in Chapter III, relay network can achieve better performance when the best relay can be chosen. The tradeoff between the amount of relay selection and the performance improvement might be an interesting research to pursue in future. The transmit power optimization can also be combined with MAC layer signaling. In Chapter III, we assumed that all nodes use the same transmit power level. However, when the transmit power level can be optimized for each hop transmission, it can further improve the relay network performance. Other relaying scheme can be also combined with the SRMAC protocol. We assumed decode-and-forward scheme, but other cooperative schemes can be adopted to SRMAC flexibly. Network coding can also be combined with relay network research. As introduced in Chapter III, network coding was shown to improve the two-way relay channel bandwidth efficiency. As peer-to-peer data exchange increases with the proliferation of mobile devices, designing MAC protocols that can support network coding in relay networks will be an interesting future direction to pursue. Analyzing the performance of network coding considering both the physical layer and the MAC layer will allow understanding realistic performance of network coding in relay networks.

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