PERFORMANCE ANALYSIS AND OPTIMIZATION OF CSMA-BASED WIRELESS MESH NETWORKS

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Abstract

Wireless Mesh Networks consist of nodes interconnected by wireless links. User data packets are transported from sources to destinations over paths comprising of multiple wireless links. The functionality underlying nodes in a wireless mesh network consists of selection of paths between sources and destinations of traffic (Routing), coordination of access to the shared wireless medium (Media Access Control (MAC)), and transmission of data packets on the wireless channel (Physical Layer functionality). In most wireless mesh networks currently deployed, these functions follow the IEEE 802.11 standard, also known as "WiFi". In this standard, the MAC protocol is Carrier Sense Multiple Access (CSMA), whereby a node is blocked from transmitting when it senses the medium busy due to transmissions from other nodes in the network. In such networks, the performance is sensitive to both physical layer parameters and routing. In this thesis, we analyze the performance of CSMA-based wireless mesh networks, and determine how to select physical layer parameters and routes, so as to achieve the best performance possible.

The first part of the thesis consists of the development of an analytical model for CSMA-based wireless mesh networks. The model accurately represents all aspects of the CSMA protocol in a multihop network (the effect of blocking, the effect of interference, and the acknowledgement traffic). The model is computationally more efficient than computer simulation models. The accuracy of results obtained by using the model has been verified by comparison to results obtained by using a high-fidelity simulation model. Given the propagation characteristics of wireless links in the network, and the traffic to be carried on these links, the model allows one to determine
whether the traffic load is feasible or not. For a feasible load, it also provides link-related performance measures; namely, the average packet error rate on each link, and the fraction of time that the channel is sensed busy by the transmitter of each link.

The second part of the thesis addresses specifically the performance optimization of CSMA-based wireless mesh networks. Key to achieving the best performance in a wireless mesh network is to maximize the number of transmissions that can take place concurrently in the network (i.e., the degree of spatial reuse of the wireless channel). This requires an optimum setting of physical layer parameters associated with links carrying traffic. The links carrying traffic are determined by the routing function, and the selection of these links is based on the links’ physical layer parameters. Thus, achieving the best performance requires joint optimization of the physical layer parameters and routes. We consider networks in which the signal attenuation between nodes follows a power law function of distance. In that case, the best performance is achieved when routing uses links on which attenuation is in the lowest possible range, as this leads to the highest degree of spatial reuse.
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I am also grateful to my associate advisor, Professor Donald Cox for his valuable comments on this work. I would also like to thank him for allowing me to use a powerful multiprocessor computer belonging to his group for this work. This computation platform was extremely valuable in generating the results in this thesis.

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Chapter 1

Introduction

Network technologies starting from the telephone network to the Internet and the cellular network have revolutionized our lives. The Internet and applications it has made possible such as Internet search engines have changed the way we work, learn, shop and perform a number of other functions.

The telephone network and cellular network primarily designed for supporting voice calls were designed as circuit-switched networks. By circuit-switched we mean that when a user initiates a call, a circuit is established between the source and the destination of the call and resources are reserved along the path. Voice data encoded into bits is transported over the established circuit. Circuit-switching results in a waste of resources when resources reserved for a call are not used (e.g. during silent periods in a conversation). The Internet in contrast was designed to support data applications such as file transfer, web surfing, e-mail, etc., and is based on the principle of packet switching. Information to be transported is encoded into bits and divided into chunks of bits called packets, each of which is appended with routing information such as a source address, a destination address, etc. and transported independently through the network. Packet switching provides the benefit of statistical multiplexing. In contrast to circuit-switching that reserves bandwidth on a link for each flow that uses the link, with packet switching, a link in the network is used on an on-demand basis when a packet corresponding to a flow arrives at the source node of the link. This results in more efficient sharing of network resources between flows.
than that with circuit switching. However, for short packets, the routing information appended to each packet constitutes significant overhead.

Wireless networks provide untethered network connectivity to users. Cellular networks are wireless networks that were originally designed for providing tetherless connectivity to the telephone network to mobile users for the purpose of making and receiving phone calls. These networks consist of base stations that users connect to with their cell phone, base station controllers that aid in tracking user locations, authentication and accounting equipment for verifying user identity and billing, and switching centers that connect a call to its intended destination through the public switched telephone network (PSTN) or other cellular switching centers. Figure 1.1 illustrates the architecture of a cellular network that provides access to the telephone network as well as to the Internet to mobile users. The name cellular network is derived from the concept of a cell - a base station in a cellular network provides coverage over a geographical area that may extend up to a few miles from the base station, referred to as a cell. Cellular network operators spend billions of dollars to acquire the license to use a portion of the radio spectrum over which they provide voice and data services to mobile users. Cells are assigned frequencies such that neighboring cells use different frequency bands from the acquired radio spectrum in order to avoid interference between simultaneously occurring transmissions in neighboring cells. With the acquired radio spectrum being limited, frequency bands in the spectrum are reused by means of assigning the same frequency band to cells that are spaced sufficiently far apart and thus do not cause interference to each other. This is referred to as frequency reuse in cellular networks, and is illustrated in figure 1.1(b) that shows a total of four frequency bands being used throughout the network (each hexagon represents a cell). With the primary goal of supporting phone calls, cellular networks were designed based on circuit-switched technologies. However, with the advent of the Internet and various data applications, there has been an increased demand for data applications such as web access, e-mail on cellular phones. Also, network equipment based on packet-switched technologies originally developed for the Internet has become cheaper and sophisticated enough to also accommodate voice traffic. Thus, with an increased demand for data services and economic benefits of having a single
unified network, cellular networks also provide access to the Internet and are moving towards a packet-switched architecture. The latest cellular network technologies such as Long-term Evolution (LTE) and Worldwide Interoperability for Microwave Access (WIMAX) are based entirely on a packet-switched architecture.

Figure 1.1: Illustration of a cellular network

Just like the telephone network is hierarchical with different levels of switching,
the Internet is hierarchical in nature, consisting of Local Area Networks (LANs) that span individual homes and offices, Metropolitan Area Networks (MANs) that span a larger area such as a city, and Wide Area Networks (WANs) that span geographical areas as large as the entire world and form the backbone connecting LANs and MANs.

Local Area Networks in the realm of the Internet were designed as a network of user stations with wired connections to interconnecting equipment referred to as LAN switches. Although a number of technologies such as Token Rings, FDDI and Ethernet were developed for wired local area networks, Ethernet has emerged as the winner, and wired local area networks today are predominantly based on Ethernet standardized by the IEEE 802.3 working group [1]. Ethernet-based LAN switches today offer connectivity at speeds up to 10 Gbps on each interface, with 40 Gbps and 100 Gbps interfaces on the horizon.

More recently, Wireless Local Area Networks (WLANs) have emerged as a wireless counterpart to wired LANs to provide untethered network connectivity over small geographical areas such as homes, offices, etc. WLANs are packet-switched networks that provide untethered access to the Internet via an entity referred to as an Access Point (AP). The AP has a wired connection to the network infrastructure, and provides high-speed wireless access to the network for users located within a few tens of meters from it as illustrated in figure 1.2. A typical access point with a stock antenna has a range of about 30 meters indoors and about 100 meters outdoors. Wireless LANs use radio frequencies that are part of an unlicensed band, i.e., these frequencies are not regulated by the FCC, use of these frequencies does not require obtaining a license. However, because wireless LANs use frequencies from the unlicensed band and because deployment of wireless LANs is not regulated, a wireless LAN can experience interference from a neighboring wireless LAN that uses the same frequency, affecting its performance. Wireless LANs today are predominantly based on the IEEE 802.11 standard [2]. Access Points and user station network adapters based on IEEE 802.11 chipsets have become extremely cheap over the last few years and can be purchased for less than a hundred US dollars today.

From a deployment perspective, Wireless LANs require a wired connection to the network infrastructure at each access point and each access point only provides limited
coverage over a short range on the order of a few tens of meters. Providing wireless network connectivity over a larger geographical area requires deploying several access points, with a wired network infrastructure providing wired network connectivity to each access point. The wired network infrastructure that allows exchange of data between access points is referred to as the Distribution System. For environments that lack such a wired infrastructure or for applications in which network nodes may be mobile, Wireless Mesh Networks have been developed an alternative to provide extended network coverage using network entities that communicate with each other over the wireless medium instead of a wired infrastructure. In other words, mesh networks use a wireless distribution system. These networks are comprised of nodes referred to as Mesh Points (MPs) that establish wireless links between them, participate in path discovery, and forward data along paths consisting of multiple wireless links. Nodes in the network that have a wired connection to the network infrastructure are referred to as Mesh Point Portals (MPPs) or gateways. Data destined to addresses outside the mesh network are routed via one of these gateway nodes. Nodes that also serve end-users in addition to forwarding data in the mesh have colocated Access Point functionality and are referred to as Mesh Access Points (MAPs). User stations connect to the network by associating over the wireless channel with a Mesh Access Point within communication range in an identical manner as they would connect to a Wireless LAN. Mesh networks can be used to provide network connectivity in a
wide range of deployments such as residential communities, campuses, cities, military environments, emergency operations, sensor networks, etc. When used to provide network connectivity in cities, a mesh network can be viewed as a wireless MAN. Figure 1.3 illustrates a wireless mesh network. Following the popularity of IEEE 802.11 based Wireless LANs and the availability of low-cost IEEE 802.11 equipment, the IEEE 802.11 standard has been widely adopted for use in wireless mesh networks as well. Task group ‘s’ of the IEEE 802.11 working group has been actively working on adding mesh capabilities to the IEEE 802.11 standard. Their work is currently published as a draft version of a mesh networking amendment to the standard, which will be incorporated into the IEEE 802.11 standard once approved [3].

![Diagram of a Wireless Mesh Network](image.png)

Figure 1.3: Illustration of a Wireless Mesh Network

From a historical perspective, it is interesting to note that the concept of connecting computer terminals to a central entity as in wireless LANs was first used in 1970
1.1. WIRELESS MESH NETWORK FUNCTIONS

in the ALOHA system at University of Hawaii in order to connect computing systems at different locations of the university to a central computer at the main campus [4]. Similarly, the concept of forwarding data between users over multiple wireless hops was first used in Packet Radio Networks in the 1970s [5]. Packet Radio Networks were developed under the sponsorship of the Defence Advanced Research Projects Agency (DARPA) for military and government applications. Proprietary versions of packet radio networks were implemented by corporations in industries such as the shipping industry to provide a competitive advantage.

In recent years, the widespread use of mobile computers and handheld devices and the demand for wireless network connectivity on these mobile devices has created a demand for Wireless LANs and wireless mesh networks. The standardization of such networks by the IEEE 802.11 working group and availability of low-cost IEEE 802.11 based devices has contributed to widespread deployment of such networks. IEEE 802.11 Wireless LANs are deployed at homes, hotels, restaurants, coffee shops, airports and other public places all over the world. IEEE 802.11 based mesh networks have been deployed in several cities around the world - Mountain View, California (the "Google WiFi" network [6]), Austin, Texas [7], and Chaska, Minnesota [8] to name a few.

This thesis focuses on the optimization of the performance of wireless mesh networks. We first provide necessary background by briefly reviewing the functionality underlying nodes in a wireless mesh network. We then describe the differentiating characteristics of wireless mesh networks that make them very different from wired networks, and the resulting complexities and challenges in designing and operating such networks. Finally, we describe the goals and contributions of this thesis with respect to addressing some of these challenges.

1.1 Wireless Mesh Network Functions

Wireless mesh networks differ from wired networks mainly due to the broadcast nature of the wireless medium. A transmission on the wireless medium is received by all nodes in the neighborhood of the transmitter at certain power levels, resulting in
interference to simultaneously occurring transmissions on the same frequency in the neighborhood of the transmitting node.

The functionality underlying nodes in a wireless mesh network is based on a layered architecture as in wired networks. The functionality mainly comprises transmission and reception of data over the wireless channel (referred to as Physical Layer), coordination of access to the shared wireless medium (referred to as Media Access Control (MAC) layer), and selection of paths between nodes in the network (referred to as Routing).

1.1.1 Physical Layer

The physical layer pertains to transmission of data packets on the wireless channel by means of functions called Modulation and Coding. Modulation refers to the process of varying the amplitude, frequency and/or phase of a radio carrier signal with the information to be transmitted. Coding involves adding redundancy to the information so that it can be correctly retrieved even if parts of the received signal are corrupted.

As a transmitted electromagnetic wave propagates through the wireless medium, it is attenuated and experiences reflection, scattering and diffraction from objects in the environment such as buildings, walls, furniture, etc. The ultimate details of this propagation can be obtained by solving Maxwell’s equations with boundary conditions that express the physical characteristics of the obstructing objects. Since these calculations are difficult, and many times necessary parameters are not available, approximations such as ray-tracing techniques are used as an alternative. Ray-tracing techniques consider all possible paths between the transmitting and receiving antennas, and determine the reflection and refraction effects experienced along these paths, while ignoring more complex scattering phenomena predicted by Maxwell’s coupled differential equations. However, most communication systems operate in complex propagation environments in which even accounting for all paths between the transmitter and receiver is impractical. Thus, a number of empirical models have been developed that characterize the propagation of radio waves in terms of three components -
• **Path Loss**: This captures the attenuation in the strength of a signal as a function of distance as the signal travels through space. For a signal transmitted with power $P_t$, the signal power $P(d)$ at distance $d$ from the transmitter is typically modeled to be $K\frac{P_t}{d^\gamma}$ where $\gamma$ is referred to as the *path loss exponent* and has a value between 1.6 and 7 depending on the particular propagation environment. For outdoor wireless networks, measurement studies using frequencies in the 2.4 to 5 GHz range have shown the path loss exponent to be between 2 and 4 [9, 10, 11]. In the case of indoor environments, measurements in the 5GHz band have shown the path loss exponent to be in the range of 1.3 to 2.4 for corridor-to-corridor (or line-of-sight) communication, 2.9 to 5.0 for room-to-corridor communication, and 4.1 to 7 for room-to-room communication [12, 13, 14, 15, 16]. The value of the path loss exponent depends on the nature of the obstructions between the transmitter and the receiver. For example, in indoor environments, the value of the path loss exponent depends on the material used in the construction of walls. Effect of different types of walls, floors, etc. on radio propagation can be found in [17].

• **Shadowing**: While path loss reflects how much the signal attenuates as a function of the distance between the transmitter and the receiver, the actual power received at distance $d$ differs from $K\frac{P_t}{d^\gamma}$. This fluctuation has two components. One of the components is fluctuations due to the presence of large objects such as walls or furniture obstructing the signal path and is referred to as *Shadowing* or *Large Scale Fading*. Shadowing is typically modeled as a random variable with a log-normal distribution.

• **Multipath fading**: The other component of fluctuation in received signal power is due to multipath propagation of the radio signal. The receiver receives several copies of the transmitted signal, each copy having taken a different path through space and reflected off different surfaces. These copies arrive at the receiver with different phases and delays, and the instantaneous signal power is determined by how these copies with different phases combine at the receiver.
CHAPTER 1. INTRODUCTION

Any relative movement between the transmitting and receiving nodes and the environment changes the phases of the signal copies at the receiver, resulting in a change in received signal power. Sometimes, a small relative movement can result in a drastic change in received signal power. This phenomenon of relatively fast changes in received signal power is referred to as *Multipath Fading* or *Small Scale Fading*. The term small scale reflects the fact that fluctuations can occur at time scales comparable to, or even less than, the packet transmission time.

A key metric in a communication system is the rate at which the transmitter can transmit information to the receiver. This rate is a function of the received signal power at the receiver, and the level of background noise and interference (power received from transmissions occurring at the same time and on the same radio channel in the vicinity of the receiver that are not destined to it).

Physical layer implementations support a range of transmission rates, referred to as PHY rates, in order to support wireless links with different propagation characteristics. These different rates are achieved by using different levels of modulation and coding. Consider for example the IEEE 802.11 Orthogonal Frequency Division Multiplexing (OFDM) physical layer, also referred to as the IEEE 802.11a/g physical layer (since the specification was developed by the IEEE 802.11a and IEEE 802.11g working groups - IEEE 802.11a used the 5GHz band whereas IEEE 802.11g used the 2.4GHz band). In OFDM, the channel bandwidth is divided into narrower subcarriers. Data to be transmitted in a packet is divided into OFDM symbols, each symbol consisting of a certain number of bits. One OFDM symbol is modulated onto each subcarrier using M-QAM (M Quadrature Amplitude Modulation) modulation in which information to be transmitted is encoded in both the amplitude and phase of the subcarrier. Symbols comprised of $\log_2 M$ bits each correspond to one of $M$ points in the space composed of the dimensions of amplitude and phase. The information to be transmitted is encoded with redundant information so as to be able to recover the original data even if parts of the packet are received in error. The number of actual data bits to the total number of bits after adding redundant bits is referred to as the *coding rate*. OFDM uses a rate $\frac{1}{2}$ convolutional encoder. Higher coding rates of $\frac{2}{3}$.
and \( \frac{3}{4} \) are achieved by puncturing the encoded bitstream i.e., removing bits according to a regular pattern known to the transmitter and receiver. Table 1.1 shows the different physical layer rates supported by the IEEE 802.11 OFDM physical layer, and the modulation techniques, coding rates corresponding to each supported rate. Higher physical layer rates use higher values of \( M \) and thus require a higher Signal to Interference plus Noise Ratio (SINR) at the receiver since higher \( M \) reduces the spacing between the \( M \) points.

<table>
<thead>
<tr>
<th>PHY rate (Mbps)</th>
<th>Modulation</th>
<th>Coding rate ( C_R )</th>
<th>Coded bits per subcarrier ( N_{BPSC} )</th>
<th>Coded bits per OFDM symbol ( N_{CBPS} )</th>
<th>Data bits per OFDM symbol ( N_{DBPS} )</th>
</tr>
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<tr>
<td>6</td>
<td>BPSK</td>
<td>1/2</td>
<td>1</td>
<td>48</td>
<td>24</td>
</tr>
<tr>
<td>9</td>
<td>BPSK</td>
<td>3/4</td>
<td>1</td>
<td>48</td>
<td>36</td>
</tr>
<tr>
<td>12</td>
<td>QPSK</td>
<td>1/2</td>
<td>2</td>
<td>96</td>
<td>48</td>
</tr>
<tr>
<td>18</td>
<td>QPSK</td>
<td>3/4</td>
<td>2</td>
<td>96</td>
<td>72</td>
</tr>
<tr>
<td>24</td>
<td>16-QAM</td>
<td>1/2</td>
<td>4</td>
<td>192</td>
<td>96</td>
</tr>
<tr>
<td>36</td>
<td>16-QAM</td>
<td>3/4</td>
<td>4</td>
<td>192</td>
<td>144</td>
</tr>
<tr>
<td>48</td>
<td>64-QAM</td>
<td>2/3</td>
<td>6</td>
<td>288</td>
<td>192</td>
</tr>
<tr>
<td>54</td>
<td>64-QAM</td>
<td>3/4</td>
<td>6</td>
<td>288</td>
<td>216</td>
</tr>
</tbody>
</table>

\[
\text{PHY rate} = C_R \times \frac{N_{BPSC}}{\text{symbol}} \times \frac{1}{\text{symbol}} \times 48 \text{ carriers} \times \frac{1}{4\mu s}
\]

Table 1.1: Data rates supported by the IEEE 802.11 OFDM PHY and the modulation schemes, coding rates used

Figure 1.4 shows for a wireless link in isolation (i.e., in the absence of interference), the relationship between Signal to Noise Ratio (SNR) at the receiver and the packet error rate for the different data rates provided by the IEEE 802.11a physical layer specification [18]. These relationships have been obtained by simulating transmission and reception of packets as per the IEEE 802.11a physical layer specification, and averaging over the outcome of thousands of transmissions. The wireless channel between the transmitter and receiver is assumed to be as per the European Telecommunications Standards Institute (ETSI) Channel A model that specifies the power-delay profile for 18 multipath components based on empirical measurements in
a Non Line Of Sight (NLOS) indoor environment. Fading realizations are generated from the power-delay profile, and each transmission is considered to experience a fading realization selected randomly with uniform probability from the range of fading realizations.

It can be seen that generally higher PHY rates require a higher SNR in order to achieve a certain packet error rate, with PHY rates of 9 Mbps and 18 Mbps behaving as anamolies to this trend. The performance in PER for 9 Mbps is worse than that of 12 Mbps for all SNR values, the PER performance of 18 Mbps is worse than that of 24 Mbps for SNR values greater than about 20 dB. When the SNR is sufficiently high to allow a high data rate modulation to operate satisfactorily, the degrading effect of the high code rate (\(\frac{3}{4}\)) in a lower data rate mode becomes dominant enough to cause the lower data rate mode to be outperformed by the higher data rate mode in which a low code rate (\(\frac{1}{2}\)) is employed. This anamoly makes it undesirable to operate a wireless link at IEEE 802.11 OFDM PHY rates of 9 Mbps and 18 Mbps.

Figure 1.4: Packet Error Rate for various data rates - IEEE 802.11 OFDM PHY, ETSI Channel A Model, MAC Frame Size = 1528 Bytes
1.1. WIRELESS MESH NETWORK FUNCTIONS

With support for variable transmit power and a range of data rates at the physical layer, important aspects of network operation include estimation of propagation characteristics between nodes in the network, appropriately choosing the transmit power and data rate on each link taking into account interactions between links, and adapting the transmit power and data rate with changes in propagation characteristics. The performance of the network is significantly impacted by the transmit powers and data rates used on links in the network.

1.1.2 Media Access Control (MAC) Layer

The wireless medium is inherently broadcast in nature. A transmission on the wireless medium is received by all nodes in the neighborhood of the transmitter at certain power levels, resulting in interference to transmissions on the same frequency occurring at the same time in the neighborhood. Thus, access to the shared broadcast medium has to be coordinated in order to avoid transmission on a link from occurring at the same time as that on a neighboring link. This is the role of the Media Access Control layer. Interference between neighboring wireless links can be reduced or avoided by separating their transmissions in at least one of the following dimensions:

- **Time:** Separation of transmissions on links in time can be achieved by the following mechanisms -

  - Using a fixed time schedule that specifies the set of links that can transmit at a given time.
  - Polling, in which a central entity polls nodes and assigns transmission times to nodes based on their traffic requirements.
  - Having nodes make reservations for transmitting on the medium in a distributed manner.
  - Using a random access protocol such as Carrier Sense Multiple Access (CSMA) in which each node looks for idle times on the channel to undertake its transmissions, refraining from transmitting when it senses the channel to be busy. A node considers the channel to be busy when it senses
an energy level that exceeds a threshold referred to as the *Energy Detect Threshold (ED Threshold)* or when the node is able to synchronize to the carrier of an ongoing transmission. Despite carrier sensing, a transmission by a node $X$ can experience a collision with another transmission due to the following possibilities -

* Node $X$ and another node $Y$ start transmitting at the same time before they sense each other’s transmissions.
* Node $X$ is outside the sensing range of a node $Y$ located in the vicinity of its intended receiver and thus node $X$ cannot sense transmissions by node $Y$ (the range from a transmitting node within which the medium is sensed busy by nodes is referred to as the sensing range or the hearing range). In that case, node $X$ can start transmitting when node $Y$ is also transmitting on the medium.
* A node $Y$ located in the vicinity of $X$’s intended receiver is outside the sensing range of node $X$, and can thus start transmitting during the transmission by node $X$.

If a transmitting node does not receive an acknowledgement from its intended destination in a certain time period, it perceives its transmission to be unsuccessful either due to a collision or due to channel errors, and contends for the channel again to retransmit the packet.

- **Frequency**: Wireless links located near each other may be made to operate on non-overlapping radio channels and thus not interfere with each other. Separating transmissions by multiple users in the frequency domain, allowing them to occur simultaneously in time is referred to as Frequency Division Multiple Access (FDMA). Multiple non-overlapping radio channels may be used in the network to reduce the number of links in a neighborhood sharing a radio channel. An important problem to be addressed in that case is intelligent assignment of these radio channels to links to achieve the best performance while satisfying the constraints of the number of radios at each node. With the number of radio channels being limited, sharing of a radio channel by a set of neighboring links
that interfere with each other is inevitable and transmissions on these links have to be separated in time as described earlier.

- **Space:** Interference between links can be reduced by confining the radio signal from a transmitter to a narrow geographical region and directing it towards its intended receiver by means of technologies such as beamforming or directional antennas. These technologies may be used in conjunction with random-access or reservation-based MAC protocols in mesh networks to reduce interference between links.

- **Code:** Finally, interference between links may also be avoided by spread-spectrum signaling using orthogonal codes on links that interfere with each other. Transmissions using orthogonal codes may overlap in time with little or no effect on each other. Allowing multiple users to transmit simultaneously on a shared channel by using a different code for each user’s transmission is referred to as Code Division Multiple Access (CDMA). Assignment of codes in a mesh network may be done using either a receiver-directed approach or a transmitter-directed approach. In the receiver-directed approach, each receiver is assigned a distinct code and transmitters must use the code assigned to the intended receiver. In a transmitter-directed approach each node is assigned a distinct code that it uses to encode its transmissions, the preamble contains information on the spreading waveform used, allowing the receiver to program its matched filter accordingly. The use of spread-spectrum is uncommon in wireless mesh networks, these networks typically use narrow-band signaling.

Regardless of use of technologies such as multiple channels, beamforming and directional antennas, separating transmissions on links that interfere with each other in time is key to the operation of mesh networks. This constitutes the function of the MAC layer. Among the various approaches described above to separate transmissions on neighboring links in time, CSMA is the most widely adopted approach. Most wireless mesh networks currently deployed are based on the IEEE 802.11 standard and use the Distributed Coordination Function (DCF) defined in this standard for
medium access. DCF is a random-access protocol based on CSMA. We provide here a brief overview of CSMA and its predecessor random-access protocol ALOHA.

Random Access Protocols

Two classes of random access protocols were developed in the late 1960s and early 1970s in the context of packet radio networks. One random access scheme, referred to as ALOHA, introduced by Abramson in 1970 is based on a user $i$ having a packet to transmit randomly choosing a time $t$ to transmit the packet [4]. The user transmits at time $t$ regardless of the state of the channel at that time. If another user is transmitting on the channel at time $t$ or if another user starts transmitting on the channel during $i$’s transmission, these overlapping transmissions experience interference from each other. The author of [4] considers traffic from $k$ users, each user having an average rate of transmissions $\lambda$ packets per second, with $\tau$ being the time occupied on the medium for each packet transmission. The author shows that the maximum channel utilization $(k\lambda \tau)$ that can be achieved with ALOHA is 0.18. A modification of this protocol called Slotted ALOHA was proposed by Roberts in 1972 [19]. In slotted ALOHA, time is divided into slots, duration of a slot being equal to the time occupied by a single packet transmission on the medium (all packets occupy a fixed amount of time on the medium). Nodes contend for medium access and start transmitting only at slot boundaries. The maximum channel utilization (as defined above) that can be achieved with Slotted ALOHA is 0.36 [19].

The fact that a node using ALOHA transmits at its randomly chosen transmission time regardless of the state of the channel can lead to a significant rate of collisions in a system with a large number of nodes and high traffic load at the nodes, limiting system throughput. If at the time chosen for transmission by a node $i$, a transmission by another node is taking place on the channel, it is wasteful of resources for node $i$ to transmit, thereby reducing the likelihood of both it’s own transmission and the ongoing transmission to be received successfully. Carrier Sense Multiple Access (CSMA) is based on the principle ”Do not talk if you hear someone else talking” [20]. A node refrains from transmitting on the channel at times when it senses the medium to be busy, thereby reducing collisions and improving system throughput.
1.1. WIRELESS MESH NETWORK FUNCTIONS

compared to ALOHA. The authors of [20] consider a traffic source consisting of an infinite number of users within sensing range of each other, who collectively form an independent Poisson source with an aggregate mean packet generation rate of \( \lambda \) packets/second. Each packet occupies time \( T \) on the medium. The authors show that the maximum channel utilization (\( \lambda T \)) that can be achieved with CSMA ranges from 0.8 to 1.0 when the ratio of propagation delay between a pair of nodes to packet transmission time is much smaller than 1, as is the case in radio networks. CSMA has been very widely adopted as a medium access protocol in both wired and wireless networks. It forms the basis of both the IEEE 802.3 Wired LAN standard (referred to as Ethernet) [21, 1], and the IEEE 802.11 Wireless LAN standard [2].

Collisions

Random access protocols such as ALOHA and CSMA are vulnerable to collisions, i.e. simultaneous transmission on the medium by more than one node. ALOHA in particular is very prone to collisions since a node transmits on the channel at its randomly chosen time even if there is an ongoing transmission on the channel at that time. With CSMA, in the case of single-hop networks where each node can sense all other nodes’ transmissions, a collision can occur if two or more nodes start transmitting at about the same time before they sense each other’s transmission. The probability of such collisions can be significant with a large number of users with a high traffic load. Moreover, if the network consists of one or more pairs of nodes such that one node cannot sense transmissions by another node given the propagation characteristics between the nodes and the transmit powers used, then physical carrier sensing cannot prevent such pairs of nodes from colliding on the medium. This is known as the Hidden Node Problem. For example, in a single-hop wireless LAN, although all nodes are within communication range of the access point, there may be nodes that are not within carrier sensing range of each other. Multihop wireless networks such as wireless mesh networks by definition consist of nodes that are far apart and not within carrier sensing range of each other. Figure 1.5 illustrates the hidden node problem. Nodes \( A \) and \( C \) cannot sense each other’s transmissions, Node \( A \) is a hidden node with respect to node \( C \) and vice-versa. Node \( A \) can start transmitting to node \( B \) during an ongoing transmission by node \( C \). Similarly, node
C can start transmitting during a transmission from node A to node B.

![Figure 1.5: Hidden node problem in CSMA-based wireless networks](image)

In wired local area networks, CSMA is used along with collision detection (referred to as CSMA/CD). A node can detect transmissions by other nodes even when it is itself transmitting. When a transmitting node detects another node’s transmission, it aborts its transmission and retries after a random period of time. To ensure that collision detection is possible before the end of transmission of a frame, the IEEE 802.3 standard requires that a packet be no smaller than a minimum packet size of 64 bytes, which is the number of bits transmitted in a single slot of duration two times the maximum propagation delay on the Ethernet cable. In contrast, nodes in a wireless multiple access system operate in a half-duplex fashion. When a node is transmitting on the medium, the power level of the transmitted signal is significantly higher than any received signal due to attenuation of the received signal with distance. This makes it impossible to receive data on the same frequency as that on which the node is transmitting. Hence, when a node is transmitting on the medium, its receiver is typically shut off. Thus, collision detection is not possible, and collision avoidance mechanisms are used instead.

**Collision Avoidance**

Both ALOHA and CSMA have been appended with collision-avoidance mechanisms [22, 23, 24]. CSMA when coupled with collision avoidance is referred to as CSMA/CA. The AppleTalk protocol in wired networks uses CSMA/CA [25]. The
basic idea of collision avoidance is to have users contend for the medium by transmitting small control packets, and once a user has succeeded in contention, the user can transmit data free of contention. This is very beneficial for large data packets, since the benefit of avoiding wasteful use of the medium for long transmission time when a collision occurs outweighs the price paid in terms of overhead introduced by the small control packets.

Busy Tone Multiple Access (BTMA) is a CSMA-based medium access control protocol with collision avoidance [24]. In BTMA, the channel bandwidth is divided into two channels (i) Message channel and the (ii) Busy Tone channel. As long as a node detects the message channel to be busy, it transmits a pure sinusoid busy tone signal on the busy tone channel. A node considers the message channel to be idle for its transmission only if it senses the message channel to be idle and it does not hear any busy tone on the busy-tone channel. Thus, in the above example, node A will not start a transmission to node B during an ongoing transmission by node C because it will hear a busy tone from node B during this time. Similarly, node C will hear a busy tone from node B during the transmission from node A to node B and will refrain from starting a transmission during this time.

With a variety of medium access control schemes to coordinate transmissions, the performance of a wireless mesh network depends on the particular MAC protocol used in the network. Most wireless mesh networks currently deployed use the IEEE 802.11 Distributed Coordination Function (DCF) based on CSMA for medium access. A lot of effort in the research community has been focused on development of MAC protocols based on reservations, motivated by wanting to avoid collisions that are cited as a reason for significant loss in network throughput with the use of CSMA [26, 27, 28, 29, 30, 31]. The IEEE 802.11s amendment to the IEEE 802.11 standard also includes an optional media access control scheme based on distributed reservations, referred to as Mesh Coordinated Channel Access (MCCA). With different options for MAC layer protocols, one needs to understand the different performance aspects of these MAC protocols in order to select an appropriate MAC protocol for use in a mesh network.
1.1.3 Routing

Since wireless mesh networks involve forwarding data between nodes that are not within communication range of each other over multiple wireless links, selection of paths between sources and destinations and traffic or routing constitutes an important functionality of wireless mesh networks.

Path selection in wireless mesh networks typically follows the paradigm of shortest path routing as is done in wired networks due to ease of distributed operation. Several routing protocols have been proposed for use in wireless mesh networks. These protocols are of two types -

- **Proactive** routing protocols that maintain routes between each pair of nodes at all times. For example, the Optimized Link State Routing Protocol (OLSR) is a proactive routing protocol [32]. As the name suggests, OLSR is a link-state protocol i.e., information about links (link state information) is disseminated throughout the network. Each network node equipped with knowledge of links in the network computes routes from itself to all other nodes in the network.

- **Reactive** or **On-demand** routing protocols that attempt to establish a route from a source node to a destination node only when the source has traffic to send to the destination. For example, the Ad-hoc On-demand Distance Vector (AODV) is an on-demand protocol that computes routes in an on-demand fashion using shortest path routing [33]. A node that needs to discover a route to a particular destination transmits a broadcast Route Request (RREQ) message with a hop count of zero and a RREQ ID. The RREQ message is flooded throughout the network - each node other than the destination that receives the RREQ increments the hop count in the message and broadcasts the modified RREQ message. Information about the originator of the request and RREQ ID are used to filter duplicate RREQ messages that a node receives from different neighbors. A node receiving a RREQ message also records a route to the originator of the RREQ with next hop being the neighbor from which the RREQ was received with the lowest hop count. When the destination receives
1.1. WIRELESS MESH NETWORK FUNCTIONS

the RREQ message, it transmits a Route Reply (RREP) destined to the originator of the RREQ via the next-hop towards the originator (the neighbor from which it received the RREQ with the lowest hop count). The RREP contains a hop count field which is set to zero by the destination. Each node receiving the RREP as the next hop towards the RREQ originator increments the hop count and forwards the RREP to its next hop towards the RREQ originator. The originator of the RREQ records the node that it receives the RREP from as its next hop towards the destination, the hop count in the received RREP represents the lowest distance in number of hops to the destination.

While the base specifications of OLSR and AODV use hop count as the link metric for routing (each link represents one hop and thus has a cost of 1), these can be augmented to use a different additive link metric.

For wireless mesh networks being standardized by the IEEE 802.11 working group, the IEEE 802.11s mesh networking amendment specifies a flexible framework in which any routing metric and any routing protocol may be used in the network. However, only one routing protocol and one routing metric can be used at any time, and mesh points have to agree on these as part of procedure for establishing links between them. IEEE 802.11s specifies a default routing protocol called Hybrid Wireless Mesh Protocol (HWMP) and a default routing metric called the Air Time Metric that represents the time occupied on the wireless medium for successfully transmitting a packet of a certain nominal size. HWMP is based on constructs borrowed from the AODV protocol, and allows two modes of operation. In one mode called the tree mode, all mesh points establish the shortest path to a certain root node in the network based on the metric used, data between any two mesh points is forwarded through the root. In the other mode called the proactive mode, a source determines the shortest path to the destination based on the metric used.

While routing protocols differ in their mechanisms for computing routes and propagating link and route information through the network, central to all shortest-path routing protocols is the link metric used. The link metric determines the actual routes used between source-destination pairs and heavily influences the performance of the mesh network. While routing in wired networks simply uses the inverse of the
bandwidth of a link as its metric, the link metric in wireless mesh networks needs to account for the complex characteristics of the wireless link and the interactions between links in order to achieve good performance.

1.2 Characteristics of Wireless Mesh Networks

As can be inferred from the above section, wireless mesh networks are very different from wired networks in aspects that are summarized below:

- Due to the broadcast nature of the wireless medium, transmission on a link in a wireless mesh network interferes with transmissions on neighboring links that occur at the same time and use the same frequency. Thus, transmissions on the medium have to be coordinated so as to avoid simultaneous transmissions on neighboring links that interfere with each other.

- In contrast to a wired link which allows data transmission at a deterministic rate when functional, the data rate that can be supported on a wireless link between two nodes is influenced by several factors. The data rate that can be supported on a link in a wireless mesh network with a low probability of packet error is determined by the signal strength at the receiving node, the level of background noise, and the level of interference power at the receiving node from transmissions in its vicinity occurring at the same time on the same radio channel. In particular, the data rate that can be supported is determined by the Signal to Noise plus Interference Ratio (SINR) at the receiving node. The signal strength at the receiver is a function of the transmission power used, and propagation characteristics between the transmitting node and the receiving node. The interference power received at the receiver from a node in its vicinity transmitting at the same time is determined by the transmit power used by the interfering node and the propagation characteristics from the interfering node to the receiver. The signal power received at the receiver changes over time in unpredictable ways due to relative movement in the environment, and can vary drastically with very small relative movement. Since interference is due
to data transmissions on other links, the level of interference experienced by
transmissions on a link is not deterministic and can vary from one transmis-
sion to another depending on which transmissions overlap and the propagation
characteristics from the source of the interfering transmission to the receiver of
the link under consideration.

• The broadcast nature of the wireless medium results in interactions between
links in a mesh network. In contrast to wired networks in which the through-
put of a link is totally independent of traffic being carried on other links, the
throughput of a link in a wireless mesh network depends on the physical layer
parameters (viz. transmit power, data rate and ED threshold) used on the link
as well as the physical layer parameters used on links in its neighborhood, and
the level of activity on these links.

1.3 Thesis motivation and goals

The above characteristics of wireless mesh networks makes the design and operation
of a wireless mesh network complex. In particular, the following issues need to be
addressed -

• How to coordinate access to the wireless medium between links to avoid simulta-
nceous transmissions on links that interfere with each other? While wireless mesh
networks currently deployed mostly use CSMA for medium access, alternative
medium access protocols have been developed based on dynamic conflict-free
reservations [26, 27, 28, 29].

• How to choose the physical layer parameters on links in the network, viz. trans-
mits power, PHY rate and the energy detect threshold. Propagation characteris-
tics of each link and the interactions between links have to be taken into account
in selecting the physical layer parameters to maximize network throughput. In
single-hop wireless LANs with nodes transmitting to a central access point, only
one successful transmission to/from the access point can take place at any time.
Obviously network throughput is maximized by using for each transmission the
maximum transmit power permissible and the highest data rate achievable at this transmit power with a low error rate. However, in a wireless mesh network, aggregate network throughput depends not only on the throughput achieved on each link, but also on the degree of spatial reuse i.e. simultaneous transmissions on multiple links at the same time. Higher data rates require a higher SINR at the receiving node for a low packet error. Higher SINR values require a higher transmit power and/or lower ED threshold (more blocking), resulting in reduced spatial reuse. Thus, the benefit of using high transmit power and high PHY rate on a link in terms of throughput of that link has to be weighed against the reduction in spatial reuse.

- How to select routes between sources and destinations of traffic flows, taking into account interactions between links used in order to achieve good network throughput.

The work in this thesis is motivated by the need to improve the performance of wireless mesh networks. Given an environment in which a wireless mesh network is to be deployed, the performance of the network depends heavily on its configuration and the protocols used in the network. Configuration includes network design aspects such as the number of nodes to be deployed and their locations, as well as selection of physical layer parameters on links in the network (viz. Energy Detect Threshold, Transmission Power, Transmission rate). Protocols used in the network include the MAC protocol and the routing protocol.

We focus on IEEE 802.11 based wireless mesh networks due to their widespread deployment. We consider IEEE 802.11 based mesh networks that use CSMA-based DCF for medium access, since such networks constitute a large majority of currently deployed mesh networks. An overview of the IEEE 802.11 standard can be found in Appendix A. We study the performance of such CSMA-based mesh networks with respect to the PHY parameter configuration and routing aspects. Due to the broadcast nature of the wireless medium, there are interactions between links in a CSMA-based mesh network in the form of blocking and interference. The throughput of a link in a wireless mesh network depends not only on its PHY parameter settings,
1.3. THESIS MOTIVATION AND GOALS

but also on the PHY parameter settings of links in its neighborhood and the rate of traffic on these links. The routing function, in particular the routing metric used, determines the amount of traffic carried by each link in the network. In this thesis, we seek to maximize the end-to-end capacity of CSMA-based wireless mesh networks by jointly optimizing PHY parameter settings and routing. This is in contrast to prior work that has either addressed selection of routes given PHY parameter settings, or selection of PHY parameters given distribution of traffic on links.

Performance of mesh networks can be evaluated by experimentation on a real test-bed or by simulation or by using an analytical model, each of these methodologies has its own benefits and disadvantages. Experimentation on a test-bed provides “real” results that cannot be doubted. However, it requires a large amount of monetary and manpower resources to build and maintain a test-bed that is large enough to yield useful results. Moreover, analysis performed by experimentation on a test-bed is restricted by the size of the test-bed, its particular topology, and its environment, providing little flexibility in studying larger networks and networks with different topologies and/or environments. Simulation tools tend to mimick the functionality in a real network and results from simulations can be made very reliable by using realistic environment and device models in the simulator. However, simulation of large mesh networks have proven to be very computation-intensive and time-consuming [34, 31].

Analytical models can provide performance results faster than simulations with relatively lower amount of computation power, and at the same time provide useful insight into system behavior. However, analytical modeling of CSMA-based wireless mesh networks is a challenging task due to the complex interactions between links in such a network. An analytical model must satisfy a number of requirements in order to be useful and accurate. Since the appropriate transmission power and PHY rate for a link depends on its propagation characteristics and is likely to be different for different links, the analytical model must be able to accommodate different transmission power and PHY rate settings on different links. In order to be accurate, an analytical model has to properly account for the complex relationships between links. It is important to properly account for blocking relationships between links, the model should properly account for possible asymmetric blocking between link pairs and blocking due to
cumulative energy received from simultaneously occurring transmissions. Similarly, it is also important to properly account for interference, not only that due to overlap with individual transmissions, but also interference due to simultaneous overlap with multiple transmissions. It is also important to account for the presence of ACKs. ACKs not only occupy time on the medium, but can interfere with data transmissions resulting in a higher packet error rate for data transmissions than if ACKs were ignored. Moreover, ACKs can also experience errors, resulting in more retransmissions of data than if ACKs were assumed to be free of errors.

In this thesis, we take the approach of using an analytical model as a performance evaluation tool in our goal of optimizing the performance of CSMA-based wireless mesh networks. However, all previously proposed analytical models for CSMA-based wireless mesh networks proved to be inadequate for our work because of being limited in one or more of the following aspects - (i) Scalability to large networks (ii) Applicability to a network with any physical layer parameter configuration on links (due to system assumptions that the model is based on, such as use of the same transmit power and/or data rate on all links) (iii) Accuracy of their results (due to modeling assumptions used in the model)

We develop an analytical model for CSMA-based wireless mesh networks that is not limited in any of the above important aspects and serves as a powerful tool for evaluating the performance of such networks.

1.4 Thesis outline and contributions

In Chapter 2, we develop our analytical model for performance analysis of CSMA-based wireless mesh networks. The model overcomes all limitations of prior work mentioned in the previous section, and has the following key features:

- The model is general in the sense that it can be used to analyze networks with any physical layer parameter values (ED Threshold, Transmit Power, PHY Rate)

- The model is accurate. It captures all complex characteristics of an IEEE
1.4. THESIS OUTLINE AND CONTRIBUTIONS

802.11 mesh network. It also uses a realistic receiver model. Whether a packet is received in error is represented as a probabilistic function of the SINR during its reception.

- The model is scalable, and can be used to analyze large wireless mesh networks consisting of hundreds to thousands of nodes with low requirements on computation power and time.

We validate our analytical model by comparing results for example network topologies against results from a high-fidelity simulation platform based on GloMoSim [35].

In Chapter 3, we address optimization of performance of CSMA-based wireless mesh networks, using the analytical model from Chapter 2 for assessing performance. We address joint optimization of physical layer parameters and routing in CSMA-based wireless mesh networks, so as to maximize the end-to-end capacity, i.e. the highest amount of traffic between source-destination pairs that can be supported by the network. We discuss tradeoffs involving performance of links, spatial reuse and distribution of link lengths used for carrying traffic that come into play in determination of network capacity. With respect to routing, we consider use of a metric for a link that is the product of expected transmission time of a packet on the link and the number of nodes blocked during this time. This represents use of the wireless medium in both time and space. For any physical layer parameters, routing using such a metric minimizes usage of network resources. We seek to find the physical layer parameters which when used in conjunction with this routing metric results in maximum end-to-end capacity. We consider networks with nodes randomly located according to a uniform density, with attenuation between nodes following a power law function of distance. We show that the best performance is achieved when the range of link lengths used by routing is the lowest possible, and the physical layer parameters are optimized to achieve the right balance between performance of these links and the level of spatial reuse.

We provide concluding remarks and discuss potential future directions of this work in Chapter 4.
Chapter 2

Analytical Model

In this chapter, we develop our analytical model for CSMA-based wireless mesh networks that serves as a tool for evaluating performance of such networks with respect to different operational aspects such as PHY parameter configuration on links and routing metrics. We consider mesh networks using IEEE 802.11 Distributed Coordination Function for medium access, such networks constitute a large majority of mesh networks currently deployed.

Given a static wireless mesh network, propagation characteristics in terms of path loss between each pair of nodes, and a traffic load carried on links in the network, the analytical model determines whether the traffic load is feasible. For a feasible load, it provides performance measures for each link in the network in terms of packet error rate and average fraction of time that the channel is busy at the source of the link. The model allows one to compute network capacity by starting with a very low feasible load and gradually increasing the load in small steps until it becomes infeasible. The model identifies bottleneck links in the network that are unable to meet their traffic requirement at this point of infeasibility.

Key features of our analytical model that make it a very useful tool for performance evaluation of mesh networks are - (i) It can be applied to a mesh network with any physical layer parameter settings on links (Energy detect threshold, transmit power and data rate) (ii) It captures all complex characteristics of wireless mesh networks leading to accurate results (iii) It scales well to large networks, providing results with
2.1. OVERVIEW OF IEEE 802.11 DCF

much lower computation power and time as compared to simulations. All prior work on analytical modeling of CSMA-based wireless mesh networks has been limited in one or more of the above respects, limiting their applicability as elaborated later in section 2.2.

We begin by first presenting in section 2.1 a brief overview of IEEE 802.11 DCF in order to provide the necessary background regarding operation of the system under consideration. We then present in section 2.2 an overview of the prior work in analytical modeling of CSMA-based wireless networks, focusing on analytical models that address the problem of determining throughput/capacity in networks with arbitrary topologies. We identify the shortcomings of these previously proposed analytical models, and highlight the need for our analytical model. Section 2.3 describes our modeling approach. In 2.4 we describe the notations used in our model followed by a detailed description of our analytical model in section 2.5. In section 2.6, we present numerical results validating steps undertaken in the development of the model and compare the results from our analytical model to those from a high-fidelity simulator. We conclude in section 2.7.

2.1 Overview of IEEE 802.11 DCF

DCF is based on CSMA/CA, and is the fundamental method for channel access defined in IEEE 802.11. Its support is mandatory in all IEEE 802.11 devices.

A node using DCF continuously senses the medium. It considers the medium to be busy and refrains from starting a transmission when it senses an energy level greater than a threshold called Energy Detect Threshold (ED Threshold). The node is said to be blocked during the time that it senses an energy level greater than ED threshold. A node transmits a packet on the medium only after it has sensed the medium to be idle continuously for a period of time called Distributed Inter Frame Spacing (DIFS), and has counted down a randomly chosen number of backoff slots with the channel in idle state. The back-off counter value is chosen randomly with uniform probability from an integer range of $[0, CW]$ where $CW$ stands for Contention Window. $CW$ is initialized to a fixed value $CW_{min}$ for the first transmission attempt of a new
packet, and is doubled for every failed attempt to transmit the packet up to a certain maximum value of $CW_{\text{max}}$. This is referred to as Binary Exponential Backoff. When a node does transmit on the medium, its transmission can experience channel errors and/or can overlap with and experience interference from transmissions occurring at the same time and on the same radio channel in the vicinity of the receiver. On successful reception of a unicast packet, the receiver waits for SIFS (Short Inter Frame Spacing) and transmits an acknowledgement (ACK) to the transmitter. The value of SIFS is smaller than DIFS, thus giving priority to transmission of an acknowledgement over transmission of a new data packet. If the transmitter does not receive an ACK within a timeout, it considers the packet to be lost, doubles the contention window and retransmits the packet. The maximum number of retransmissions for a packet is specified by a parameter referred to as the retry limit. Due to binary exponential backoff, a node that experiences a high rate of packet errors uses a large contention window and transmits less frequently on the channel. Binary exponential problem is known to aggravate unfairness in CSMA [36, 37, 38]

While DCF as outlined above is the basic mode of channel access in IEEE 802.11 that is mandatory to be supported in all IEEE 802.11 devices, the standard also specifies an optional extension to DCF that incorporates use of control messages for collision avoidance, referred to in the standard as the RTS/CTS mode. In this optional mode, upon counting down its backoff slots, a node with data to transmit first transmits a short Request-to-Send (RTS) packet to its intended destination. The RTS frame includes a duration field that covers the entire duration of the data transmission and the corresponding acknowledgement. If the RTS is successfully received at the receiver and the receiver detects the channel to be idle, it waits for an amount of time equal to Short Inter-Frame Spacing (SIFS) and transmits a Clear-to-Send (CTS) control frame destined to the source of the RTS. The CTS frame contains duration of the remaining portion of the transaction (following the RTS). On successfully receiving the CTS, the source waits for SIFS and transmits the data packet (multiple fragments of a data packet are transmitted back-to-back without requiring to contend for the medium again with SIFS time between receiving an ACK for a fragment and transmitting the next fragment). All other nodes in the
2.2. PRIOR WORK

neighborhood that successfully receive the RTS, CTS and data frames remain silent for the duration specified in these frames.

Besides avoiding collisions of data packets in single-hop networks, use of RTS/CTS also reduces collisions in the presence of hidden nodes although it does not eliminate collisions completely. e.g. in the example of figure 1.5, node A first sends a RTS frame to node B. If node C is transmitting at that time, node B does not respond with a CTS, node A doubles its contention window and tries again, thus avoiding a collision with node C. If the channel is sensed idle at node B and it successfully receives the RTS from node A, it responds with a CTS. If node C receives the CTS successfully, it refrains from starting a transmission during the transmission by node A. Note that this RTS/CTS protocol is based on similar concepts as in BTMA and SRMA, except that the control messages do not have a dedicated channel and are sent on the same channel as the data packets. RTS/CTS messages have been used in wired networks in the Apple’s LocalTalk Link Access Protocol [25], whereas in wireless networks they were introduced by Karn in [39], and later expanded upon in [40, 41].

RTS/CTS is beneficial for large data packets, since the benefit of avoiding wasteful use of the medium for long transmission time when a collision occurs outweighs the price paid in terms of overhead introduced by RTS/CTS. However, for small packet sizes, the RTS/CTS exchange introduces overhead per transmission. Thus, the IEEE 802.11 standard defines an RTS threshold that can be programmed at each node. For packet sizes less than the RTS threshold, the node transmits the packet directly without first sending a RTS. For packet sizes greater than the RTS threshold, the node first undertakes a RTS/CTS exchange before transmitting the packet.

2.2 Prior Work

CSMA has been widely used as the medium access protocol in both single-hop wireless LANs and multihop wireless networks. Consequently, there has been a great deal of interest in analytical modeling of CSMA-based wireless networks, and several analytical models have been proposed in the research community over the years addressing different network topologies.
Tobagi and Kleinrock performed detailed analysis of the original CSMA schemes proposed by them in the context of single-hop packet radio networks [20, 24, 42]. Some models that analyze the performance of IEEE 802.11 DCF in single-hop wireless LANs include [43, 44, 45, 46, 47, 48]. Tobagi analyzes the performance of CSMA in a two-hop packet radio network [49].

Multihop wireless networks such as mesh networks introduce several modeling complications owing to the fact that a node is not within communication range of all other nodes, and thus nodes in the network see different views of the channel. An excellent overview and assessment of analytical models proposed for multihop packet radio networks until 1987 can be found in [50]. Analytical models for CSMA-based wireless mesh networks with general topologies are based on one of two approaches.

One class of analytical models is based on tracking the state of the system. Boorstyn et al. proposed the first analytical model for CSMA-based wireless mesh networks using such an approach [51, 52, 53]. The state of the system at any time is represented by the set of nodes actively transmitting at that time. Assuming that packet sizes are exponentially distributed and that time between successive transmissions by a node is also exponentially distributed, they model the system as a Markov chain and derive relationships between node throughputs and the steady state probabilities of the Markov chain. However, this analytical model is based on assumptions that blocking between nodes is symmetric and that the fate of a transmission is determined only by activity in the network at its beginning, regardless of what happens during the transmission (perfect capture). These assumptions do not hold true in reality. Blocking can be asymmetric due to use of different transmission powers on different links and possible asymmetric path loss. Perfect capture is not possible in CSMA systems since most CSMA systems use narrow-band signaling. Brázio and Tobagi propose an analytical model that overcomes these limitations [54, 55]. They represent the state of the system at any time by the set of links with ongoing transmissions at that time. Again, assuming exponential packet sizes and that time between successive transmissions by a node follows an exponential distribution, they model the system as a Markov chain and derive relationships between link throughputs. The model allows for different PHY rates on different links and can accommodate
2.2. PRIOR WORK

asymmetric blocking, thereby allowing for use of different transmit powers on different links. It also accounts for activity occurring in the network during a transmission by using an auxiliary Markov chain, thus being able to accommodate various capture models.

The other class of analytical models is based on using a major simplification in the modeling of CSMA with exponential backoff introduced by Bianchi [56]. This work considers an idealized IEEE 802.11 network with a finite population of nodes, all within hearing range of each other and each node always having a packet to transmit. All nodes use the same PHY rate for transmission. Bianchi showed that a node using CSMA/CA with binary exponential backoff can be modeled as starting a transmission on the channel in an idle slot with constant probability that is a function of its packet error rate. The resulting analytical model is shown to match simulation results extremely well. Bianchi’s work forms the basis of a class of scalable analytical models for IEEE 802.11 based wireless mesh networks that use this expression for average probability of channel access at each node instead of enumerating the state space represented by the set of nodes/links active at any time. Expressions are derived relating throughputs achieved by nodes in the network in terms of the channel access probability at each node. Carvalho and Garcia-Luna-Aceves present an analytical model to compute the saturation throughput achieved by each node in a wireless mesh network [57]. However, the model cannot be used to compute the achieved throughputs for finite loads. Medepalli and Tobagi propose an analytical model that computes the throughput achieved by each node for a finite offered load by using an average cycle time approach [37, 58]. The probability of channel access by a node under saturation is modulated by the probability of having a non-empty transmission queue to derive the probability of channel access under finite load. Time between two consecutive successful transmissions on a link is referred to as the Cycle Time for the link, throughput of a link is directly related to its cycle time. Cycle time for a link is expressed in terms of its transmission time, probability of accessing the channel, transmission times and channel access probabilities of nodes that block it. One major drawback of this model is that it assumes the use of the same transmit power and PHY rate on all links in the network.
Garetto, Salonidis and Knightly propose an analytical model for IEEE 802.11 wireless mesh networks with a focus on the problem of flow starvation \[38, 59\]. The model is a hybrid between relating the throughput of a node to channel access probabilities of itself and its neighbors, and using Markov chain modeling. They analyze the channel as seen by each node in terms of the four possible states - (i) idle (ii) occupied by a successful transmission by the node (iii) occupied by a collision involving a transmission by the node, and (iv) busy due to activity of other stations. The throughput achieved by a node is expressed in terms of steady state probabilities of the channel being in these states, and the average duration of each of these states. To compute the probability of the channel being busy at a node \(i\) and the average busy duration, the authors use the Markovian modeling methodology of \[51\] and compute steady state probabilities of the system being in states such that at least one node that blocks node \(i\) is active. The authors address the scalability issue with using Markov chain analysis in their model. For large highly dense networks they propose an approximation in which for a target node \(i\), maximal cliques covering all nodes that block node \(i\) and their mutual intersections are identified, and virtual nodes are used to represent the aggregate activity pattern of each clique. However, we note that while this makes the model more tractable for highly dense networks, it really does not solve the problem of state explosion when analyzing large mesh networks with reasonable node densities. Moreover, most real-world deployments of mesh networks tend not to have very high node densities. Also, with a focus on MAC-level interactions and identifying starvation in mesh networks, this model is based on very ideal assumptions at the physical layer viz. (i) all nodes use the same transmit power (ii) each node has a fixed transmission range over which it can be received successfully and a fixed carrier sensing range over which it causes the channel to be sensed busy (iii) there are no power capture effects, a packet is not received correctly if it overlaps with any transmission by a node within carrier sensing range of the receiver (iv) the communication channel is free of errors.

The analytical model by Brázio and Tobagi \[54\] is very powerful and allows one to determine network capacity in a wireless mesh network with any settings of transmit power and PHY rate on links. However, it is based on tracking the state of
the system and thus suffers from the problem of state space explosion for large networks. The analytical model by Medepalli and Tobagi [37] allows one to determine network capacity in large wireless mesh networks, but its applicability is restricted to networks using the same transmit power and PHY rate on all links while in reality links in a wireless mesh network may have different transmit power and PHY rate settings appropriate for their corresponding propagation characteristics. A common drawback of both these models and all other models for multihop networks described above with the exception of [57] is that acknowledgement traffic is ignored and ACKS are considered to be instantaneous and error-free. Also, these models assume a very simplistic interference model. The work in [54] assumes that a transmission is either successful or not depending on the identities of links that interfered with the transmission, whereas the work in [37] assumes that a transmission is in error if it overlaps with another transmission within carrier sensing range of the receiver regardless of the level of interference. In reality, whether a transmission is successful or not is probabilistic, the probability of success depends on the SNIR during its reception.

Thus, there is a need for an analytical model for wireless mesh networks that can be applied to any general mesh network with any configuration of PHY parameters, is accurate, and is scalable to large networks. We develop an analytical model that satisfies these key requirements.

2.3 Modeling Approach

Our analytical model is based on evaluating the view of the channel as seen by each link carrying traffic in the network, averaged over a long period of time. A node using IEEE 802.11 DCF for medium access counts down backoff slots with the channel in idle state for each transmission undertaken on the link. Thus, for a link to be able to support its traffic, its source should sense enough idle time to allow for counting down of backoff slots for the traffic required to be carried on the link. Hence, for each link carrying traffic in the network, we evaluate (i) the fraction of time spent in counting down backoff slots for traffic required to be supported on the link, and (ii) the fraction of time that the channel is busy at the source of the link due to
transmissions on the link itself and transmissions that cause received power at the source of the link to exceed its energy detect threshold, resulting in the link being blocked.

Due to the use of exponential backoff in DCF, the fraction of time spent in backoff for transmissions on a link depends on the probability of incurring retransmissions on the link. With the contention window being initialized to $CW_{\text{min}}$ for a new packet and doubled up to a maximum of $CW_{\text{max}}$ for each retransmission of the packet, we express the fraction of time spent in backoff on a link in terms of the probability of incurring retransmissions, the contention window range, and the rate of traffic offered on the link.

With respect to the fraction of time that the channel is busy at the source of a link, it is important to account for the channel being sensed busy due to energy from a single ongoing transmission exceeding the ED threshold at the source, as well as cumulative energy received from multiple simultaneously occurring transmissions exceeding the ED threshold. By analyzing timelines of simulation runs, we observe that it suffices to account for blocking due to cumulative energy received from up to two simultaneous transmissions (see figure 2.9). The amount of time that the channel is sensed busy at a node due to cumulative energy from three or more simultaneous transmissions that individually and pairwise do not block the node is negligible. We express the fraction of time that the channel is busy at the source of a link in terms of (i) Time occupied by transmissions on links from which received power at the source exceeds ED threshold accounting for overlap between such transmissions, and (ii) Time occupied by simultaneous transmissions on pairs of links such that cumulative received power at the source from simultaneous transmissions on each pair exceeds its ED threshold, but received power from individual links in the pair does not.

The fraction of time spent in backoff for transmissions on a link and fraction of time occupied by transmissions on the link both depend not only on the rate of traffic required to be carried on the link, but also on the rate of retransmissions on the link resulting from packet errors in data transmissions or ACK transmissions due to channel errors and interference. Higher rate of retransmissions results in a higher fraction of time spent in backoff due to exponential backoff, and a higher fraction
of time used on the medium by transmissions on the link. Similarly, the fraction of
time that the channel is sensed busy at the source of a link due to transmissions on
links that block it also depends on the rate of traffic required to be carried on these
links as well as the rate of retransmissions on the links. Thus, an important aspect
of the analytical model is evaluation of the rate of retransmissions on each link in the
network carrying traffic.

A packet transmitted on a link in a mesh network using DCF is retransmitted
up to a certain number of times referred to as the retry limit, if either the data packet
is not received correctly by the destination of the link or if the acknowledgement
transmitted by the destination is not received correctly at the source of the link.
Thus, in order to evaluate of the rate of retransmissions on each link, we evaluate
the packet error rate for data transmissions on the link and the packet error rate for
ACK transmissions in the reverse direction.

The probability of error for a packet transmission on a certain target link, whether
the transmission is a data transmission or an ACK transmission depends on the Signal
to Interference plus Noise Ratio (SINR) at the receiver during the reception of the
packet. Since transmissions on interfering links can start and end at arbitrary times
during the transmission on the target link, the Interference power varies during the
reception of the packet. We assume in our model that the probability of error for a
packet is determined by the lowest SINR during its reception regardless of the fraction
of packet reception time over which the SINR is at this lowest value. However, the
lowest SINR and hence the probability of error varies from packet to packet since each
packet experiences interference from different sources. For a packet transmission
undertaken on the target link, we evaluate the probabilities that the transmission
overlaps with and hence experiences interference from individual interfering links
and probabilities that the transmission overlaps simultaneously with transmissions
on pairs of interfering links. The average packet error rate for the target link is then
evaluated as a average of the probabilities of error for different overlap situations
that transmissions on the link encounter, weighted by the probability of occurrence
of each situation. It suffices to consider interference from simultaneous overlap with
up to two interfering links since the likelihood that a transmission undertaken on a
link overlaps simultaneously with three or more transmissions on links in the vicinity of the receiver is very low as verified by analyzing simulation results (see figure 2.11).

In the evaluation of probability of error for a data transmission on a target link, it is important to consider interference not only from data transmissions in the vicinity of the receiver, but also interference from ACK transmissions in the vicinity of the receiver as illustrated by simulation experiments (see figure 2.10). Thus, for evaluating the average packet error rate for data transmissions on a target link, we consider in the set of interfering links, both links on which data transmissions occur in the vicinity of the receiver and the reverse links on which ACKs are transmitted for these data transmissions. On the other hand, for ACK transmissions, we only consider overlap with data transmissions since the likelihood of a short ACK transmission experiencing interference from another short ACK transmission is much lower than the likelihood of it experiencing interfering from data transmissions due to the fact that ACKs occupy much lower time on the medium compared to data transmissions.

Owing to complex interactions between links in a mesh network, none of the above elements such as fraction of time spent in backoff of a link, packet error rate on the link, etc. can be evaluated independent of the other elements. Each element is expressed in terms of the other elements that it depends on, properly capturing the dependencies involved, and the resulting system of equations is solved iteratively to arrive at a solution.

**Modeling Assumption**

In evaluating the probability that a transmission undertaken on a target link \( i \) overlaps with a transmission on another link \( j \), our model is based on a key modeling assumption that during the time a link is not blocked, start of a transmission on the link is equally likely to occur at any time and represents a random look in time. Analysis of IEEE 802.11 DCF has shown that a link that with traffic to transmit at all times can be modeled as having a uniform probability of starting a transmission in an idle slot [56, 60]. Using this result and assuming that a link with finite load has a uniform probability of having a non-empty transmission queue at any time, the probability that a transmission starts on the link in a slot sensed idle by its source is uniform across all slots sensed idle by its source.
Proper accounting of blocking relationships

It is important to note that when evaluating the probability that a transmission undertaken on a target link $i$ overlaps with a transmission on another link $j$, one needs to account for the blocking relationship between links $i$ and $j$ as well as blocking relationships between links $i$ and $j$ and their neighbors. Previously proposed analytical models based on using Bianchi’s expression for average probability of channel access ignore these blocking relationships. In evaluating overlap of transmissions on a link $j$ with other links, these models use the same average probability of a transmission occurring on link $j$ for all links that $j$’s overlap is evaluated with. To illustrate the error in this approach, consider the simple example in figure 2.1 showing four links $i, j, k, m$ in a mesh network with transmissions on link $m$ blocking both links $i$ and link $j$. With a high rate of transmissions on link $m$, transmissions on links $i$ and $j$ are forced to occur in a shortened period of time when there is no ongoing transmission on link $m$ whereas transmissions on link $k$ can occur at any time including time when there is an ongoing transmission on link $m$ blocking link $j$. As a result, the probability that a transmission undertaken on link $i$ overlaps with a transmission on link $j$ is much higher than the probability that a transmission undertaken on link $k$ overlaps with a transmission on link $j$, whereas the approach used in prior work uses the same average rate of transmissions on link $j$ to evaluate likelihood of overlap with both links $i$ and $k$. In our analytical model, when computing the probability that a transmission undertaken on link $i$ overlaps with a transmission on link $j$, we properly take into account blocking relationships between links $i$ and $j$ and blocking relationships between them and their neighbors such as link $m$. 
Figure 2.1: Example illustrating an error in some previously proposed analytical models for multihop wireless networks

2.4 System Model and Notations

We consider a static wireless mesh network consisting of a set of fixed nodes $\mathcal{N}$ and a set of links $\mathcal{L}$ as illustrated in figure 2.2(a). Each node is equipped with an omnidirectional antenna, antennas at all nodes are configured to operate on the same radio channel. Propagation characteristics are specified in terms of path loss between each pair of nodes. $\Gamma_{UV}$ denotes the path loss from node $U$ to node $V$. As discussed in section 1.1.1, the path loss can vary with time due to relative movement in the environment. For the purpose of simplicity and in order to focus on capturing interactions between links, we assume for now that the path loss does not vary with time, i.e. the path loss $\Gamma_{UV}$ captures the effects of attenuation and shadowing, but does not account for fading.
The physical layer at each node supports multiple transmission rates and variable transmit power. A node transmitting on a link uses transmit power and PHY rate that is well-suited for for the propagation characteristics from itself to the particular destination node.

The set of links carrying traffic is denoted by $\mathcal{L}_U$. Each link $i \in \mathcal{L}_U$ has a source node denoted by $S(i)$, a destination node denoted by $D(i)$ and an offered traffic load of $\lambda_i$ packets per second. Node $S(i)$ uses power $P_i$ and physical layer rate $R_i$ when transmitting on link $i$.

$i'$ is used to denote the link in the reverse direction for transmission of acknowledgements from $D(i)$ to $S(i)$. Note that if node $D(i)$ also transmits data to node
$S(i)$, that is considered a separate link $j$ as illustrated in figure 2.2(b). $P_i$ and $R_i$ denote the transmit power and rate used for transmission of ACKs on link $i'$. To simplify the problem, we assume that all data frames transmitted on a link $i$ are of fixed size and each transmission on link $i$ occupies time $t_i^D$ at the physical layer rate used $R_i$. $t_i^A$ denotes the time occupied by the ACK frame. We refer to the transmission of a data frame on link $i$ followed by a SIFS period and transmission of an ACK on link $i'$ collectively as a transaction on link $i$, of duration $t_i = t_i^D + SIFS + t_i^A$ as illustrated in figure 2.2(c). We assume that the size of packets transmitted on each link is less than the fragmentation threshold, thus each packet is transmitted in a single fragment. We also assume basic mode of medium access, RTS/CTS is not used.

$B_{ij}$ denotes the blocking effect of link $i$ on link $j$. $B_{ij} = 1$ if link $j$ is blocked during a transmission on link $i$, $B_{ij} = 0$ otherwise.

\[
B_{ij} = 1 \text{ if links } i \text{ and } j \text{ share the same transmitter}
\]
\[
B_{ij} = 1 \text{ if } \left[ \frac{P_i}{\Gamma_{S(i),S(j)}} + N(S(j)) \right] \geq ED \text{ threshold at } S(j)
\]
\[
B_{ij} = 0 \text{ otherwise}
\]

where $N(S(j))$ is the background noise at node $S(j)$.

In accordance with the IEEE 802.11 standard, packet transmission consists of transmission of a preamble followed by a PLCP header and Physical layer Service Data Unit (PSDU) respectively. Both the PLCP and data portions are followed by a CRC to allow the receiver to determine whether these portions were received successfully. The preamble and PLCP header are transmitted at the lowest supported PHY rate. Packet reception by a node is modeled as comprising of synchronization to the preamble followed by reception of PLCP header and the PSDU. Probability of error at each of these phases depends on the SINR during the phase.

Our analysis assumes that a function that maps the SINR during synchronization to probability of error in synchronization is known for each PHY rate, we use $F_S$ to denote this function. For the purpose of simplicity, reception of the PLCP header is
2.4. SYSTEM MODEL AND NOTATIONS

assumed to be successful once synchronization is achieved. Similarly, we assume that a function that maps SINR during packet reception to probability of error in packet reception (once synchronization is achieved) is known for each PHY rate, we use $F_R$ to denote this function for PHY rate $R$. Functions $F_S$ and $F_R$ can be obtained by simulations or by measurements on an experimental testbed.

The numerical results in this chapter have been derived using the IEEE 802.11a physical layer on each link. The relationship between SNR and probability of synchronization error used is that obtained by Vyas et al. by performing measurements on an experimental testbed [61]. This relationship is shown in figure 2.3(a). With respect to probability of error during PSDU reception, we use the relationships derived by Awoniyi and Tobagi by means of simulations [18]. These relationships are shown in figure 2.3(b). For the purpose of deriving numerical results in this chapter and validating results from our model against those from simulations, interference is assumed to have the same effect on packet reception as Additive White Gaussian Noise (AWGN) as is often done. The received interference power is added to the background noise to compute the SINR, and the probability of synchronization error and packet error are computed as a function of this SINR as per the relationships in figures 2.3(a) and 2.3(b) respectively. Noise is modeled as Additive White Gaussian Noise (AWGN) and the noise power is hence given by $K T B$, where $K$ is the Boltzmann constant ($1.38x10^{23}$ Wsec/K), $T$ is the absolute temperature (taken as 290K) and $B$ is the channel bandwidth (20 MHz for IEEE 802.11 OFDM physical layer). This amounts to a background noise of -101 dBm.

Studies based on measurements on an experimental testbed have shown that effect of interference on packet reception may not be as severe as that of white noise of the same power [12]. We address in Chapter 3 how much results regarding network throughput and optimum system parameters can differ when the effect of interference is modeled as per the observations in [12], compared to when the effect of interference on packet reception is assumed to be the same as that of noise.

Since transmissions on interfering links can begin and end at arbitrary points during the reception of a packet, SINR can vary during the reception of a packet. We assume that the probability of a packet being received in error is determined by the
lowest SINR during its reception regardless of the duration for which the SINR is at this lowest value. Overlap of the strongest interfering transmission with a few data symbols of a packet has the same effect as overlap with more symbols.

The IEEE 802.11a OFDM physical layer supports data rates of \{6, 9, 12, 18, 24, 36, 48, 54\} Mbps. However, as discussed in chapter 1, rates 9 and 18 Mbps exhibit anamolies and it is not desirable to use these rates. Thus, we restrict ourselves to the use of \{6, 12, 24, 36, 48 and 54\} Mbps.

### 2.5 Analytical Model

Clearly, for a link \(i\) to be able to meet its throughput requirement of \(\lambda_i\) packets per second, the fraction of time that the channel is busy at the source of the link (due to transmissions on link \(i\) and on links that block it) plus the fraction of time that the link is counting down back off slots for its transmissions must be less than one. Using \(\Theta_i\) to denote the fraction of time that the channel is sensed busy at the source of link \(i\), and \(b_i\) to denote the average total backoff time per packet transmitted on link \(i\), the traffic load \(\lambda = \{\lambda_i\}\) is feasible iff the following medium time constraint is
satisfied at each link $i$ in set $\mathcal{L}_U$ carrying traffic

$$\lambda_i b_i + \Theta_i < 1 \forall i \in \mathcal{L}_U$$

### 2.5.1 Average Total Backoff per packet

We first write an expression for the average total backoff time $b_i$ per packet transmitted on link $i$. Due to exponential backoff, $b_i$ is related to the probability of incurring a retransmission on link $i$. We use $\beta_i$ to denote the probability that a packet transmitted on link $i$ has to be retransmitted (due to the data packet being received in error at node $D(i)$ or the ACK being received in error at node $S(i)$). Let us assume for now that $\beta_i$ is known, we shall later derive relationships that allow one to compute $\beta_i$. Using $W_n$ to denote the average contention window size at the $n^{th}$ retry i.e. $W_n = \frac{1}{2} \min\{2^n(CW_{min} + 1) - 1, CW_{max}\}$, $\Delta$ to denote slot duration and $M$ to denote the maximum number of retransmissions per packet, we have

$$b_i = \sum_{n=0}^{M} (W_n \Delta) \beta_i^n$$

### 2.5.2 Fraction of time channel is busy

The channel may be sensed busy at the source of link $i$ either due to a transmission on an individual link in its neighborhood, or due to cumulative energy received from multiple simultaneous transmissions in its neighborhood each of which individually does not block link $i$. In order to account for blocking due to reception of cumulative energy, it is sufficient to account for up to two simultaneously occurring transmissions. We have analyzed several packet transmission timelines from simulations using a high-fidelity simulator developed in our research group using GloMoSim as the base, and we observe that the fraction of time that a link $i$ is blocked due to cumulative energy received from three or more transmissions that individually and pairwise do not block link $i$ is negligible. Thus, we can express the fraction of time that the channel is busy for link $i$ in terms of the fraction of time occupied by transmissions on links that individually block link $i$ and the fraction of time occupied by simultaneous
transmissions on pairs of links that individually do not block link \( i \) but simultaneous transmissions on these pairs block link \( i \).

We use \( \mathcal{C}_i \) to denote the set of links that block link \( i \), and \( \mathcal{C}_i^+ \) to denote the set of links that block link \( i \) including link \( i \). i.e.

\[
\mathcal{C}_i = \{ k \mid B_{ki} = 1 \}; \mathcal{C}_i^+ = \{ k \mid B_{ki} = 1 \} \cup \{ i \}
\]

We use \( \mathcal{C}_i^2 \) to denote the set of pairs of links such that individual links in each pair do not block link \( i \), but simultaneous transmissions on the pair of links block link \( i \).

\[
\mathcal{C}_i^2 = \{ < m, n > \mid B_{mi} = 0; B_{ni} = 0; \frac{P_m}{\Gamma_{S(m),S(i)}} + \frac{P_n}{\Gamma_{S(n),S(i)}} + N(S(i)) \geq ED \text{ threshold at } S(i) \}\]

Using \( \Theta_{\mathcal{C}_i^+} \) to denote the fraction of time such that a transaction on at least one link in set \( \mathcal{C}_i^+ \) is taking place, \( \Theta_{\mathcal{C}_i^2} \) to denote the fraction of time such that simultaneous transmissions occur on a pair of links in set \( \mathcal{C}_i^2 \), we approximate the fraction of time channel is busy at link \( i \) as:

\[
\Theta_i = \Theta_{\mathcal{C}_i^+} + \Theta_{\mathcal{C}_i^2}
\]

Computation of how busy the channel is requires accounting for the offered load on links as well as retransmissions due to packet errors. We use \( \lambda'_i \) to denote the actual average rate of transmissions on link \( i \) including retransmissions. A packet transmitted on link \( i \) undergoes an \( n^{th} \) retransmission with probability \( \beta_i^n \). Thus, \( \lambda'_i \) is given by

\[
\lambda'_i = \lambda_i \sum_{n=0}^{M} \beta_i^n
\]

Since transactions on links in set \( \mathcal{C}_i^+ \) can occur simultaneously, it is important to account for the overlap among these transactions when computing \( \Theta_{\mathcal{C}_i^+} \). We observe in several simulation runs that the amount of time occupied by simultaneous transactions on three or more links in set \( \mathcal{C}_i^+ \) is negligible compared to the amount of time occupied by transactions on only one link or simultaneous transactions on two links in set \( \mathcal{C}_i^+ \) (see figure 2.9). This is due to blocking between links located near each other in the
neighborhood of link $i$. Thus, we approximate $\Theta_{C_i^+}$ as the total time occupied by transactions on links in set $C_i^+$ minus the time occupied by simultaneous transactions on pairs of links $\{k,l\}$ in set $C_i^+$, in an unit time window.

$$\Theta_{C_i^+} = \sum_{j \in C_i^+} \lambda'_j t_j - \sum_{k,l \in C_{i,2}^+} \Omega_{kl}$$  \hspace{1cm} (2.5)$$

where $C_{i,2}^+$ denotes the set of pairs of links in set $C_i^+$ and $\Omega_{kl}$ denotes the fraction of time such that transactions on links $\{k,l\}$ occur simultaneously on the medium. Note that $\Theta_{C_i^+}$ computed using equation 2.5 is a slight underestimation of the true union of transmission times of links in set $C_i^+$. In such a computation of $\Theta_{C_i^+}$, time during which transactions on a set $S$ of three or more links belonging to $C_i^+$ occur simultaneously is subtracted from the sum of transaction durations $\sum_{j \in C_i^+} \lambda'_j t_j$ once for each pair of links in set $S$ (i.e. $\frac{|S||S|-1}{2}$), whereas it should actually be subtracted $|S| - 1$ times. However, on observing simulation traces, we note that the fraction of time occupied by simultaneous transmissions on $m$ links in set $C_i^+$ is very small for $m = 3$, even smaller for $m = 4$ and so on. Thus, any error in computation of $\Theta_{C_i^+}$ as per equation 2.5 is negligible.

Evaluation of $\Theta_{C_i^+}$ in equation 2.5 requires computation of $\Omega_{kl}$ for each pair of links $\{k,l\}$ in set $C_i^+$, the fraction of time on the channel with overlap between transactions on links $k$ and $l$. This can be expressed in terms of the rates of transmission on links $k$ and $l$, probability that one of the two links starts transmitting during a transmission on the other link, and the average duration of each such overlap.

$$\Omega_{kl} = \lambda'_k \psi_{kl} \tau_{kl} + \lambda'_l \psi_{lk} \tau_{lk}$$  \hspace{1cm} (2.6)$$

where $\psi_{kl} = \Pr\{\text{Tx undertaken on link }k \text{ starts during an ongoing transaction on link } l\}$

$\tau_{kl} =$ Average Overlap duration between a transaction on link $l$ and a transaction on link $k$ that starts during the transaction on link $l$

There are two possibilities to consider when evaluating $\psi_{kl}$:
1. $B_{lk} = 1$: In this case, since link $l$ blocks link $k$, a transaction on link $k$ can start during a transaction on link $l$ only if backoff counters on links $k$ and $l$ expire at the same time and transmissions on both links start in the same slot. The probability of this occurring is very small, and indeed on analyzing simulation traces, we see that only a negligibly small fraction of transmissions on a link start during a transmission on a particular link that blocks it. We thus ignore this small probability and make a simplifying assumption that $\psi_{kl} = 0$ if $B_{lk} = 1$.

2. $B_{lk} = 0$: In this case, a transaction on link $k$ can start at any time during a transaction on link $l$. Since a transmission on link $k$ is equally likely to start at any time when it is not blocked, probability that it starts during an ongoing transaction on link $l$ is equal to the fraction of the time link $k$ is not blocked that is occupied by transactions on link $l$ as illustrated in figure 2.4. We express the time occupied by transactions on link $l$ when link $k$ is not blocked as the total time occupied by transactions on link $l$ minus the time that transactions on link $l$ occur simultaneously with transactions on links that block link $k$.

![Diagram](image.png)

$T_{k \text{ blocked}}$: Link $k$ is blocked from starting transmissions during this time (amounting to $\Theta_{C_i}$ per second on an average)

$T_{k \text{ unblocked}}$: Transmissions on $k$ are equally likely to start at any time here (amounting to $(1 - \Theta_{C_i})$ per second on an average)

Figure 2.4: Time occupied by transmissions on link $l$ when link $k$ is not blocked
Thus,

\[
\psi_{kl} = \begin{cases} 
0 & \text{if } B_{lk} = 1 \\
\frac{\lambda_l^l t_l - \sum_{m \in C_k} \Omega_{lm}}{1 - \Theta_{c_k}} & \text{if } B_{lk} = 0
\end{cases}
\]  

(2.7)

Also, for a transaction on link \( k \) that occurs during a transmission on link \( l \), the starting time of the transaction on \( k \) is equally likely to be anywhere during the transaction on link \( l \), say at time \( t \) from the start of transaction on link \( l \) as illustrated in figure 2.5. If \( t_k \geq t_l \), overlap time is \( t_l - t \) and \( \tau_{kl} = \frac{1}{t_l} \int_{0}^{t_l} (t_l - t) dt = \frac{t_l^2}{2} \).

Figure 2.5: Overlap time of a single transmission on link \( k \) and a single transmission on link \( l \) with transmission on link \( k \) starting first

If \( t_k < t_l \), for \( 0 \leq t \leq t_l - t_k \), overlap duration is \( t_k \), and for \( t_l - t_k \leq t \leq t_l \), overlap duration is \( t_l - t \). Hence, \( \tau_{kl} = \frac{1}{t_l} \int_{0}^{t_l} (t_l - t) dt + \int_{t_l - t_k}^{t_l} (t_l - t) dt = t_k (1 - \frac{t_k}{2t_l}) \).

Thus,

\[
\tau_{kl} = \begin{cases} 
\frac{t_l}{2} & \text{if } B_{lk} = 0 \text{ and } t_k \geq t_l \\
t_k (1 - \frac{t_k}{2t_l}) & \text{if } B_{lk} = 0 \text{ and } t_k \leq t_l
\end{cases}
\]  

(2.8)
The expression for fraction of time occupied by simultaneous transmissions on pairs of links (equation 2.6) is useful not only for computing the fraction of time $\Theta_{C_i^+}$ that channel is busy at link $i$ due to transactions on links in set $C_i^+$, but also for computing the fraction of time $\Theta_{C_i^2}$ that channel is busy at link $i$ due to simultaneous transmissions on pairs of links in set $C_i^2$. $\Theta_{C_i^2}$ can simply be expressed as the sum of fraction of times that transmissions on each pair of links in set $C_i^2$ overlap.

$$\Theta_{C_i^2} = \sum_{<m,n> \in C_i^2} \Omega_{mn}$$  \hspace{1cm} (2.9)

The key component that remains to be derived is the probability of incurring a retransmission $\beta_i$ on link $i$. This appears in the computation of the actual rate of transmissions on link $i$ (equation 2.4) and the average time spent in backoff per packet transmitted on link $i$ (equation 2.2).

### 2.5.3 Probability of incurring retransmissions

A packet transmitted on link $i$ needs to be retransmitted if either the data frame is not successfully received by $D(i)$ or the ACK transmitted on link $i'$ is not successfully received by $S(i)$. Using $\beta_i^D$ to denote the probability that a data frame transmitted on link $i$ is not received successfully at $D(i)$ and $\beta_i^A$ to denote the probability that an ACK transmitted on link $i'$ is not received successfully at $S(i)$, we can express the probability of incurring a retransmission on link $i$, $\beta_i$ as

$$\beta_i = 1 - [(1 - \beta_i^D)(1 - \beta_i^A)]$$  \hspace{1cm} (2.10)

We first derive an expression for the PER $\beta_i^D$ experienced by data transmissions on a target link $i$, followed by an expression for the PER $\beta_i^A$ experienced by ACK transmissions on link $i'$. 
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PER for data transmissions

PER for data transmissions on link $i$, $\beta_i^D$ depends on the probabilities that a frame transmitted on link $i$ overlaps with and hence experiences interference from transmissions on interfering links, and the lowest SINR value during reception of such packets. Frames transmitted on a link $i$ can experience interference from data transmissions as well as ACK transmissions. Thus, it is necessary to compute probabilities that a data transmission on the target link $i$ overlaps with data transmissions on links in the vicinity of $D(i)$ as well as probabilities that a data transmission on target link $i$ overlaps with ACK transmissions on links in the vicinity of $D(i)$.

The fraction of transmissions on link $i$ that overlap with a transmission on links that block $i$ and are blocked by $i$ is negligible compared to the fraction of transmissions that overlap with links that either do not block $i$ or are not blocked by $i$. Other studies of multihop wireless networks have also shown that indeed packet errors on a link $i$ due to collisions with links that block $i$ and are blocked by $i$ account for a small fraction of the overall packet error rate on link $i$ [38, 59]. Thus, when analyzing the probability of packet errors on link $i$, we only focus on overlap with links $k$ that do not block link $i$ or are not blocked by link $i$ and the corresponding acknowledgement links $k'$. For a target link $i$, we refer to the set of links $k$ such that $B_{ik} = 0$ or $B_{ki} = 0$ as the set $\mathcal{H}_i$ of hidden links for link $i$.

$$\mathcal{H}_i = \{k \mid B_{ik} = 0 \text{ or } B_{ki} = 0\}$$

In theory, this set would include links located far away from the target link with the received interference power at $D(i)$ from transmissions on these links being so insignificant that the probability of error for a data transmission on link $i$ that overlaps with transmissions on these links is almost the same as the probability of error for a data transmission that does not overlap with transmissions on these links. In the interest of computation efficiency, the set $\mathcal{H}_i$ can be truncated to include only those links $j$ such that the probability of a data transmission on link $i$ or $i'$ being received in error is increased significantly due to overlap with a transmission on link $j$ or $j'$.

We first derive expressions for the probabilities that a data transmission on link
i overlaps with data transmissions on interfering links in set $\mathcal{H}_i$ followed by probability that a data transmission on link $i$ overlaps with ACK transmissions on the corresponding acknowledgement links.

**Probability that a data transmission on link $i$ overlaps with data transmissions:**

We use $\zeta_{ij}$ to denote the probability that a transmission undertaken on target link $i$ overlaps with a data transmission on link $j \in \mathcal{H}_i$.

$\zeta_{ij} = \Pr\{\text{Tx undertaken on link } i \text{ overlaps with a Tx on link } j\}$

$\zeta_{ij}$ is the sum of probabilities of two mutually exclusive events

1. **Probability $\zeta_{ij}^1$ that the transmission starts during an ongoing data transmission on link $j$:**

   We have derived $\psi_{ij}$ as the probability that a transmission on link $i$ starts during a transaction on link $j$. Since a transmission on link $i$ is equally likely to occur at any time during the transaction, probability $\zeta_{ij}^1$ that a transmission on link $i$ starts during an ongoing data transmission on link $j$ is simply

   $$\zeta_{ij}^1 = \psi_{ij} \frac{t^D_j}{t_j}$$

2. **Probability $\zeta_{ij}^2$ that the transmission starts when there is no ongoing data transmission on link $j$, but link $j$ starts transmitting during the data transmission on link $i$:**

   In a long time window of duration $T$, the average number of transmissions on link $j$ that start during a data transmission on link $i$ is $T \lambda'_j \zeta_{ji}^1$ and the number of transmissions made on link $i$ during this time is $T \lambda'_i$. Thus, the average number of transmissions on link $j$ during a single transmission on link $i$ is $\frac{\lambda'_j \zeta_{ji}^1}{\lambda'_i}$. Given a transmission on link $i$, if $p_{ij}$ is the probability that a transmission on link $j$ starts during the transmission, we have:

   $$\sum_{n=1}^{n=M_{ij}} np_{ij}^n = \frac{\lambda'_j \zeta_{ji}^1}{\lambda'_i} \quad (2.11)$$
where \( M_{ij} = \text{ceiling}(\frac{t^D_i}{t_j}) \) is the maximum number of transmissions on link \( j \) that can start during a data transmission on link \( i \). The probability that at least one transmission on link \( j \) starts during a transmission on link \( i \) is \( \sum_{n=1}^{n=M_{ij}} p^n_{ij} \). Thus, probability \( \zeta^2_{ij} \) that a transmission on link \( i \) starts when there is no ongoing transmission on link \( j \), but link \( j \) starts transmitting during the transmission on link \( i \) is:

\[
\zeta^2_{ij} = (1 - \zeta^1_{ij}) \sum_{n=1}^{n=M_{ij}} p^n_{ij}
\]

Since \( p_{ij} \) is typically very small, we can ignore the higher order terms involving \( p_{ij} \) and use the following as a good approximation:

\[
\zeta^2_{ij} \approx (1 - \zeta^1_{ij}) \frac{\lambda_j \zeta^1_{ji}}{\lambda_i}
\]

Thus, we have

\[
\zeta_{ij} = \psi_{ij} \frac{t^D_i}{t_j} + (1 - \psi_{ij}) \frac{t^D_i}{t_j} \frac{\lambda_j \zeta^1_{ji}}{\lambda_i} \tag{2.12}
\]

**Probability that a data transmission on link \( i \) overlaps with ACK transmissions:**

Following our notation, we use \( \zeta_{ij'} \) to denote the probability that a transmission undertaken on link \( i \) overlaps with the transmission of an ACK on link \( j' \). We compute \( \zeta_{ij'} \) in a manner similar to the computation of \( \zeta_{ij} \) as the sum of probabilities of two mutually exclusive events illustrated in figure 2.6:

1. **Probability \( \zeta^1_{ij} \), that the data transmission on target link \( i \) starts during an ongoing transaction on link \( j \) at a time such that it overlaps with the ACK part of the transaction (figure 2.6a):**

   We have derived \( \psi_{ij} \) as the probability that a transmission on link \( i \) starts during a transaction on link \( j \). If \( t^D_i + t^A_j < t_j \), then a transmission on link \( i \) that starts less than \( t^D_i + t^A_j \) before the end of a transaction on link \( j \) overlaps with the transmission of an ACK on link \( j' \) if the data transmission on link \( j \) is successfully received by \( D(j) \). If \( t^D_i + t^A_j \geq t_j \), then all transmissions on link \( i \) that start during a transaction on link \( j \) overlap with the transmission of an ACK on
Figure 2.6: Overlap of a data transmission on link $i$ with ACK transmission on link $j'$ if the data transmission on link $j$ is successfully received by $D(j)$. Thus:

$$\zeta_{ij'}^1 = \psi_{ij} \frac{t_i^D + t_j^A}{t_j} (1 - \beta_j^D) \quad \text{if } t_i^D + t_j^A < t_j$$

$$\zeta_{ij'}^1 = \psi_{ij} (1 - \beta_j^D) \quad \text{if } t_i^D + t_j^A \geq t_j$$

Factor $(1 - \beta_j^D)$ is included to account for the fact that an ACK is transmitted on link $j'$ only if the corresponding data frame transmitted on link $j$ is received successfully at its destination node $D(j)$.

2. **Probability $\zeta_{ij'}^2$, that the transmission starts when there is no ongoing transaction on link $j$, but a transaction on link $j$ starts during the data transmission on target link $i$ such that the ACK portion of the transaction on link $j$ overlaps with the data transmission on target link $i$ (figure 2.6b):**

If $t_j^D + SIFS \geq t_i^D$, then the ACK portion of a transaction on link $j$ that starts during a transaction on link $i$ cannot overlap with the data transmission on link
2.5. ANALYTICAL MODEL

$i$ and $\zeta_{ij'}^2 = 0$.

If $t_j^D + SIFS < t_i^D$, and a transaction on link $j$ starts within a period $t_{ij'}^v = t_i^D - (t_j^D + SIFS)$ time from the start of a data transmission on link $i$, the ACK portion of the transaction overlaps with the data transmission on link $i$. In a long time window of duration $T$ seconds, the average number of transmissions on link $j$ that start within $t_{ij'}^v$ from the start of a transaction on link $i$ is $T\lambda_j^'\psi_{ji}^\frac{t_{ij'}}{t_i}$ and the number of transmissions made on link $i$ during this time is $T\lambda_i^'$. Thus, the average number of transmissions on link $j$ within $t_{ij'}^v$ of start of a single transmission on link $i$ is $\frac{\lambda_j^'\psi_{ji}^\frac{t_{ij'}}{t_i}}{\lambda_i^'}$. Given a data transmission on link $i$, if $q_{ij}$ denotes the probability that a transmission on link $j$ starts within $t_{ij'}^v$ of the start of this data transmission, we have

$$
\sum_{n=0}^{n=N_{ij}} n q_{ij}^n = \frac{\lambda_j^'\psi_{ji}^\frac{t_{ij'}}{t_i}}{\lambda_i^'}
$$

(2.14)

where $N_{ij} = \text{ceiling}(\frac{t_{ij'}}{t_j})$ is the maximum number of transmissions on link $j$ that can start within $t_{ij'}^v$ of start of a transmission on link $i$. The probability that at least one transmission on link $j$ starts within $t_{ij'}^v$ of start of a transmission on link $i$ is then $\sum_{n=0}^{n=N_{ij}} q_{ij}^n$. Thus,

$$
\zeta_{ij'}^2 = (1 - \psi_{ij})(1 - \beta_j^D) \sum_{n=0}^{n=N_{ij}} q_{ij}^n \quad \text{if } t_j^D + SIFS < t_i^D
$$

$$
\zeta_{ij'}^2 = 0 \quad \text{if } t_j^D + SIFS \geq t_i^D
$$

Since $q_{ij}$ is typically very small, we can ignore the higher order terms involving $q_{ij}$ and use the following as a good approximation:

$$
\zeta_{ij'}^2 = (1 - \psi_{ij})(1 - \beta_j^D) \frac{\lambda_j^'\psi_{ji}^\frac{t_{ij'}}{t_i}}{\lambda_i^'} \quad \text{if } t_j^D + SIFS < t_i^D
$$

$$
\zeta_{ij'}^2 = 0 \quad \text{if } t_j^D + SIFS \geq t_i^D
$$

(2.15)
Again, a factor \((1 - \beta_j^D)\) is included in the expression for \(\zeta_{ij}^2\) to account for the fact that an ACK is present in a transaction on \(j\) only if the data frame transmitted on \(j\) is received successfully at node \(D(j)\).

\[
\zeta_{ij'} = \zeta_{ij'}^1 + \zeta_{ij'}^2
\]

\textit{Probability that a data transmission overlaps simultaneously with multiple interfering transmissions}

For an accurate assessment of PER for data transmissions on link \(i\), it is important to also compute probabilities that a data transmission on link \(i\) simultaneously overlap with multiple transmissions on links in the neighborhood of \(D(i)\). Packets that encounter such overlap with multiple simultaneous transmissions experience cumulative interference power at the receiver, and the probability of error in reception of such packets can be significantly higher than if they overlapped with only one of the interfering transmissions. On studying the timelines of several simulation runs, we observe that the fraction of transmissions on a link that overlap simultaneously with three or more transmissions in the neighborhood of the receiver is very low, again this can be attributed to blocking between links located in the vicinity of the receiver. Also, since ACKs occupy a small amount of time on the medium, the probability that a transmission on link \(i\) overlaps simultaneously with multiple transmissions involving one or more ACKs in the neighborhood of the receiver \(D(i)\) can be ignored. Thus, it suffices to focus on simultaneous overlap with data transmissions on up to two interfering links in set \(\mathcal{H}_i\) (see figure 2.11).

We use \(\psi_{ijk}\) to denote the probability that a transmission undertaken on link \(i\) starts when there are simultaneously ongoing data transmissions on links \(j\) and \(k\). Again, under our assumption that each transmission on link \(i\) is a random look during the time that it is not blocked, \(\psi_{ijk}\) is the fraction of time link \(i\) is not blocked that is occupied by simultaneous transmissions on links \(j\) and \(k\). We first consider overlap between links \(j\) and \(k\) with the transmission on link \(k\) having started first, the fraction of time with such overlap is \(\lambda_j^i \psi_{ijk} \tau_{jk}\). Of this, the fraction of time during which link \(i\) can start transmitting is given by the ratio of time occupied by transmissions on link \(k\) during which both \(i\) and \(j\) are unblocked to the time occupied by transmissions on
link $k$ during which only link $j$ is unblocked. Similarly, we can compute the fraction of time with overlap between $j$ and $k$ with transmission on link $j$ having started first during which a transmission can start on link $i$. Thus, we have:

$$
\psi_{ijk} = \frac{\frac{\lambda_j' t_k - \sum_{m \in C_i \cup C_j \cup C_k} \Omega_{km}}{1 - \Theta_{C_j}} \lambda_j' \tau_{jk} + \frac{\lambda_k' t_k - \sum_{m \in C_i \cup C_j \cup C_k} \Omega_{jm}}{1 - \Theta_{C_k}} \lambda_k' \tau_{kj}}{\lambda_i'}
$$

(2.17)

We use $\zeta_{ijk}$ to denote the probability that a data transmission on link $i$ overlaps simultaneously with transmissions on links $j$ and $k$. This can be expressed as the sum of the probabilities of the following mutually exclusive events: (i) Transmission on link $i$ starts during simultaneous transmissions on links $j$ and $k$; (ii) Transmission on link $i$ does not start during simultaneous transmissions on links $j$ and $k$, but transmissions on links $j$ and $k$ start during the transmission on link $i$ and overlap with each other. The latter event occurs with two possibilities - transmission on $j$ starting first and transmission on link $k$ starting first). We can then express $\zeta_{ijk}$ as:

$$
\zeta_{ijk} = \psi_{ijk} + (1 - \psi_{ijk}) \left( \frac{\lambda_j' \psi_{jki}}{\lambda_i'} + \frac{\lambda_k' \psi_{kij}}{\lambda_i'} \right)
$$

(2.18)

Having computed probabilities that a data transmission on link $i$ overlaps with and experiences interference from transmissions on links in set $\mathcal{H}_i$ and corresponding acknowledgements, and probabilities that it simultaneously overlaps with transmissions on pairs of links in set $\mathcal{H}_i$, it remains to express $\beta_i^D$ in terms of these probabilities.

**PER for data transmission: Simple example**

The evaluation of average packet error rate on a link for a general set of interfering links $\mathcal{H}_i$ and the corresponding acknowledgement links is fairly involved. We first illustrate our concept here with respect to an example scenario comprising of a target link $i$ and two interfering links $j$ and $k$. For the purpose of illustrating the concept with a simple example, we only consider interference from transmissions on links $j$ and $k$ and ignore interference from ACKs on links $j', k'$. Assume that $j$ is the stronger of the two interferers. Of all transmissions on link $i$,

- A fraction $\psi_{ijk}$ start during simultaneous transmissions on both $j$ and $k$. The
probability that the receiver experiences an error in synchronizing to the preamble of such a transmission is: 
\[ \beta_{ijk,s}^D = \mathcal{F}_S(\frac{P_i/T_{S(i),D(i)}}{(N(D(i))+(P_j/T_{S(j),D(i)})+(P_k/T_{S(k),D(i)})}) \]

There is no stronger interference that can occur during the PSDU reception phase, and probability of error in PSDU reception if synchronization is successful is 
\[ -\beta_{ijk,p}^D = \mathcal{F}_R(\frac{P_i/T_{S(i),D(i)}}{(N(D(i))+(P_j/T_{S(j),D(i)})+(P_k/T_{S(k),D(i)})}) \]

Probability of error in reception of this fraction \( \psi_{ijk} \) of packets is: \( \beta_{ijk}^D = 1 - [(1 - \beta_{ijk,s}^D)(1 - \beta_{ijk,p}^D)] \)

- A fraction \( \zeta_{ij}^1 = (\zeta_{ij}^1 - \psi_{ijk}) \) start during a transmission on the stronger interferer \( j \) alone. The probability that the receiver experiences an error in synchronizing to the preamble of such a transmission due to interference from \( j \) alone is: 
\[ \beta_{ij^*,s}^D = \mathcal{F}_S(\frac{P_i/T_{S(i),D(i)}}{(N(D(i))+(P_j/T_{S(j),D(i)})+(P_k/T_{S(k),D(i)})}) \]

Of these packets, a fraction \( \frac{\lambda_k \psi_{ki}}{\lambda_i} \) experience simultaneous interference from both \( j, k \) during PSDU reception due to transmission on \( k \) starting during simultaneous transmissions on \( i \) and \( j \). For such packets, probability of error in PSDU reception is \( \beta_{ij^*,p}^D \). For the remaining packets, probability of error in PSDU reception due to interference from \( j \) alone is 
\[ \beta_{ij^*,p}^D = \mathcal{F}_R(\frac{P_i/T_{S(i),D(i)}}{(N(D(i))+(P_j/T_{S(j),D(i)})+(P_k/T_{S(k),D(i)})}) \]

Thus, for the fraction of packets that start during a transmission on \( j \) alone, probability of error in PSDU reception is 
\[ \beta_{ij^*,p}^D = \frac{\lambda_k \psi_{ki}}{\lambda_i} \beta_{ij^*,p}^D + (1 - \frac{\lambda_k \psi_{ki}}{\lambda_i}) \beta_{ij^*,p}^D, \] and overall probability of packet error is 
\[ \beta_{ij^*}^D = 1 - [(1 - \beta_{ij^*,s}^D)(1 - \beta_{ij^*,p}^D)] \]

- A fraction \( \zeta_{ik}^2 = (\zeta_{ik}^2 - \psi_{ijk}) \) start during a transmission on the weaker interferer \( k \). The probability that the receiver experiences an error in synchronizing to the preamble of such a transmission is: 
\[ \beta_{ik,s}^D = \mathcal{F}_S(\frac{P_i/T_{S(i),D(i)}}{(N(D(i))+(P_j/T_{S(j),D(i)})+(P_k/T_{S(k),D(i)})}) \]

Of these packets, a fraction \( \frac{\lambda_i \psi_{ik}}{\lambda_i} \) experience simultaneous interference from both \( j, k \) during PSDU reception due to transmission on \( j \) starting during simultaneous transmissions on \( i \) and \( k \). For such packets, probability of error in PSDU reception is \( \beta_{ik^*,p}^D \). Another fraction \( \zeta_{ij}^2 = \frac{\lambda_i \psi_{ij}}{\lambda_i} \) experience interference from the stronger interferer \( j \) starting during PSDU portion of the transmission on link \( i \), but not in the presence of a transmission on \( k \) also. The probability of error in PSDU reception for such packets is \( \beta_{ij^*,p}^D \). The remaining packets experience interference from \( k \) alone during PSDU reception as during synchronization, and the probability of error in PSDU reception for these is
2.5. ANALYTICAL MODEL

\[\beta_{ik*}^D = \mathcal{F}_R(S_{(i),D(i)}^{P_{i}/P_{S(i),D(i)}}).\]

Thus, for the fraction of packets that start during a transmission on \(k\) alone, probability of error in PSDU reception is:

\[\beta_{ik,k}^D = \frac{X_i^\psi_{ik}}{X_i^\lambda} \beta_{ik,k}^D + (\zeta_{ij}^2 - \frac{X_i^\psi_{ij}}{X_i^\lambda}) \beta_{ij,k}^D + (1 - \zeta_{ij}^2) \beta_{ik*,p}^D.\]

Overall probability of error is \(\beta_{ik*}^D = 1 - [(1 - \beta_{ik*,s}^D)(1 - \beta_{ik,k}^D)]\)

- A fraction \(\psi_{i,isolation} = (1 - \psi_{ijk} - \zeta_{ij}^1 - \zeta_{ik}^1)\) start in the clear with no interference. The probability of synchronization error at the receiver for such a transmission is \(\beta_{i,isolation,s} = \mathcal{F}_S(S_{(i),D(i)}^{P_{i}/P_{S(i),D(i)}}).\) Of these, a fraction \(\frac{X_i^\psi_{ik}}{X_i^\lambda} \psi_{ik} + \frac{X_i^\psi_{ij}}{X_i^\lambda} \psi_{ij}\) experience simultaneous interference from transmissions on \(j, k\) both starting during PSDU transmission on \(i\) and overlapping among themselves. For such packets, probability of error in PSDU reception is \(\beta_{ijk,k}^D.\) Another fraction \((\zeta_{ij}^2 - \frac{X_i^\psi_{ij}}{X_i^\lambda})\) experience interference from the stronger interferer \(j\) starting during PSDU portion of the transmission on link \(i,\) but not overlapping with that on \(k\) also. The probability of error in PSDU reception for such packets is \(\beta_{ij,k,*,p}^D.\) Another fraction \(\zeta_{ik}^2(1 - \zeta_{ij}^2)\) experience interference from transmission on \(k\) alone starting during PSDU transmission on \(i,\) the probability of error in PSDU reception for such packets is \(\beta_{ik*,p}^D.\) A fraction \((1 - \zeta_{ij}^2)(1 - \zeta_{ik}^2)\) do not experience any interference during PSDU reception, and probability of error for such transmissions is \(\beta_{i,isolation,*}^D = \mathcal{F}_R(S_{(i),D(i)}^{P_{i}/P_{S(i),D(i)}}).\) Thus, for the fraction of packets on \(i\) that start in the absence of interference, probability of error in PSDU reception is \(\beta_{i,isolation,p} = \frac{X_i^\psi_{ik}}{X_i^\lambda} \beta_{ik,k}^D + \frac{X_i^\psi_{ij}}{X_i^\lambda} \beta_{ij,k,*,p}^D + \zeta_{ik}^2(1 - \zeta_{ij}^2) \beta_{ik*,p}^D + (1 - \zeta_{ij}^2)(1 - \zeta_{ik}^2) \beta_{i,isolation,*}^D.\)

Overall probability of error for packets that start in isolation is \(\beta_{i,isolation}^D = 1 - [(1 - \beta_{i,isolation,*}^D)(1 - \beta_{i,isolation,p}^D)]\)

Average packet error rate for data transmissions on link \(i\) in this example, accounting for all above situations is then

\[\beta_i^D = \psi_{ijk} \beta_{ijk,k}^D + \psi_{ij,k} \beta_{ij,k}^D + \psi_{ik*} \beta_{ik*,p}^D + \psi_{i,isolation} \beta_{i,isolation}^D.\]

**PER for data transmission: General expression**

It can be seen from the above example that evaluation of average packet error rate is complex, even in the simple situation involving only two interferers. Under our receiver model assumption that the probability of error in packet reception is
determined by the lowest value of SINR during packet reception, we calculate the average PER on a link \( i \) as follows, averaging over the different interference situations that a packet transmitted on link \( i \) may experience:

- We use \( \mathcal{Z}_i = \{ \mathcal{Z}_{ix} \} \) to denote interference situations that a packet transmitted on link \( i \) may experience - consisting of interference from individual data transmission links \( j \in \mathcal{H}_i \), individual ACK transmission links \( j' \) such that \( j \in \mathcal{H}_i \) and simultaneous interference from pairs of data transmission links \( j, k \in \mathcal{H}_i \), sorted in decreasing order of received interference power at receiving node of link \( i \). Note that the last element of this set would be \( \mathcal{Z}_{i, isolation} \) to denote no interference.

- We use \( \delta_{ix} \) to denote probability that a packet transmission on link \( i \) starts off experiencing situation \( \mathcal{Z}_{ix} \) and \( \beta_{ix,s}^D \) to denote probability of synchronization error when this happens (computed from transmit power of interfering link(s) in situation \( \mathcal{Z}_{ix} \) and path loss from these links to \( D(i) \) as done in above example). If interference situation \( \mathcal{Z}_{ix} \) involves pairs of links \( j, k \), then \( \delta_{ix} = \psi_{ijk} \). If interference situation \( \mathcal{Z}_{ix} \) involves a single link \( j \), then \( \delta_{ix} = \zeta_{ij}^1 - \sum_{k \in \mathcal{H}_i} \psi_{ijk} \).

- For fraction of packets \( \delta_{ix} \) that experience interference situation \( \mathcal{Z}_{ix} \), we use \( \beta_{ix^*, p}^D \) to denote probability of error in PSDU reception if no stronger interference situation occurs during PSDU reception. It remains to account for probabilities of the stronger interference situations \( \mathcal{Z}_{i,1:x-1} \) occurring during PSDU transmission on link \( i \) after synchronization to the preamble. We use \( \kappa_{ix,y} \) to denote probability that interference situation \( \mathcal{Z}_{iy} \), but no stronger interference situation starts during a PSDU transmission on link \( i \) that starts off experiencing interference situation \( \mathcal{Z}_{ix} \). We use \( \beta_{iy,p}^D \) to denote the probability of error in PSDU reception for packets that experience worst interference situation \( \mathcal{Z}_{iy} \) during their reception. \( \kappa_{ix,y} \) and \( \beta_{iy,p}^D \) are calculated as follows assuming that if interference situation \( \mathcal{Z}_{iy} \) starts after start of packet transmission on \( i \), it starts during the PSDU transmission phase, not during the short preamble -
1. If interference situation \( Z_{iy} \) involves a single data transmission link \( j \) that results in stronger interference at \( D(i) \) than \( j' \), then

\[
\kappa_{ix,y} = \zeta_{ij}^2 \prod_{m_D} (1 - \zeta_{im_D}^2) \prod_{m_A} (1 - \zeta_{im_A}^2) \prod_{m_{DA}} (1 - \zeta_{im_D}^2)
\]

\[
\beta_{iy,p}^D = \mathcal{F}_{R_i}\left(\frac{P_i/\Gamma_{S(i),D(i)}}{N(D(i)) + (P_j/\Gamma_{S(j),D(i)})}\right)
\]

wherein (i) \( m_D \) are data transmission links that result in stronger interference at \( D(i) \) than link \( j \); their corresponding ACK transmission links result in weaker interference at \( D(i) \) than link \( j \); and transmissions on both \( j \) and \( m_D \) can overlap with a transmission on link \( i \) (i.e., at least one link among links \( m_D \) and link \( j \) does not block the other, or transmission time of link \( j \) or link \( m_D \) is less than data transmission time of link \( i \)) (ii) \( m_A \) are ACK transmission links \( k' \) other than \( j' \) that result in stronger interference at \( D(i) \) than link \( j \); their corresponding data transmission links result in weaker interference at \( D(i) \) than link \( j \); and data transmissions on both \( j \) and \( k \) can overlap with a transmission on link \( i \) (iii) \( m_{DA} \) are data transmission links such that these links and their corresponding ACK transmission links both cause stronger interference at \( D(i) \) than link \( j \); and transmissions on both \( j \) and \( m_D \) can overlap with a transmission on link \( i \).

The idea in the above computation of \( \kappa_{ix,y} \) is to compute the probability that a transmission experiences interference situation \( Z_{iy} \), but not any stronger interference situation during PSDU reception.

2. If interference situation \( Z_{iy} \) involves a single data transmission link \( j \) that results in weaker interference at \( D(i) \) than \( j' \), then

\[
\kappa_{ix,y} = (\zeta_{ij}^2 - \zeta_{ij'}) \prod_{m_D} (1 - \zeta_{im_D}^2) \prod_{m_A} (1 - \zeta_{im_A}^2) \prod_{m_{DA}} (1 - \zeta_{im_D}^2)
\]

\[
\beta_{iy,p}^D = \mathcal{F}_{R_i}\left(\frac{P_i/\Gamma_{S(i),D(i)}}{N(D(i)) + (P_j/\Gamma_{S(j),D(i)})}\right)
\]
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wherein \( m_D, m_A, m_{DA} \) have the same meaning as in case 1. The term
\( (\zeta^2_{ij} - \zeta^2_{ij'}) \) is the probability that a data transmission on \( j \) starts during
the PSDU transmission on \( i \), but no ACK transmission on \( j' \) starts during
the PSDU transmission on \( i \).

3. If interference situation \( Z_{ix} \) involves a single data transmission link \( j \) and
\( Z_{iy} \) involves \( j' \),

\[
\kappa_{ix,y} = \frac{t^D_i + t^A_j}{t_j} (1 - \beta^D_j) \prod_m (1 - \zeta^2_{im}) \text{ if } t^D_i + t^A_j < t_j
\]

\[
\kappa_{ix,y} = (1 - \beta^D_j) \prod_m (1 - \zeta^2_{im}) \text{ if } t^D_i + t^A_j \geq t_j
\]

where \( m \) are data or ACK transmission links that result in stronger interference at \( D(i) \) than \( j \).

\[
\beta^D_{iy,p} = \mathcal{F}_{R_i}(\frac{P_i/\Gamma_{S(i),D(i)}}{N(D(i)) + (P_j/\Gamma_{S(j'),D(i)})})
\]

4. If interference situation \( Z_{ix} \) involves a single data transmission link \( j \) and
\( Z_{iy} \) involves an ACK transmission link \( k' \neq j' \) such that \( k \) results in
stronger interference than \( k' \), then \( \kappa_{ix,y} = 0 \) (since ACK transmission
on \( k' \) only follows data transmission on \( k \) whose stronger interference is
accounted for in 1).

5. If interference situation \( Z_{ix} \) involves a single data transmission link \( j \) and
\( Z_{iy} \) involves an ACK transmission link \( k' \neq j' \) that results in stronger
interference than \( k \), then

\[
\kappa_{ix,y} = \zeta^2_{ik'} \prod_{m_D} (1 - \zeta^2_{im_D}) \prod_{m_A} (1 - \zeta^2_{im_A}) \prod_{m_{DA}} (1 - \zeta^2_{im_D})
\]

\[
\beta^D_{iy,p} = \mathcal{F}_{R_i}(\frac{P_i/\Gamma_{S(i),D(i)}}{N(D(i)) + (P_j/\Gamma_{S(k'),D(i)})})
\]

wherein \( m_D, m_A, m_{DA} \) have the same meaning as in case 1.
6. If interference situation $Z_{iy}$ involves a pair of links $j, k$ other than the link(s) involved in situation $Z_{ix}$, with $j$ being the stronger interferer, then

$$\kappa_{ix,y} = \frac{\lambda^y_{kj} \psi_{kj}}{\lambda^y_i} + \frac{\lambda^y_{jk} \psi_{jk}}{\lambda^y_i}$$

$$\beta^D_{iy,p} = \mathcal{F}_S(\frac{P_i / \Gamma_{S(i),D(i)}}{N(D(i)) + (P_j / \Gamma_{S(j),D(i)}) + (P_k / \Gamma_{S(k),D(i)})}) - \mathcal{F}_R(\frac{P_i / \Gamma_{S(i),D(i)}}{N(D(i)) + (P_j / \Gamma_{S(j),D(i)})})$$

Note that here we only account for additional probability of error due to simultaneous overlap with both $j$ and $k$ compared to probability of error due to overlap with the stronger interferer among $j, k$ because this fraction of packets is also part of the fraction in cases 1 and 2 above.

7. If interference situation $Z_{ix}$ involves a single data transmission link $j$ and $Z_{iy}$ involves a pair of links $j, k$, then $\kappa_{ix,y} = \frac{\lambda^y_{kj} \psi_{kj}}{\lambda^y_i}$

$$\beta^D_{iy,p} = \mathcal{F}_S(\frac{P_i / \Gamma_{S(i),D(i)}}{N(D(i)) + (P_j / \Gamma_{S(j),D(i)}) + (P_k / \Gamma_{S(k),D(i)})})$$

Probability of error in PSDU reception for fraction of packets $\delta_{ix}$ is calculated as:

$$\beta^D_{ix,p} = \sum_{y=1}^{x-1} \kappa_{ix,y} \beta^D_{iy,p} + [(1 - \sum_{y=1}^{x-1} \kappa_{ix,y}) \beta^D_{ix,s}]$$

(2.19)

and overall probability of packet error (in synchronization or PSDU reception) for fraction of packets $\delta_{ix}$ is

$$\beta^D_{ix} = 1 - [(1 - \beta^D_{ix,s})(1 - \beta^D_{ix,p})]$$

(2.20)

Average packet error rate $\beta^D_i$ on link $i$ is then:

$$\beta^D_i = \sum_x \delta_{ix} \beta^D_{ix}$$

(2.21)
PER for ACK transmissions

We now consider link $i'$ as the target link, and compute the probability that an ACK transmitted on link $i'$ overlaps with a data transmission on an interfering link $j \in \mathcal{H}_i$. Since ACKs only account for a small fraction of the time usage of the wireless medium, we ignore the interference that ACKs experience from transmission of ACKs on other links.

**Probability that an ACK transmission on link $i'$ overlaps with data transmissions:**

Following our notation, we use $\zeta_{i'j}$ to denote the probability that an ACK transmitted on link $i'$ overlaps with transmission of a data packet on link $j$. We compute $\zeta_{i'j}$ in a manner similar to $\zeta_{ij}$ and $\zeta_{ij'}$ as a sum of probabilities of occurrence of events illustrated in figure 2.7.

![Diagram of overlap of an ACK transmission on link $i'$ with data transmission on $j$](image)

Figure 2.7: Overlap of an ACK transmission on link $i'$ with data transmission on $j$
1. Probability $\zeta_{i'j}^1$ that the transaction involving the ACK on target link $i'$ starts during an ongoing transaction on link $j$ at a time such that the ACK on link $i'$ overlaps with data transmission on link $j$ (figure 2.7a):

If $t_i^D + SIFS \geq t_j^D$, the ACK portion of a transaction on link $i$ that starts during a transaction on link $j$ cannot overlap with the data transmission on link $j$. If $t_i^D + SIFS < t_j^D$, for transactions on link $i$ that start within a period $t_{ij} = t_j^D - (t_i^D + SIFS)$ from the start of a transaction on link $j$, the corresponding ACK on link $i'$ (if transmitted) overlaps with data transmission on link $j$. Thus,

\[
\zeta_{i'j}^1 = 0 \quad \text{if } t_i^D + SIFS \geq t_j
\]

\[
\zeta_{i'j}^1 = \psi_{ij} \frac{t_j^D - t_i^D - SIFS}{t_j} \quad \text{if } t_i^D + SIFS < t_j
\]

(2.22)

2. Probability $\zeta_{i'j}^2$ that the transaction involving the ACK on target link $i'$ does not start during period $t_{ij}^v$ from start of a transaction on link $j$, but a transmission on link $j$ starts during the transaction on link $i$ and overlaps with the ACK on target link $i'$ (figure 2.7b):

If $t_j^D + t_i^A < t_i$, if a transaction on link $j$ starts less than $t_j^D + t_i^A$ before the end of a transaction on link $i$, the data transmission on link $j$ of this transaction overlaps with the ACK transmission on target link $i'$. In a long time period of duration $T$ seconds, the average number of transmissions on link $j$ that start during such a part of duration $t_j^D + t_i^A$ in the transaction on link $i$ is $T\lambda_j \psi_{ji} \frac{t_j^D + t_i^A}{t_i}$, the average number of transmissions on link $i$ during this time is $T\lambda_i'$. At most one transmission on link $j$ can start during a time period $t_j^D + t_i^A$. Hence, given an ACK transmission on link $i'$, the probability that a transmission on link $j$ starts less than $t_j^D + t_i^A$ before the end of the ACK transmission and overlaps with the ACK transmission is $\frac{\lambda_j \psi_{ji} \frac{t_j^D + t_i^A}{t_i}}{\lambda_i'}$.

If $t_j^D + t_i^A \geq t_i$, all data transmissions on link $j$ that start during a transaction on link $j$ during a transaction on link $i$ overlap with the ACK transmission on link $i'$. Again, during a long time period of duration $T$ seconds, the average
number of transmissions on link \( j \) that start during a transaction on link \( i \) is \( T \lambda_j \psi_{ji} \). The average number of transmissions on link \( i \) during this time is \( T \lambda_i \). With \( t_j^D + t_i^A \geq t_i \), at most one transmission on link \( j \) can start during a transaction on link \( i \). Hence, given an ACK transmission on link \( i \), probability that a transmission on link \( j \) starts during the corresponding transaction of link \( i \) and overlaps with the ACK transmission is \( \frac{\lambda_j \psi_{ji}}{\lambda_i} \).

Thus,

\[
\zeta_{i,j}^2 = (1 - \zeta_{i,j}^1) \frac{\lambda_j \psi_{ji} t_j^D + t_i^A}{\lambda_i} \quad \text{if} \quad t_j^D + t_i^A < t_i
\]

\[
\zeta_{i,j}^2 = (1 - \zeta_{i,j}^1) \frac{\lambda_j \psi_{ji}}{\lambda_i} \quad \text{if} \quad t_j^D + t_i^A \geq t_i \quad (2.23)
\]

\[
\zeta_{i,j} = \zeta_{i,j}^1 + \zeta_{i,j}^2 \quad (2.24)
\]

Since ACKs are small in size, the probability that an ACK overlaps with transmissions on more than one link in set \( H_i \) is small. We verify this by analyzing simulation traces, and make a simplifying assumption that overlaps of an ACK transmission on link \( i' \) with links in set \( H_i \) are mutually exclusive of each other. Also, due to the same reason that ACKs are very small in size, we ignore the interference experienced by ACKs from other ACKs. We thus compute average packet error \( \beta_i^A \) for ACK transmissions on link \( i \) from probabilities \( \zeta_{i,j} \) in a similar manner as done for \( \beta_i^D \) but limiting ourselves to interfering links comprising only links in set \( H_i \) (in computation of \( \beta_i^D \), we also considered pairs of links, and links carrying ACK transmissions corresponding to data transmissions on links in \( H_i \)).

We create set \( Z_{ix} = \{Z_{ix'}\} \) comprising interference from each of the links in \( H_i \). Probability of an ACK experiencing interference situation \( Z_{ix'} \) at its start of transmission, \( \delta_{ix} = \zeta_{i,j} \) where \( j \) is the interfering link involved in interference situation \( Z_{ix'} \). Since ACK transmissions are short, we assume that interference situation does not change during the ACK transmission. Thus, for fraction of packets \( \delta_{ix} = \zeta_{i,j} \), probability of synchronization error is \( \beta_{ix,s} = F_S(\frac{P_i/T_{S(i),D(i)}}{N(D(i)) + (P_j/T_{S(j),D(i)})}, \frac{P_i/T_{S(i),D(i)}}{N(D(i)) + (P_j/T_{S(j),D(i)})}) \), probability of error in PSDU reception is \( \beta_{ix,p} = F_R(\frac{P_i/T_{S(i),D(i)}}{N(D(i)) + (P_j/T_{S(j),D(i)})}) \) where \( F_R \) maps SINR to
probability of error in reception of a 14 byte ACK packet (in computing probability of error in data transmissions, we used $F_{R_i}$ for 1528 byte packets). Overall probability of error in ACK transmission $\beta_{Ax} = 1 - \left[(1 - \beta_{Ax,s}^A)(1 - \beta_{Ax,p}^A)\right]$ We then express average packet error for ACK transmissions on link $i'$ that correspond to data transmissions on link $i$ as:

$$\beta_i^A = \sum_x \delta_{ix} \beta_{ix}^A$$ \hspace{1cm} (2.25)

Equations 2.2 through 2.25 are solved iteratively and constraint in equation 2.1 is evaluated to determine if the traffic load $\lambda$ is feasible.

### 2.6 Model Validation

We now present numerical results validating some of the steps undertaken in the development of the analytical model, followed by a comparison of the results from the analytical model with those from simulation runs.

#### 2.6.1 Validation of modeling steps

Given the complex interactions between links in a wireless mesh network, we use a high-fidelity simulator as an aid to gain insight into what aspects are important to account for in the analytical model to be accurate and what aspects can be ignored/approximated to avoid undue complexity in the model. We observe simulation results and timelines for several topologies in order to validate some of the steps taken in the development of analytical model. We present here our observations for one particular network topology shown in figure 2.8 comprising 100 nodes randomly located in a 200m x 200m area with path loss modeled by the Power Law path loss model with an exponent of 4.1. Traffic offered consists of unidirectional constant bit rate one-hop flows with 95 packets of size 1528 bytes per second between 50 distinct source-destination pairs within communication range of each other as shown in figure 2.8. Each node uses an ED threshold of -91 dBm. The maximum transmit power limit at each transmitter is 23 dBm. The physical layer at each node is 802.11a. Data rate on a link is chosen to be the highest rate supported by the PHY for which the
transmit power needed to achieve a target packet error rate of 0.02 in isolation (No Interference) is less than the maximum allowed; transmit power for the link is set to this value that achieves 2% packet error rate in isolation. ACKs are transmitted at the same data rate as the corresponding data traffic, and at a transmission power equal to a value that achieves 2% PER in isolation for the 14 byte ACK size. 95 packets per second represents the maximum uniform load on the 50 flows that can be supported in the network. In order to gain insight into some aspects such as importance of modeling acknowledgements, we run simulations with modified system behavior as elaborated below with respect to these aspects.

Figure 2.8: Topology used to justify approximations made in the development of the analytical model: 100 randomly located nodes in 200m x 200m area with unidirectional traffic between 50 distinct neighboring source-destination pairs
2.6. MODEL VALIDATION

Blocking due to cumulative energy

Figure 2.9 shows for a 40 seconds simulation run the total amount of time that the source node of each link is blocked, the amount of time that it is blocked due to energy received from a single transmission exceeding its ED threshold, and the amount of time that it is blocked due to energy received from one or two simultaneously occurring transmissions exceeding its ED threshold. It can be seen that the amount of time that a node is blocked due to energy received from a single transmission or due to cumulative energy received from two simultaneously occurring transmissions accounts almost entirely for the amount of time that the node is blocked.

![Graph showing time blocking due to energy](image)

Figure 2.9: Total time that sources of links in figure 2.8 are blocked, time they are blocked due to energy received from a single transmission, and time that they are blocked due to energy received from up to two simultaneously occurring transmissions

Importance of accounting for interference from acknowledgements

A transmission on a link in a mesh network experiences interference not only from data transmissions in its vicinity, but also from ACK transmissions in its vicinity. In order to investigate the importance of accounting for interference on data transmissions
from acknowledgements, we observe probability of retransmission on links from two different simulation runs. In one simulation run, we modify the simulator such that power received from acknowledgement transmissions is not included in the interference power for data transmissions. The other simulation run uses the proper simulator with interference power at any instant calculated as the sum of power received from all transmissions ongoing at that time, including ACKs. Figure 2.10 compares the probability of retransmission on links obtained from the two simulation runs, and highlights that it is indeed very important to account for interference from ACK transmissions. The destructive effect of acknowledgements on data transmissions has also been reported by Brážio et al. in wireless LANs with hidden nodes [62].

![Figure 2.10: Probability of retransmission on links in figure 2.8 with and without receive power from acknowledgements included in interference power](image)

**Interference due to simultaneous overlap with multiple transmissions**

Figure 2.11 shows the packet error rate on all 50 links for three different simulation runs that differ in their accounting of interference. In one simulation run, if a transmission simultaneously overlaps with more than one transmission, only the highest interference power among the powers received from the simultaneously overlapping transmissions is considered in determining whether the packet is received correctly. In another simulation run, if a transmission simultaneously overlaps with more than one
transmission, the sum of the highest two interfering powers is considered in determining whether the packet is received correctly. Finally, the last simulation run accounts for interference accurately by summing up power received from all simultaneously interfering transmissions. As can be seen, the packet error rate from considering interference from up to two simultaneously interfering transmissions is very close to the actual packet error rate considering interference from all simultaneously interfering transmissions. Thus, in the packet error rate computation in our analytical model, we only consider simultaneous overlap with up to two interfering links, and refrain from getting into the immense complexity of computing probability of simultaneous overlap with more than two interfering links.

![Figure 2.11: Packet Error Rate on all links accounting for interference from the strongest interferer, cumulative interference from the two strongest interferers, cumulative interference from all simultaneously occurring transmissions.](image)

2.6.2 Validation of analytical results

To validate numerical results from our analytical model, we consider a wireless mesh network with $F$ flows between distinct source-destination pairs. We define a vector $\alpha = [\alpha_1, \alpha_2, \ldots, \alpha_F]$ ($\sum_{i=1}^{F} \alpha_i = 1$) representing the relative traffic requirement among the flows. We use our analytical model to find the network capacity subject to the
relative traffic requirement i.e. the highest scalar $S$ such that traffic $S\alpha$ is feasible. Individual flow throughput at capacity is then $S_i = S\alpha_i$. Similarly, we find the network capacity using simulations; we gradually increase the load uniformly in accordance to the relative traffic requirement, until one or more links are unable to meet their traffic demand. Both analysis and simulations use relationship $\mathcal{F}_S$ between SINR to probability of synchronization error and relationships $\mathcal{F}_R$ between SINR to probability of error in PSDU reception, shown in figure 2.3. We compare the network capacity and link PERs at capacity from the analytical model with corresponding values from simulations.

In addition to comparing network capacity and PER values, we also compare intermediate variables of our analysis. We record a timeline of transmission start and end times for each link throughout a simulation run with traffic load on links equal to the maximum load identified as feasible by simulation. This timeline is used to compute the fraction of transmissions on a link $i$ that overlap with a transmission on another link $j$ for all ordered link pairs $<i,j>$. These values are compared to the corresponding values of $\zeta_{ij}$ from analysis at the maximum traffic load deemed feasible by the analysis.

**NOTE:** PER and overlap probability depend on the traffic load, but since the capacity points identified by analysis and simulation are close to each other, we are able to compare PER and overlap probabilities at capacity from analysis with PER and overlap probabilities at capacity from simulation.

We have extensively compared results from our analysis to those from simulation for several topologies. We present here results for a single topology shown in figure 2.12. The network consists of 32 nodes randomly located in a 90m x 90m area with unidirectional traffic between nodes within communication range. Note that while such a traffic pattern does not involve ”multihopping” of a traffic flow on multiple wireless links, it suffices for the purpose of validating that our analytical model properly captures interactions between links carrying traffic in a wireless mesh network and provides accurate results. Path loss between nodes is modeled by the Power Law path loss model with a path loss exponent $\gamma$ of 4.1 (representative of an indoor environment[13]). IEEE 802.11 OFDM PHY is used as the physical layer on each
link. Energy Detect Threshold is set to -91 dBm at each node, background noise at each node is -101 dBm, and the maximum transmit power limit at each transmitter is 23 dBm. Data packets are of size 1528 bytes at the MAC layer (including all headers). PHY rate on a link is chosen to be the highest rate supported by the PHY for which the transmit power needed to achieve a target packet error rate of 0.02 in isolation (No Interference) is less than the maximum allowed; transmit power for the link is set to this value that achieves 2% packet error rate in isolation. Transmit power and PHY rate used on each link are specified adjacent to the link in figure 2.12. ACKs are transmitted at the same PHY rate as the corresponding data traffic, and at a transmission power equal to a value that achieves 2% PER in isolation for the 14 byte ACK size. Figure 2.13 shows link throughput, packet error rate and overlap probability between pairs of links at network capacity as obtained from the analysis and simulation for equal traffic demand on all flows $\alpha_i = 0.0625 \forall i$. Figure 2.14
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shows the same for unequal relative traffic demand $\alpha = [0.0323 \ 0.0323 \ 0.0646 \ 0.0323 \ 0.1292 \ 0.1292 \ 0.0323 \ 0.0426 \ 0.0323 \ 0.1292 \ 0.0646 \ 0.0323 \ 0.0426 \ 0.1292 \ 0.0426]$. Overlap probability is shown only for pairs of links such that one of them does not block the other. For pairs of links that block each other, the overlap probability as per the analytical model is zero, and overlap probability from simulations is found to be close to zero as well. Link pairs are sorted in descending order of the overlap probability for the link pair as observed in the simulation, and values from overlap probability from analysis and simulation are plotted in this order of link pairs. Results from the analytical model match those from the simulations well, and both analysis and simulation identify link 9 as the bottleneck with equal traffic demand, and link 6 as the bottleneck with the arbitrarily chosen relative traffic demand.
2.6. MODEL VALIDATION

Figure 2.13: Model Validation: Results for topology in figure 2.12 with equal traffic demand on all links
Figure 2.14: Model Validation: Results for topology in figure 2.12 with unequal traffic demand on links
2.7 Conclusion

In this chapter, we have developed an analytical model for CSMA-based wireless mesh networks that is general (can accommodate any configuration of PHY parameters), accurate (properly accounts for complex relationships between links), and scalable to large network topologies. All analytical models previously proposed for wireless mesh networks fall short in one or more of the above respects, and thus our limited in their applicability. Our model fulfills a need for an analytical model that satisfies these key requirements, making it a powerful tool for researchers and network designers for performance evaluation. We have validated the results of our model by comparison against those from a high-fidelity simulation platform, and now use it for our work on optimizing the performance of CSMA-based wireless mesh networks.
Chapter 3

Performance Optimization

Having developed our analytical model for CSMA-based wireless mesh networks, we now study the performance of such networks with respect to network capacity i.e., the highest amount of end-to-end traffic that can be supported in the network. Given a mesh network in terms of locations of nodes and propagation characteristics between them, the performance of the network depends heavily on (i) routes used to forward traffic, and (ii) physical layer parameters (Transmit powers and data rates used on links, Energy Detect Threshold used at nodes for deeming the channel busy).

Achieving the best performance in a CSMA-based wireless mesh network requires striking the right balance between the performance of links carrying traffic and the extent of spatial reuse of the wireless medium. When a node transmits a packet on the medium, neighboring nodes sense the medium busy and are blocked from transmitting; the set of nodes blocked depends on the transmit power and ED threshold. Blocking allows the transmission of a packet to have a good chance of success by avoiding strong interference from neighboring nodes. The lower the ED threshold is, the lower is the interference and the more likely is the packet correctly received by its intended receiver. Nodes that are not blocked may transmit at the same time. That is, in a mesh network that spans a wide area, the wireless medium may be used by multiple concurrent transmissions that are spaced apart in the network. This aspect, referred to as spatial reuse, contributes significantly to the aggregate throughput of the network. While a lower ED threshold reduces interference on links and improves
the performance of individual links, it forces concurrent transmissions to be farther apart, reducing the level of spatial reuse. To achieve the best overall performance, one must find the right balance between the need to improve the performance of individual links, and the need to achieve a high degree of spatial reuse.

A typical mesh network consists of a set of nodes deployed in a physical space; the specific location of nodes is determined by various physical factors and constraints. However, nodes must be at some appropriate distance from each other to permit good communication among these nodes. An example of a deployed mesh network is Google’s mesh network in Mountain View, California [6]. It is thus reasonable to consider that mesh networks can be represented by a random but uniform placement of nodes in the space to be served according to a certain node density. Given such a mesh network, one needs to determine which links should be established, as well as the appropriate physical layer parameters that should be used on these links; namely, transmit power and data rate. One should also determine an appropriate value for the ED threshold. With the goal of achieving the best overall network performance in mind, this cannot be determined without bringing routing into the picture. Indeed, which links get used to carry traffic and thus need to be established is determined by routing; so is the distribution of traffic on links in the network.

Routing in a multi-hop network is based on finding minimum cost paths; the cost of a path is the sum of costs of links in the path. In wired networks, the cost metric of a link is often considered to be the inverse of the link bandwidth since it represents the amount of time that the link is used by a packet transmission. In wireless networks, given the multiaccess/broadcast nature of the wireless medium, errors may occur in packet transmissions due to noise and interference, and a packet may be transmitted multiple times before it is received correctly. Thus an appropriate metric is the expected transmission time (ETT) averaged over multiple packet transmissions [63]. This is in fact the default routing metric specified in the IEEE 802.11s draft, and is referred to as the Air time metric. It may also be useful to account for the number of nodes $N_B$ that are blocked during the transmission time of a packet. In this case, an appropriate routing metric would be the product $ETT.N_B$, which represents use of the medium both in time and space [64].
We note, however, that the amount of resources used in carrying traffic in the network is a function of the physical layer parameters. Indeed, the probability of success of a packet transmission on a link is function of the received signal strength at the receiver (which is function of the transmit power used by the transmitter), the data rate used, and the level and extent of interference experienced during the packet reception. The extent of interference is directly determined by the set of interferers and their physical layer parameters. The set of interferers is a function of the spatial reuse factor, which is function of the transmit power used by the transmitting node and the ED threshold values used at other nodes.

In this chapter, we address the performance of CSMA-based wireless mesh networks with respect to the configuration of the physical layer parameters and the link metric used for shortest path routing.

In section 3.1, we present a brief overview of the prior work on physical layer parameter selection and routing in wireless mesh networks. In section 3.2, we present the system model and traffic model considered.

In section 3.3, we illustrate the impact of physical layer parameters on network throughput by means of a simple network topology consisting of two identical links. We show that the optimum values of physical layer parameters depend not only on how the two links affect each other (i.e. path loss between the nodes involved), but also on the relative traffic requirement of links. Network throughput can be improved significantly if physical layer parameters are selected in accordance with the traffic requirement of links.

In section 3.4, we present a heuristic algorithm for selection of transmit power and physical layer data rate on a set of links in a mesh network so as to maximize their aggregate throughput, given relative traffic demand on the links and the ED threshold used at nodes in the network.

Since optimization of physical layer parameters in response to the current traffic pattern is impractical as traffic in the network changes dynamically, it behooves us to consider selection of physical layer parameters in a traffic-agnostic manner. In section 3.5, we develop such a traffic-agnostic algorithm for selection of transmit power and data rate on links, based on minimizing the time-space product $\text{ETT} \cdot N_B$, accounting
for potential interference. Again, the ED threshold is assumed to be given.

In section 3.6, we develop a novel link metric for routing that accounts not only for the resources used by a transmission on the link in terms of time and space, but also for the availability of resources in the neighborhood of the link.

In section 3.7 which represents the most significant contribution of this chapter, we seek to achieve the best performance in a mesh network by jointly optimizing physical layer parameters and routing. This work is in contrast to the work in the earlier sections and prior work in the field of mesh networks that focuses on routing considering physical layer parameters to be given, or focuses on physical layer parameter selection considering traffic on links to be given.

Finally, we conclude in section 3.8.

3.1 Prior Work

The problems of physical layer parameter configuration and routing in multihop wireless networks have both received a lot of attention in the research community. However, these problems have only been dealt with independently.

One stream of research focuses on routing metrics to improve end-to-end network capacity assuming values of physical layer parameters used on links are given. However, the network capacity that a routing metric is able to achieve depends heavily on the physical layer parameters that the routing function is presented with.

Another stream of work assumes that the set of links carrying traffic is known, and the impact of physical layer parameters of these links on their aggregate throughput is evaluated. Some heuristic algorithms have been proposed to select physical layer parameters on a set of links carrying traffic so as to improve their aggregate throughput. However, in reality, the set of links carrying traffic and the amount of traffic on each link as determined by the routing function depends heavily on the physical layer parameters in the first place.

None of the prior work addresses the distribution of traffic on links resulting from routing, and studies the optimum physical layer parameters and their effect given how routing may adapt to these parameters.
3.1.1 Prior work on routing metrics

Like in wired networks, routing in wireless mesh networks is based on the shortest path paradigm due to its ease of distributed implementation. Each link is assigned a cost based on a metric, and traffic from a particular source to a destination is forwarded along the path that minimizes the sum of costs of links along the path. Several routing protocols have been proposed for use in multihop wireless networks such as MANETs and wireless mesh networks based on such shortest-path computation. These routing protocols can be classified into two categories - (i) Proactive routing protocols in which each node maintains routes to all other nodes at all times (e.g. OLSR [32]). (ii) Reactive or On-demand routing protocols that attempt to establish a route from a source node to a destination node only when the source has traffic to send to the destination (e.g. AODV [33]).

Regardless of the particular routing protocol used, the routing metric used by the protocol is the key aspect that determines the distribution of traffic on links in the network and thus determines network throughput. In this section, we categorize routing metrics proposed for wireless mesh networks based on the characteristics of links that they account for, and provide a brief overview of the metrics.

Transmission Time Metrics

Routing in wired networks is typically based on using the inverse of the link bandwidth as its metric, which represents the time used on the link by transmission of a packet. With this metric, high-bandwidth links that use lesser transmission time per packet are assigned lower costs and are preferred over links with lower bandwidth resulting in selection of high-throughput paths. Following the same idea and the same goal of selecting high-throughput paths, there have been proposals to use the transmission time of a packet of a certain nominal size on a link as its metric, taking into account retransmissions due to packet errors. Such metrics include Expected Transmission Time (ETT) [63] and Medium Time Metric (MTM) [65].
Space-Time Metrics

Above routing metrics that account only for time used on a link ignore interactions between links in a wireless mesh network and the impact of using a link on the rest of the network. While in wired networks, the resource used by a transmission is purely in terms of time used on the link, in wireless mesh networks, the resource used by a transmission comprises of \textit{time} used on the medium and the \textit{space} over which transmissions are blocked during this period. Yang et al. propose a routing metric referred to as Interference-aware Resource Usage (IRU) that is the product of expected transmission time and the number of nodes blocked during the transmission \cite{64, 66}. This accounts for true space-time resource usage.

Congestion Metrics

A number of routing metrics have been proposed that account for potential throughput by means of accounting for congestion and diverting traffic around heavily congested parts of the network.

Lee and Gerla propose using the number of packets queued at each node as the routing metric for all links emanating from that node \cite{67}. Ma and Denko propose an enhanced version of the ETT metric, accounting also for the average number of packets queued at the link and the number of nodes that have selected the source of the link as the next hop for a route \cite{68}. Nguyen et al. propose a link metric that accounts for the channel utilization at the source of the link and the average contention window when transmitting frames on the link \cite{69}.

All the above load-aware link metrics only take into account the level of congestion at the link itself (in the form of number of packets queued or channel utilization). Due to the shared nature of the wireless medium, a routing metric for a link should account not only for congestion observed at the link itself, but also for congestion in its neighborhood. Using a link that may not be congested but has congested neighboring links only makes congestion worse at these neighboring links. Hassanein and Zhou propose a metric for a link that is the sum of number of active paths through the source of the link and the number of active paths through its neighboring nodes \cite{70}. 

However, the number of active paths through a node cannot be directly related with the level of congestion. Le et al. propose a metric for a link that is the sum of number of packets queued at the source and destination nodes of the link and the number of packets queued at their neighboring nodes [71].

All the above routing metrics that attempt to account for congestion ignore space-time resource usage of links which in fact determines at what load congestion is experienced in some part of the network. We present a novel routing metric that accounts for space-time resource usage of a link as well as the level of congestion experienced in the neighborhood of the link.

### 3.1.2 Prior work on selection of physical layer parameters

Physical layer parameters in a CSMA-based wireless mesh network include (i) Transmit power used on links (ii) Physical layer rate used on links (iii) Energy Detect Threshold used at nodes. Each of these parameters plays a critical role in determining network capacity along with the routes used. Maximizing network capacity requires one to optimally select each of these parameters. Prior work on selection of physical layer parameters in CSMA-based networks consists of (i) rate adaptation algorithms that focus on selection of physical layer rate and adapting the rate to variations in channel conditions (ii) selection of transmit power and data rate (iii) optimization of spatial reuse (determined by transmit power, ED threshold values) so as to maximize the aggregate throughput given traffic on a set of links.

A survey of research on selection of physical layer parameters in wireless mesh networks can be found in [72].

**Selection of physical layer rate**

There has been a large body of work on selection of physical layer rate with transmit power being fixed, in both single-hop wireless LANs consisting of user stations communicating with an access point, and multi-hop wireless networks.

In single-hop wireless local area networks consisting of user stations communicating with an access point, only one successful transmission can occur on the channel
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at any time between a user station and the access point. Clearly throughput of the WLAN is maximized if each link between a user and the access point is made to operate at the highest physical layer rate at which a low error rate can be achieved for the current channel conditions within the maximum transmit power limit. Several heuristic algorithms have been proposed for rate adaptation assuming fixed transmit power in single-hop wireless LANs with the goal of maximizing network throughput by operating links at the highest physical layer rate possible and adapting the rate setting to variations in channel conditions [73, 74, 75, 76, 77, 78, 79].

Holland et al. propose a rate adaptation protocol for multihop wireless networks with a similar goal of operating each link at the highest feasible physical layer rate [80]. The protocol makes use of the IEEE 802.11 RTS/CTS exchange, the intended destination of a transmission chooses the physical layer rate depending on the SNR and informs the source of the rate to use for the data transmission in the CTS message. Accordingly, this scheme is referred to as Receiver Based Auto Rate (RBAR). Sadeghi et al. propose a rate adaptation protocol referred to as Opportunistic Auto Rate (OAR) that is based on extending the RBAR protocol with a mechanism to allow a node that sees good channel conditions to access the channel back-to-back and exploit the good conditions [81].

While operating each link at the highest feasible rate maximizes network throughput in a single-hop wireless LAN setting with multiple users transmitting to an access point, that is not the right thing to do in a multihop network where multiple links can transmit at the same time. In wireless mesh networks, the increase in throughput on a link by operating it at a higher rate comes at the cost of a potential decrease in network throughput since the higher SINR required to operate the link at the higher rate can only be achieved by blocking transmissions over a larger part of the network, reducing spatial reuse. The overall throughput of a wireless mesh network depends not only on the throughput of individual links, but also on the degree of spatial reuse i.e. simultaneous transmissions on multiple links. As a result, the above rate adaptation algorithms that aim to operate each link at the highest feasible rate do not perform well in a multihop network setting. Wu et al. experiment with some of the above rate adaptation algorithms and static rate settings in a mesh network test-bed.
and rightly observe that throughput can be significantly improved when links are operated at an intermediate rate setting compared to using the above rate adaptation algorithms or using a static setting corresponding to the highest rate feasible [82].

Selection of transmit power and physical layer rate

Toumpis and Goldsmith analyze the capacity regions of TDMA-based multihop wireless networks consisting of a few nodes as a function of the rate, power used on links and the transmission schedule [83, 84]. Peng et al. propose a heuristic to appropriately select transmit power, rate and transmission schedule in a TDMA-based multihop network so as to achieve good network throughput [85]. In the context of CSMA-based networks, Ruffini and Reumerman propose a rate-power adaptation procedure based on minimizing a cost function that is the product of packet transmission time and the number of nodes blocked by the transmission [86]. However, in their evaluation of packet transmission time, they only consider retransmissions due to channel errors and ignore interference.

Optimization of spatial reuse

Yang and Vaidya focus on links between transmitters and receivers that are separated by the maximum transmission range and seek the optimum blocking distance so as to maximize the aggregate throughput of such links [87]. The authors consider that a transmission on a link always experiences interference from transmissions on six first-tier interferers located at blocking distance $D$ from the source of the link, and separated by distance $D$ from each other. Considering that the throughput of a link is a function of its SINR as given by Shannon’s capacity equation, they show that network throughput taking into account spatial reuse is maximized at an optimum ratio of blocking distance $D$ to link length $l$ that is determined by the propagation path loss exponent $\gamma$ of the environment (optimum ratio = 3.2 for $\gamma = 3$).

In [88], the same authors as above propose a heuristic algorithm in which each node selects the ED threshold and physical layer rate to use for different links and dynamically updates it based on local knowledge regarding transmission successes.
and failures. In [89], the authors propose a heuristic algorithm for selection of ED threshold, transmit power and physical layer rate to maximize aggregate throughput of links, given a set of links carrying traffic. The ED threshold is selected to the same value at all nodes, such that the longest link between nodes separated by the maximum transmission range can be operated at the lowest physical layer rate. Each node selects the transmit power and physical layer rate for each link and dynamically updates this value as conditions change.

As we show later by jointly considering physical layer parameters and routing, highest network capacity is achieved when the range of link lengths used for carrying traffic is the shortest possible without detours, and physical layer parameters are selected so as to achieve the highest throughput on this range of link lengths. Thus, if the network topology permits use of shorter links, as is the case in the topology we consider, links between nodes separated by the maximum transmission range never get used and it would be wrong to select physical layer parameters based on assuming usage of these long links. Such a choice of physical layer parameters would yield suboptimal results.

3.2 System Model and Traffic Model

3.2.1 System Model

We consider a mesh network in which each node is equipped with an omnidirectional antenna, and all links operate on the same radio channel. Nodes use IEEE 802.11 DCF for medium access. The RTS/CTS feature is not used. Clear channel assessment is based on the energy level sensed, nodes consider the medium busy when they sense an energy level greater than the ED Threshold.

We use our analytical model from chapter 2 to obtain numerical results for network capacity in this chapter. The model as developed in chapter 2 accounts for acknowledgements (ACKs) with respect to the time occupied by acknowledgements, the possibility of errors in reception of ACKs, and the interference caused by ACKs.
on data transmissions. The numerical results presented in this chapter use a simplified version of the model that accounts for time occupied by ACKs, but assumes that ACKs are always successful and ignores the interference caused by ACKs on data transmissions.

The receiver model is considered to be as described in section 2.4 of Chapter 2. As in Chapter 2, we consider the physical layer to be that as per the IEEE 802.11a OFDM specification, with rates 9 and 18 Mbps not used due to reasons described in Chapter 1. The receiver characteristics pertaining to synchronization and packet reception considered in chapter 2 are used (shown in figure 2.3). As is often done in the literature and as was done in Chapter 2, one may consider that interference can be modeled as AWGN, and consider the above receiver model to be valid for the combined effect of noise and interference. This is referred to as SNR-based receiver model in this chapter. Numerical results in sections 3.3 through section 3.6 are derived using the SNR-based receiver model.

However, we recognize that receiver performance in the presence of interference may be different from that in the presence of noise. Measurements conducted by the same authors of [61] in the same environment have shown that the effect of interference due to transmissions from other nodes in the same network may not be as severe as that of white noise of the same power. Considering a high level of interference, exceeding noise by 10 dB, measurement results have shown that the synchronization error and PSDU error curves as a function of SIR are those in the above model but shifted by 5 dB to the left. That is, equal error rates are achieved with an SIR 5 dB smaller than SNR [12]. These results were confirmed to hold when interference is caused by a single interferer or two interferers overlapping in time. There is reason to believe that they hold also when the number of interferers is greater than two. In any case, as indicated in Chapter 2, the likelihood of a transmission experiencing simultaneous interference from more than two interferers in a mesh network is extremely low, and thus this model is applicable. We refer to this model as the SIR-based receiver model in this chapter.

In section 3.7 that addresses optimization of network performance by joint optimization of physical layer parameters and routing, we show that when the maximum
allowed transmit power of 29 dBm is used in the network topology considered, the level of interference experienced by links used for carrying traffic exceeds noise by 10 dB. We thus use the SIR-based receiver model in this section. Moreover, in this section, we show the sensitivity of results to the receiver model used.

3.2.2 Traffic Model

The performance of a wireless mesh network depends on the particular usage scenario(s) supported. Typical usage scenarios include a combination of: (i) traditional data applications such as web browsing, file transfers and downloads, and electronic mail, (ii) voice communication, and (iii) video streaming and conferencing. A general assessment of the performance of mesh networks supporting any combination of these is quite complex. We limit ourselves to stream-type traffic as is the case with voice and video communication. We consider end-to-end traffic to consist of constant bit rate flows, where the rate and size of packets is determined by the applications throughput and delay requirements. Voice traffic typically consists of fixed size packets carrying data corresponding to 20 ms of speech generated at equal intervals of 20 ms. The amount of data carried in a packet is dependent on the voice encoding scheme: for G.711, the data rate is 64 Kbps; for G.729, the rate is 8 Kbps. Video consists of a succession of frames with a constant frame rate. Encoded frames differ in type (I, P and B types), and thus in the amount of data required to encode them and the role they play. A packet may contain either a complete frame or a portion of a frame depending on the encoded video data rate, the type of frame in question, and the maximum packet size allowed. The data rate of a video stream varies widely depending on the content and the desired quality, as well as the encoding scheme. In the context of wireless networks, it is reasonable to consider that the data rate per stream is in the range of 64 Kbps to 384 Kbps.

In a real network supporting stream traffic, requests for communication are random in time and space. We consider that: (i) the source node and destination node for a request are randomly selected among all nodes in the network, (ii) the times at which such requests are made are random in time following a stochastic process (e.g.,
Poisson process), and (iii) the duration of the communication for each request is also random (e.g., following an exponential distribution with a certain mean duration). We also consider that the flows corresponding to these requests maintain their routes fixed throughout the entire duration of the communication. Given a certain set of flows already present in the network, when a new request is generated, a path from the source to the destination is selected according to the routing metric. Then a test is made to guarantee that the selected path can accommodate the new flow. If the test is positive, the new flow is routed on the selected path; otherwise it is rejected. With these considerations, the capacity of the network may be expressed in terms of the highest rate of requests that can be supported given a certain target rejection rate. The capacity of the network may also be expressed in terms of the maximum average number of flows that can be simultaneously supported, or equivalently in terms of the maximum aggregate data load that can be supported, summing the throughput of all flows.

### 3.3 Two Link Topology

We now address selection of physical layer parameters on links in a wireless mesh network. We start by illustrating the improvement in aggregate throughput that can be obtained by optimum selection of physical layer parameters, by means of a network topology consisting of two links. We show that the optimum choice of physical layer parameters depends not only on the location of the two links in the network with respect to each other, but also on their relative traffic demands.

Consider the scenario in figure 3.1 comprising of two parallel links of length 20 m each, located in an environment with path loss modeled by the power law path loss model with a path loss exponent of 3. We uniformly increase the rate of traffic on each link to find the highest throughput that can be achieved for different transmit power and data rate settings. Results are derived using the SNR-based receiver model.

We first search over the allowed transmit power and PHY rate space to find the optimum transmit power and PHY rate that results in the highest throughput on each link. Figure 3.2 shows the highest achievable throughput on each link with use
of optimum transmit power and physical layer data rate on each link as a function of the separation between the two links. It can be seen that as the separation between links is increased, up to a certain separation (120 m), it is better that the two links use the highest data rate that they can achieve (54 Mbps in this case), block each other and share the medium. Up to this point of separation, transmitting simultaneously with any transmit power and data rate setting results in a lower throughput than that can be achieved by sharing the medium. As the separation is increased beyond this, the links are able to transmit simultaneously at a lower data rate with low enough packet error and achieve a higher throughput than if they transmitted at the highest physical layer rate and shared the medium. The optimum values of data rate and transmit power are shown in figures 3.3(a) and fig 3.3(b) respectively. For separation up to 120m, the optimum ED threshold is any value lower than the power received at the source of one link from a transmission on the other link, thus forcing the two links to share the medium. For separation greater than 120m, the optimum ED threshold is any value higher than the power received at the source of one link from a transmission on the other link, allowing the two links to transmit simultaneously.
With separation between the two links in this region, it is best to share the medium at the highest PHY rate feasible.

With separation between the two links in this region, it is better to allow the links to transmit simultaneously at an appropriate transmit power and PHY rate.

Figure 3.2: Highest achievable throughput on each link in the topology in figure 3.1, with use of optimum transmit power and physical layer data rate.
3.3. TWO LINK TOPOLOGY

With separation between the two links in this region, it is best to share the medium at the highest PHY rate feasible.

With separation between the two links in this region, it is better to allow the links to transmit simultaneously at an appropriate transmit power and PHY rate.

(a) Optimum physical layer rate

(b) Optimum transmit power

Figure 3.3: Optimum transmit power and PHY rate to maximize throughput in topology in figure 3.1
CHAPTER 3. PERFORMANCE OPTIMIZATION

If on the other hand, each link operated in a selfish mode at the highest feasible physical layer data rate of 54 Mbps, with the maximum transmit power of 29 dBm, and say the ED threshold used in the network was -91 dBm, for values of separation between the links up to 280m, the links would block each other and each link would get a throughput of approximately 17.5 Mbps as shown in figure 3.4(a). If for the same ED threshold, each link operates at the highest feasible PHY rate (54 Mbps for the attenuation along the link length considered), but using a transmit power that is enough to achieve an average packet error of 10% in isolation (17.96 dBm), the throughput achieved on each link is as shown in figure 3.4(b). The links now start transmitting simultaneously at a shorter separation of 120m, but interference is very strong, resulting in high packet error rates at the high PHY rate of 54 Mbps. For separation between 120m and 180m, the achieved throughput is now infact lower than if the links used a higher transmit power and continued to share the medium.

We see from figures 3.2 and 3.4 that network throughput can be significantly improved by using optimum transmit power and data rate on each link that accounts for the interference from the other link. The optimum transmit power and data rate to use depends not only on the values of path loss between nodes, but also on the relative traffic demand between links. We define the relative traffic demand as a vector $\alpha = [\alpha_1, \alpha_2]$ ($\alpha_1 + \alpha_2 = 1$). For the same scenario of figure 3.1 with separation between links fixed at 150m, we now consider two different relative traffic demands (i) $\alpha = [0.67, 0.33]$, i.e. one link is required to support twice the throughput of the other link (ii) $\alpha = [0.8, 0.2]$, i.e. one link is required to support four times the throughput of the other link. Table 3.1 shows the highest throughput that can be achieved on the two links using optimum transmit power and PHY rate settings found by exhaustively searching over the range of transmit power and data rate. Along with this highest achievable throughput using the optimum transmit power and data rate, the table also shows for comparison purposes the throughput on each link if the links are operated at the optimum transmit power and data rate found earlier for an equal traffic demand.
3.3. TWO LINK TOPOLOGY

With link separation in this region, the links block each other and share the medium. Thus, each link gets half the achievable throughput at 54 Mbps.

With separation between the two links in this region, the links transmit simultaneously.

(a) Transmit power = 29 dBm

With separation between the two links in this region, they block each other and share the medium.

With separation between the two links in this region, the links transmit simultaneously and interfere with each other. Throughput on each link is low due to PER from interference. PER decreases and throughput increases with increasing separation between links.

(b) Transmit power reduced to achieve 0.1 PER in the absence of interference

Figure 3.4: Throughput on each link in the topology of figure 3.1 with each link operating at 54 Mbps, ED threshold = -91 dBm
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<table>
<thead>
<tr>
<th>Relative demand = [0.67 0.33]</th>
<th>Relative demand = [0.8 0.2]</th>
</tr>
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<tr>
<td><strong>Throughput</strong></td>
<td><strong>Throughput</strong></td>
</tr>
<tr>
<td>with optimum transmit</td>
<td>with optimum transmit</td>
</tr>
<tr>
<td>power and PHY rate setting</td>
<td>power and PHY rate setting</td>
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<tr>
<td>28.12 Mbps</td>
<td>29.37 Mbps</td>
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<td>14.06 Mbps</td>
<td>7.34 Mbps</td>
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<tr>
<td><strong>Optimum PHY rate</strong></td>
<td><strong>Optimum PHY rate</strong></td>
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<tr>
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<td>48 Mbps</td>
</tr>
<tr>
<td>24 Mbps</td>
<td>12 Mbps</td>
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<td><strong>Optimum transmit power</strong></td>
<td><strong>Optimum transmit power</strong></td>
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<tr>
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<td>20.5 dBm</td>
</tr>
<tr>
<td>14 dBm</td>
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<tr>
<td><strong>Throughput</strong></td>
<td><strong>Throughput</strong></td>
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<td>power and PHY rate setting</td>
<td>power and PHY rate setting</td>
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<tr>
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<td>(36 Mbps, 20.75 dBm)</td>
</tr>
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<td>21.64 Mbps</td>
<td>22.82 Mbps</td>
</tr>
<tr>
<td>10.82 Mbps</td>
<td>5.7 Mbps</td>
</tr>
</tbody>
</table>

Table 3.1: Throughput on each link for two different unequal traffic demands

We can see from table 3.1 that the optimum transmit power and PHY rate setting is sensitive to the relative traffic demand of links, and such an optimum setting found knowing the relative traffic demand can result in an improvement in throughput compared to using the optimum settings found assuming equal traffic demand on links. In essence, the link with a lower relative traffic demand can be made to operate at a lower data rate and transmit power, causing less interference to the link with a higher relative traffic demand and allowing it to operate at a higher data rate. We now develop a heuristic algorithm for finding transmit powers and data rates on links so as to maximize the throughput on links in a mesh network, given the relative traffic requirement on links.
3.4 Transmit power and rate selection given traffic

Given a relative traffic requirement $\alpha = [\alpha_1, \alpha_2, ... \alpha_L]$ on links in a wireless mesh network ($\sum_{i=1}^{L} \alpha_i = 1$), ED threshold setting at each node, and average path loss between all pairs of nodes, we seek to obtain the transmit powers and PHY rates that results in the highest scalar $S$ such that traffic $S\alpha$ can be supported in the network. Since $\sum_{i=1}^{L} \alpha_i = 1$, the highest value $S^*$ of the scalar $S$ is the aggregate network throughput or capacity subject to the relative traffic requirement $\alpha$. We search for the transmit power and PHY rate setting that maximizes the aggregate network throughput by using a greedy heuristic algorithm. Our heuristic algorithm is presented in figure 3.4. We start by initializing the PHY rate on each link to the minimum PHY rate supported by the PHY, and using a transmit power that achieves a low target packet error rate (e.g. 10%) in isolation. We then search for the transmit power settings that allows us to scale the traffic load to the highest value $S\alpha$. We identify the bottleneck link at which the fraction of time channel is busy plus the fraction of time spent in backoff equals one at this highest load. The traffic load can be scaled up further by increasing the PHY rate at the bottleneck link or at one of the links that block the bottleneck link. We refer to the set of links consisting of the bottleneck link and links blocking it as the candidate set. We test for the network capacity $S\alpha$ with an increase in the PHY rate by one level on each link in the candidate set, one at a time, keeping the PHY rate of all other links unchanged. We increase by one level the PHY rate of the candidate link that results in the highest network capacity. At each step corresponding to new PHY rate settings of links, we keep a record of the highest capacity $S\alpha$ observed so far, and the corresponding PHY rates and transmit powers on links. The procedure is continued until the PHY rate at the bottleneck link and all other links in the candidate set reaches the maximum rate supported by the PHY.
1. **Initialization**: Rate $R_i$ on link $i = r_{min}$ $\forall$ $i$; Power $P_i$ on link $i =$ power that achieves $PER = PER_{target}$ at rate $r_{min}$ on link $i$ in isolation.

2. **Identify network capacity and bottleneck link**: Find the highest scalar $S$ such that traffic $S\alpha$ is feasible, and the bottleneck link $b$ that is unable to support its traffic if the traffic load is scaled beyond $S\alpha$. $S$ is referred to as the network capacity. Candidate set $C_S = b \cup$ Links that block link $b$.

3. Highest network capacity $S^* = S$, chosen PHY rates $R^* = \{R_i\}$, chosen transmit powers $P^* = \{P_i\}$.

4. **Search for transmit power settings to increase $S$ for current PHY rate settings**: Repeat the following steps until the network capacity $S\alpha$ cannot be increased any more by increasing transmit power of any link in set $C_S$

   - Initialize $S_{test}^* = S^*$.
   - For each link $j$ in $C_S$
     - Find network capacity $S_{test}$ with transmit power on link $j$ increased to $P_{j_{test}} = P_j + P_{increment}$, transmit power on all other links unchanged.
     - If $S_{test} > S_{test}^*$, $S_{test}^* = S_{test}$.
   - For the candidate link $k$ that results in the highest value of capacity $S_{test}^*$, if $S_{test}^* > S^*$ increase $P_k = P_k + P_{increment}$
   - If $S_{test}^* \leq S^*$, quit transmit power search

5. Search for an increase in PHY rate that achieves highest network capacity: Initialize $S_{test}^* = 0$. For each link $j$ in candidate set $C_S$,

   - If $R_j < r_{max}$, with PHY rate on link $j$ increased to $R_{j_{test}} =$ next higher rate above $R_j$ (PHY rates on all other links unchanged), find highest network capacity $S_{test}^*$ and corresponding transmit powers $P_{test}$ using transmit power search in step 4.
   - If $S_{test} > S_{test}^*$, $S_{test}^* = S_{test}$, $P_{test}^* = P_{test}$.

6. If there is no link with $R_j < r_{max}$, quit transmit power and PHY rate search. Highest network capacity = $S^*$, chosen PHY rates $R^* = \{R_i\}$, chosen transmit powers $P^* = \{P_i\}$.

7. For the candidate link $k$ that results in the highest value of capacity $S_{test}^*$, increase $R_j = R_{j_{test}}$, set $P_{current} = P_{test}^*$, go to step 5

Figure 3.5: Heuristic algorithm to obtain transmit power and PHY rate settings for links in a CSMA-based wireless mesh network that result in the highest network throughput, given relative traffic requirements on links in the network
Numerical results: Transmit power and data rate selection to maximize network capacity for a given relative traffic demand

Consider the network shown in figure 3.6, consisting of 16 randomly located nodes in a 180m x 180m area with a path loss exponent of 4.1. ED threshold = -91 dBm at all nodes. We are given traffic on 8 unidirectional links between neighboring nodes, with a relative traffic requirement $\alpha = \{0.0385 \ 0.154 \ 0.154 \ 0.0385 \ 0.154 \ 0.154 \ 0.154 \ 0.154\}$, i.e. the offered load on links 1 and 4 is one-fourth that on all other links. We apply the above algorithm to find the optimum transmit powers and physical layer data rates so as to achieve the highest aggregate throughput on the links subject to this relative traffic demand. SNR-based receiver model is used\(^1\).

Figure 3.6: Example illustrating impact of rate, power choice on network throughput

With each link made to operate at the highest physical layer data rate that achieves a PER less than 10% in isolation within a transmit power limit of 29dBm, and transmit powers found using step 4 in figure 3.4, the data rates used on the links\(^1\)Synchronization is assumed to be free of errors. These results were derived using our analytical model before the model was enhanced to account for the likelihood of synchronization error as a function of SINR.
are \{54, 54, 54, 48, 48, 54, 54, 54\} Mbps respectively as shown in figure 3.7(a), and the transmit powers used are \{22.9, 26, 10.65, 28.9, 27.12, 28.78, 25.46, 12.52\} dBm respectively as shown in figure 3.7(b). The throughput of each link at capacity is shown in figure 3.7(c), and the energy used in transmissions on each link (computed as the product of transmission time \(\frac{T_M}{1 - PER}\) and transmit power \(P_t\)) is shown in figure 3.7(d). The network capacity is 33 Mbps and aggregate energy used in transmissions on all links is 578 nW-Hr.

With transmit powers and data rates determined by our heuristic in figure 3.4, the PHY rates used on links are \{6, 24, 24, 12, 24, 24, 24\} Mbps respectively as compared to the previous PHY rate setting in figure 3.7(a), and transmit powers used are \{13.38, 20.51, 2.11, 23.55, 23.15, 23.63, 17.83, 7.63\} dBm respectively as shown in figure 3.7(b). The throughput of each link at capacity with use of these transmit powers and rates is compared to throughput under highest feasible PHY rate setting in figure 3.7(c), and the energy used in transmissions on each link is compared in figure 3.7(d). The aggregate network throughput under this setting is 84 Mbps and the aggregate energy used in the network for transmissions is 207 nW-Hr.

Thus, we see that network throughput can be greatly improved by appropriate selection of transmission power and PHY rate on links. Although our heuristic algorithm aims to maximize network throughput with no consideration for energy, it is important to note that network throughput is maximized due to improved spatial reuse by using a lower transmit power compared to that required for operating at the highest PHY rate, and this also decreases the energy utilization. For our example topology, we find that using the appropriate transmission power and PHY rate on links can result in a 154% increase in capacity with a 64% decrease in energy used for transmission.
3.5 Traffic-independent power and rate selection

The above section has addressed selection of transmit power and data rate on links in a wireless mesh network so as to maximize the aggregate throughput of a set of links, given relative traffic requirement on the links. With traffic flows starting and ending in a network in a dynamic manner, instead of wanting to maximize the throughput on a set of flows, an alternative goal may be to maximize the likelihood of being able to accept a new flow without affecting throughput of existing flows. In that case,
CHAPTER 3. PERFORMANCE OPTIMIZATION

given the traffic currently being carried on links in the network, transmit powers and data rates have to be chosen so as to maximize the minimum value of the fraction of channel time sensed idle at nodes in the network. However, regardless of the goal, if transmit power and data rate choices are made depending on the current traffic in the network, these choices have to be constantly adapted with variation in traffic. Since the value of the metric of a link used for routing depends heavily on its transmit power and/or physical layer data rate, such constant adaptation of transmit power and data rate would also drastically change the metric value with traffic, possibly changing the routes for traffic that determined the traffic pattern on links in the first place. It becomes impractical to operate a network in this manner with transmit powers, physical layer rates and routes constantly changing with traffic. Thus, it behooves us to consider a transmit power and physical layer rate selection mechanism that captures interactions between links, but does not depend on the current state of the network with respect to traffic.

We now develop such a heuristic for selecting transmit power and data rate on links in a wireless mesh network, ED threshold is assumed to be given. Our heuristic algorithm is based on selecting the transmit power and data rate on each link such that its space-time resource utilization expressed as the product $\text{ETT}.N_B$ is minimized. However, a major challenge in developing such an algorithm is that of accounting for interference. $\text{ETT}$ depends on the physical layer parameter values of interfering links and the traffic being carried on these links.

In order to achieve our design goal of being independent of the current traffic in the network, we account for interference as follows. For each link $i$, we identify the set of nodes that are not blocked by a transmission on the link (nodes at which power received due to a transmission on link $i$ alone is less than ED threshold). Among these unblocked nodes, we identify the node that when transmitting on its shortest link results in the strongest interference power $I_{\text{target}}$ at the receiver of link $i$. For each PHY rate $r$, we find the transmit power $P_r$ required to achieve a low target packet error rate $P_{\text{ERR}}_{\text{target}}$ in the presence of interference $I_{\text{target}}$, and the number of nodes blocked $N_{B_r}$ when transmitting at power $P_r$. We choose the PHY rate $r_*$ and transmit power $P_{r_*}$ that results in the minimum value of the product $T_{m_r}N_{B_r}$ where
3.5. **TRAFFIC-INDEPENDENT POWER AND RATE SELECTION**

$T_{m_r}$ is the amount of channel time used for a single transmission on the medium at PHY rate $r$.

Note that the selection of transmit power used on a link depends on the transmit powers used by the potential interferers on their shortest links, which in turn depend on the transmit powers of their potential interferers. Thus, selection of transmit powers and rates on all links in the network follows an iterative process. Each node periodically advertises the minimum transmit power among the transmit powers it uses on its links. A node $X$ hearing such advertisements compiles a *Potential Interference Report* and broadcasts it over one hop so that nodes that nodes that have a link to node $X$ are made aware of the minimum transmit powers being used by nodes in $X$’s neighborhood. Source of a link $i$ that has not heard any Potential Interference reports from the destination of the link starts by selecting a transmit power and PHY rate on link $i$ that achieves the target packet error rate $PER_{target}$ and minimizes the product $T_{m_r} N_{B_r}$ in the absence of interference, and reports the minimum of these transmit powers on its links as its minimum transmit power. As the node receives Potential Interference reports from destinations of its links, it updates its choice of transmit power and PHY rates on its links and the minimum transmit power level that it reports in its advertisements.

Figure 3.8 describes one iteration of the transmit power and rate selection algorithm for a link $i$. We refer to our algorithm as the *Minimization of Interference-aware Space-Time resource usage (MIST)* algorithm. The algorithm as presented here is executed for each link at its source and assumes knowledge of the following each node for each link $i$ emanating from it.

1. Path loss from the source of the link to all its neighbors.

2. Path loss from all neighbors of the destination of the link to the destination of the link.

3. For each neighbor of the destination, the minimum transmit power $P_{min}$ among transmit powers used on all links emanating from it

Path loss from a node $X$ to all its neighbors can be assessed in a network simply by periodically transmitting broadcast probes containing the transmit power used
for the probes. A Node $Y$ receiving the probe record the power level at which the probe was received and can thus calculate the path loss from the originator of the probe to itself. Node $Y$ includes in its probes the identities of the nodes from which probes were received and the power level at which the probes were received. Thus, node $X$ on receiving probes from its neighbors such as $Y$ knows the power levels at which the neighbors are receiving its probes, and can compute the average path loss to its neighbors. In addition, each node $Y$ broadcasts over one hop path loss from its neighbors to itself allowing nodes that have a link to node $Y$ to know the path loss from potential interfering nodes to node $Y$. The minimum transmit power used by potential interferers is conveyed in Potential Interference reports as discussed above.

1. For each rate $r = \{R_1, R_2, ..., R_{max}\}$ supported by the PHY

   (a) Search through transmit power range $P_{min}$ to $P_{max}$ in increments of $P_{increment}$.
   
   For each tested transmit power $P_{test}$
   
   i. Compute the set of nodes blocked and number of nodes blocked $N_B$, knowing path loss to all neighbors and ED threshold at each neighbor.
   
   ii. From the neighbors advertised by the destination of the link, path loss from these neighbors to it, and the value of $P_{min}$ for each of these nodes, find the unblocked node that results in the highest interference power at the destination of the link.
   
   iii. Knowing path loss to the destination, SINR to PER mapping, compute PER for the link when experiencing interference from the interferer identified above transmitting at a transmit power level of $P_{min}$ advertised by it.
   
   iv. If $PER < PER_{target}$, terminate the transmit power search for PHY rate $r$.
   
   Set $P_r = P_{test}$, $N_{B_r} = N_B$.

2. Above step results in a vector of $\{P_r, N_{B_r}, T_{M_r}\}$ elements, one for each PHY rate $r$ where $T_{M_r}$ is the channel time per transmission of a packet of a certain nominal size at rate $r$. Operate link at PHY rate $r^*$ for which product $T_{M_r^*}N_{B_r^*}$ is the minimum, and at transmit power $P_{r^*}$.

Figure 3.8: Traffic-independent algorithm to obtain transmit power and data rate settings for links in a CSMA-based wireless mesh network based on accounting for potential interference - Minimization of Interference-aware Space-Time resource usage (MIST) algorithm
3.5. TRAFFIC-INDEPENDENT POWER AND RATE SELECTION

We consider the network in figure 3.9 consisting of a grid of nodes with a distance of 20 m between adjacent nodes along each dimension of the grid. Traffic is being carried on 14 parallel paths of 14 hops each as shown in the figure.

Figure 3.9: An outdoor wireless mesh network consisting of a grid of nodes, distance between adjacent nodes along each dimension = 20m, path loss exponent = 3; Traffic is being forwarded on 14 parallel paths, each path consisting of 14 links of length 20m each

We consider transmit power and PHY rate configured according to the following three schemes. An ED threshold of -91 dBm is used at each node. For each scheme we evaluate the highest equal traffic load that can be supported on each of the 14 paths, and the packet error rate on each link at this highest load.

- **Scheme 1:** Each link is operated at the highest PHY rate feasible with a PER less than 10% in the absence of interference within a transmit power limit of 29 dBm, Transmit power used is that needed to achieve 10% PER in the absence
of interference. Thus, in this scheme, each link operates in a selfish mode at the highest feasible PHY rate.

- **Scheme 2:** At each link, for each PHY rate, the transmit power required to achieve a PER of 10% in the absence of interference and the corresponding value of number of nodes blocked $N_B$ is computed. The link is operated at the PHY rate that results in the lowest $T_mN_B$ value and the corresponding transmit power. This schemes minimizes the space-time resource usage, ignoring interference.

- **Scheme 3:** Transmit power and PHY rates are determined as per our MIST algorithm described in figure 3.8, with a target packet error rate $PER_{target}$ of 0.3 in the presence of interference from the unblocked interfering that results in the highest received power at the destination of the link when transmitting at its minimum transmit power.

Table 3.2 shows the transmit power and PHY rate used on each link as a result of using the above three schemes, and the aggregate network throughput i.e. the sum of equal traffic loads that can be supported on the 14 flows. Results are derived using the SNR-based receiver model\(^2\).

<table>
<thead>
<tr>
<th>Transmit power and PHY rate selection scheme</th>
<th>PHY rate used on each link</th>
<th>Transmit power used on each link</th>
<th>Aggregate network throughput with equal traffic on all 14 flows</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scheme 1</td>
<td>54 Mbps</td>
<td>17.78 dBm</td>
<td>3.22 Mbps</td>
</tr>
<tr>
<td>Scheme 2</td>
<td>12 Mbps</td>
<td>0.36 dBm</td>
<td>3.22 Mbps</td>
</tr>
<tr>
<td>Scheme 3</td>
<td>24 Mbps</td>
<td>8 dBm</td>
<td>7.7 Mbps</td>
</tr>
</tbody>
</table>

Table 3.2: Aggregate throughput of flows in figure 3.9 for different transmit power and physical layer data rate configurations; ED threshold = -91 dBm

Figure 3.10 shows the packet error rates on the links with the highest supported

\(^2\)Synchronization is assumed to be free of errors. These results were derived using our analytical model before the model was enhanced to account for the likelihood of synchronization error as a function of SINR.
equal traffic load being carried on the 14 flows for each of the above three schemes. We see from the results in table 3.2 and figure 3.10 that the aggregate network throughput is much lower with transmit powers and PHY rates selected as per the first two schemes, as compared to the aggregate network throughput with transmit powers and PHY rates selected as per our algorithm described in figure 3.8. The low throughput with scheme 1 is because each link operates at the highest feasible PHY rate, resulting in very low spatial reuse. Each link shares the medium with a large number of links resulting in low network throughput. In scheme 2, each link is configured to operate at the PHY rate that minimizes the \( T_m N_B \) product with transmission power chosen so as to achieve 10% PER in the absence of interference. While this increases the degree of spatial reuse, links experience considerably high packet error rates due to interference that was ignored in the transmit power and rate selection. The MIST algorithm that selects transmit power and PHY rate so as
to minimize the $T_m N_B$ product taking into account interference not only results in good spatial reuse, but also results in efficient operation of links with low packet error rates, thereby improving network throughput considerably compared to the other two schemes.

Note that the MIST heuristic algorithm is based on two main design parameters - (i) estimate of interference (ii) Target PER in the presence of the interference estimated above. We have considered only one choice for each of these design parameters. Interference was estimated to be that due to the unblocked interferer which when transmitting with the minimum transmit power among its transmit powers on different links, results in the strongest interference at the receiver of the link under consideration. We consider unblocked nodes to be transmitting with their minimum transmit power in estimating interference, because routing metrics such as $ETT.N_B$ that minimize space-time resource utilization tend to use "short" links with lower transmit power and hence low $N_B$ assuming the transmit power of links has been set appropriately to ensure good performance in terms of $ETT$. Target PER in the presence of interference was considered to be 0.3. How the transmit power and data rate assignments and the resulting network throughput varies with different choices for these two design parameters has not been addressed.

3.6 Congestion Aware Space Time (CAST) Routing Metric

We now develop a novel routing metric for wireless mesh networks that accounts for the space-time resources used by a link, as well as the level of congestion at the nodes blocked by a transmission on the link. While the IRU/$ETT.N_B$ routing metric accounts for the time used by a successful transmission on a link and the number of nodes blocked during that time, it ignores the throughput that can be achieved on the link. Given traffic flows being carried in the network at any time, the additional throughput that can be supported on a link without affecting the throughput of flows present in the network depends on (i) The fraction of time that is sensed idle at the
source of the link with the backoff counter at zero, and (ii) the fraction of time sensed idle with backoff counter at zero at nodes blocked by the link. Thus, we propose the following routing metric that accounts for resources used by a transmission on the link in terms of time on the medium and the space blocked in the network, as well as for the level of congestion at the source of the link and at nodes blocked by transmissions on the link. We refer to our metric as the Congestion-Aware Space-Time (CAST) metric. The level of congestion in the neighborhood of the medium is accounted for as the sum of inverse of idle time fractions at the nodes blocked by a transmission on the link including the source node of the link. The metric for a link \( i \) in the network is given by

\[
CAST \text{ Metric for link } i = \frac{1}{1 - PER_i} \cdot \frac{T_{m_i}}{\sum_{K \in B_i^+} \frac{1}{\tau_{idle_K}}}
\]

where \( PER_i \) is the packet error rate on link \( i \) given the current traffic in the network, \( T_{m_i} \) is the channel time used by a single transmission of a packet of a certain nominal size on link \( i \), \( B_i^+ \) is the set of nodes blocked by a transmission on link \( i \) including its own source, and \( \tau_{idle_K} \) is the fraction of time at node \( K \) such that the medium is sensed idle and the node is not counting down backoff slots.

Note that with no traffic in the network, the above metric for a link is equivalent to \( ETT \cdot N_B \) since \( \tau_{idle} = 1 \) at each node blocked and sum of inverse of idle time fractions at nodes blocked by the link is equal to the number of nodes blocked \( N_B \). However, with traffic in the network, in the computation of routing metric for a link, each node blocked is weighted by the level of congestion at the node. Thus, a link that sees a low \( \tau_{idle} \) or that blocks a node with low \( \tau_{idle} \) is assigned a high metric value and the routing function will try to route around such a link.

To evaluate the performance of the CAST routing metric, we consider a mesh network with 400 nodes located in a geographical area of 600m x 600m. One node is randomly located in each 30m x 30m square. The network topology is shown in figure 3.11. Path loss exponent \( \gamma = 3 \), representative of outdoor networks. An ED threshold of -91 dBm is used, and transmit powers and data rates are configured on links using the MIST algorithm described in section 3.5 with \( PER_{target} = 0.3 \).

We consider traffic flows arriving at a uniform rate of \( \lambda \) flows per second (one
flow arrives in the network every $\frac{1}{\lambda}$ seconds), each flow lasts for $\mu$ seconds. Each flow carries constant bit rate traffic at the rate of 6 packets per second, each packet being 1528 bytes at the MAC layer. As each flow arrives in the network, a route is calculated for the flow as per the routing metric used, with the metric for each link evaluated taking into account the traffic in the network at the time of arrival of the flow. We then determine if the new flow routed on the chosen path along with the existing traffic in the network is feasible (using our analytical model). If the combined traffic is feasible, the flow is admitted into the network. If the combined traffic is not feasible, the flow is rejected. Figure 3.12 shows for different routing metrics, the fraction of a sequence of 500 flows that are rejected for different arrival rates $\lambda$, the duration of each flow $\mu$ is considered to be 15 seconds. SNR-based receiver model is used in the generation of results shown in figure 3.12\textsuperscript{3}.

It can be seen that using $ETT.N_B$ for routing results in a much lower rejection rate as compared to using $ETT$ for routing, and using the CAST metric results in

\textsuperscript{3}Synchronization is assumed to be free of errors. These results were derived using our analytical model before the model was enhanced to account for the likelihood of synchronization error as a function of SINR.
3.7. **JOINT OPTIMIZATION OF PHY PARAMETERS AND ROUTING**

Figure 3.12: Fraction of arriving flows that are rejected vs. arrival rate with transmit power and PHY rate for each link chosen as per the MIST algorithm. Mean flow duration = 15 seconds. ED threshold = -91 dBm

an even lower rejection rate. Considering a target rejection rate of 10%, with $ETT$ metric for routing, the network can support an offered load (defined as the product $\lambda \mu$) of about 75 flows; with $ETT.N_B$ metric for routing, the network can support an offered load of about 180 flows; with CAST metric for routing, the network can support an offered load of about 255 flows.

### 3.7 Joint optimization of PHY parameters and routing

While the previous sections dealt with selection of physical layer parameters and routing independently, we now seek to obtain the best possible performance by jointly optimizing both physical layer parameters and routing. We use $ETT.N_B$ as the routing metric since using such a metric minimizes the resources used for any physical layer parameter values. We find the optimum physical layer parameter values that
yield the best network performance when used in conjunction with this routing metric. We consider the network topology shown in figure 3.11, with 400 nodes in a geographical area of 600m x 600m. Path loss exponent is considered to be 3. For the purpose of numerical results in this section, the topology is considered to be wrapped at its edges to eliminate bias in results due to nodes located close to the edge(s).

We are interested in network capacity defined as the aggregate throughput that can be supported by the network summed over the throughput of all flows in the network at any given time, averaged over a period of time covering arrival and departure of several flows. Since we evaluate network capacity for many combinations of physical layer parameter values in this section, considering a dynamic model for arrivals and departures proved to be compute intensive, even with the analytical model we developed. Instead, we consider a fixed number of flows between randomly selected sources and destinations and find the highest possible aggregate load that can be supported under the constraint that all flows are of equal rates. This approach is satisfactory for our purpose; indeed if the number of flows considered is about the same as the maximum number of flows that can be supported given the application’s data rate per flow, then the result in terms of network capacity would be equivalent to that obtained with the dynamic arrival and departure model. It should also be satisfactory for the study of interaction between routing and physical layer parameters.

Using this approach, however, it is important to guarantee that the paths used to route a set of flows are the same as (or at least equivalent to) those that would be taken in the dynamic arrival and departure model, which naturally makes use of the traffic-dependent routing metric \((ETT.NB)\). This is easily achieved by using the following iterative procedure. Starting with an empty network, we find paths between sources and destinations assuming that the data rate associated with each flow is zero. In this situation, transmission on links do not experience any interference, and ETT for a link is based only on the link’s propagation characteristics and physical layer parameters (transmit power and data rate used). Fixing these routes, we find the maximum aggregate load supported by the network by uniformly increasing the data rate on all flows until one or more flows cannot be supported. Given the current distribution of traffic on links in the network and the resulting level of interference
experienced by the various links, ETT is updated for all links, and a new set of routes is found based on the new values of link metrics. This is repeated until no increase in aggregate throughput is possible.

We consider several traffic scenarios consisting of unidirectional flows between randomly chosen source-destination pairs. Each scenario is specified by the number of flows, the packet rate per flow and the packet size used. All flows use the same packet size and have the same packet rate. We consider scenarios with (i) 75 flows and 200 flows with 1528 bytes per packet as may be used in video streaming, and (ii) 75 flows with a smaller packet size of 228 bytes that would represent voice encoded at 64Kbps using the G.711 encoding scheme. With such encoding, each packet contains 20 ms of speech in 160 bytes which after addition of headers at various layers amounts to 228 bytes. One packet every 20 ms corresponds to a MAC layer throughput requirement of 91.2 Kbps.

3.7.1 Equal transmit power and rate on all links

Due to the large dimensionality of the problem, we first consider use of equal transmit power, equal rate on all links, and use of the same ED threshold value at all nodes. We later investigate use of different transmit powers or rates on different links. We consider that all links use the maximum transmit power specified in the IEEE 802.11 standard for OFDM ($P = 29$ dBm) and the same data rate $R$. We derive the network capacity that can be supported for different values of $R$ and ED threshold.

We show in figure 3.13 the aggregate throughput for a traffic scenario consisting of 200 flows and a packet size of 1528 bytes, using the SIR-based receiver model. For each value of $R$, there is an optimum value of ED threshold that maximizes network capacity. The optimum value of ED threshold decreases with the data rate since a higher rate requires a higher SINR. The results show that the curve corresponding to 24 Mbps dominates all other rates. With the receiver model considered, the SIR requirement for synchronization exceeds the SIR for correct reception of the PSDU for 6 and 12 Mbps data rates; as for the 24 Mbps data rate, the same is true except for PSDU reception error rates below 0.2. Thus it is not surprising that the performance
with 24 Mbps is superior to 6 and 12 Mbps. As for data rates higher than 24 Mbps, the smaller ED threshold which translates to lower spatial reuse factor contributes to the lower achievable overall network performance. With $R = 24$ Mbps, the highest network capacity is obtained at an optimum value of ED threshold $= -80$ dBm. The aggregate network throughput at the optimum value of ED threshold is 14.1 Mbps corresponding to a per-flow throughput of 70.65 Kbps and a per-flow packet rate of 5.78 packets per second.

![Graph](image)

Figure 3.13: Aggregate throughput of 200 flows, Packet size = 1528 bytes

We now are interested in seeing how sensitive the results are to the traffic scenario considered. We start by considering a packet size of 1528 bytes, and number of flows = 75, 200, 400, and 600, different sets of source-destination pairs in each case. We derive the maximum aggregate throughput for different values of ED threshold around the optimum value of -80 dBm seen above. We show in table 3.3 the aggregate throughput, and verify that any difference in results is rather insignificant. With 12 Mbps for 75 flows of 1528 byte packets, the per-flow throughput is 160Kbps and the packet rate per flow is 13 packets per second. This is roughly representative of a
video stream with 15 frames per second and 1528 bytes per frame.

<table>
<thead>
<tr>
<th>Flow set</th>
<th>Number of flows</th>
<th>ED = -78 dBm</th>
<th>ED = -79 dBm</th>
<th>ED = -80 dBm</th>
<th>ED = -81 dBm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>75</td>
<td>10.97</td>
<td>11.92</td>
<td>11.46</td>
<td>11.0</td>
</tr>
<tr>
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<td>12.37</td>
</tr>
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<tr>
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<td>600</td>
<td>14.23</td>
<td>14.82</td>
<td>14.08</td>
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</tr>
</tbody>
</table>

Table 3.3: Aggregate throughput (in Mbps) for sets of flows between random source-destination pairs. \( P = 29 \) dBm, \( R = 24 \) Mbps

We now consider a set of 75 flows with a packet size of 228 byte, representative of voice traffic. As can be seen from figure 3.14, the maximum aggregate throughput is still obtained using a data rate of 24 Mbps at an ED threshold of -77 dBm. The highest aggregate throughput is 8.14 Mbps. The slightly higher value of optimum ED threshold may be attributed to the fact that the the the relationships between SIR and probability of error in reception of a 228 byte PSDU for different rates are shifted towards lower values of SIR by 1 to 2 dB as compared to those for 1528 byte packets. We note however that even at an ED threshold of -80 dBm, the aggregate throughput is not much lower. With an aggregate throughput of 8.14 Mbps, the per-flow throughput is 108 Kbps, slightly higher than the 91.2 Kbps required for G.711 voice traffic. The decrease in throughput with shorter 228 byte packets is attributed to higher per-packet overhead that is incurred for a larger number of smaller packets as compared to smaller number of larger packets. The overhead consists of (i) fixed physical layer packet overhead consisting of preamble and PLCP header and (ii) overhead in media access control in terms of backoff, inter-frame spacings and acknowledgements.
We now look at what the results would be if one was to use the SNR-based receiver model that has a 5 dB higher requirement in SINR for the same synchronization and PSDU error rates. The higher SINR requirement requires that the ED threshold be smaller; i.e., the set of nodes blocked be larger. Thus, for this comparison, we consider a larger network to ensure that spatial reuse is still realizable in the network even though concurrent transmissions have to be farther apart. We choose a network occupying an area of 1200m x 1200m, again with one node placed randomly in each 30m x 30m square. We evaluate the highest aggregate throughput and the optimum ED threshold using both the SNR-based and SIR-based receiver models. In both cases, $R = 24$ Mbps is the optimum physical layer rate. The optimum ED threshold is $-80$ dBm for the SIR-based receiver model and $-85$ dBm for the SNR-based receiver model. We find the maximum aggregate throughput achieved is 21 Mbps and 11 Mbps respectively for the SIR-based and SNR-based receiver models. The lower throughput achieved with the SNR-based receiver model is attributed to the lower degree of spatial reuse that can be achieved when using such a receiver model as compared to the SIR-based receiver model. This difference of a factor of two in maximum aggregate throughput is quite significant.
3.7. JOINT OPTIMIZATION OF PHY PARAMETERS AND ROUTING

We now examine the links used by routing and their performance. For the scenario of 200 flows with 1528 bytes for which results are shown in figure 3.13, we show in figure 3.15 the distribution of link lengths for links used by routing at the optimum (see curve labeled ED = -80 dBm). The links used fall in the range of 15m to 45m with 80% of the links falling in the narrow range of 25m to 43m.

![Figure 3.15: CDF of lengths of links carrying traffic; P = 29 dBm, R = 24 Mbps](image)

The performance of the links used at the optimum is shown in figure 3.16 as a scatter plot of the average PER as a function of the link length. The PER increases with the link length since: (i) the received signal strength decreases with the link length, and (ii) the level of interference experienced at the receiver increases with the link length due to the fact that the receiver is closer to the interfering nodes. We illustrate the latter fact by showing in figure 3.17 the complementary cumulative distribution function of the interference experienced by links of lengths 15, 30 and 45 meters that are used for forwarding traffic (Note that, as stated in section 3.2.1, interference here refers to the highest level experienced during the reception of a packet transmitted on the link). The reason why no links longer than 45 m get used at this optimum can be easily seen from figure 3.18 in which we show the received signal strength and the level of interference experienced (shown in terms the mean, the
median, and percentiles) as a function of link length, as well as background noise $N$. Using the maximum transmit power at all nodes, interference dominates noise by more than 10 dB rendering the SIR-based receiver model appropriate to use. According to the SIR-based receiver model the SIR has to be greater than 10 dB for the link performance to be meaningful. This condition is met by links shorter than 45 m.

![Graph showing average PER of links vs link length](image)

**Figure 3.16:** Average PER of links carrying traffic at optimum, $P = 29$ dBm, ED threshold = -80 dBm, $R = 24$ Mbps

We now examine the situations where the ED threshold is different from the optimum value of -80 dBm. For a higher ED threshold of -68 dBm, nodes that are allowed to transmit simultaneously can be closer to each other, increasing both the likelihood of packet overlap and the level of interference. Accordingly, the maximum aggregate throughput achievable is lower than at optimum. The distribution of lengths of links used by routing is the same as with the optimum ED threshold (see plot labeled ED threshold = -68 dBm in figure 3.15). This suggests that as far as routing is concerned, the shortest appropriate links are used. On the other hand, for an ED threshold of -86 dBm, routing makes use of longer links than at the optimum, as can be seen from figure 3.15. This is certainly due to the fact that higher blocking range reduces the level of interference experienced by links, rendering longer links more attractive.
3.7. JOINT OPTIMIZATION OF PHY PARAMETERS AND ROUTING

Figure 3.17: CCDF of interference experienced by transmissions on used links at optimum, $P = 29$ dBm, ED threshold = -80 dBm, $R = 24$ Mbps

Figure 3.18: Signal power, noise and interference experienced at capacity by used links, $P = 29$ dBm, ED threshold = -80 dBm, $R = 24$ Mbps
The links used in routing in this case range from 30 m to about 72 m. The overall decrease in maximum achievable load in this case is attributed to the lower degree of spatial reuse; this decrease, however, is not as severe as if routing were to be limited to links shorter than 45 m, because routing adjusted its selection of links so as to decrease resources used. We find that if links longer than 45 m are not established, the aggregate throughput for the set of 200 flows is 7.3 Mbps compared to 11.3 Mbps if longer links are established and made available to routing.

The distribution of lengths of links used for carrying traffic in figure 3.15 seems to suggest that the optimum PHY parameter settings may be found by finding the "shortest possible range of link lengths" in a topology, and finding the physical layer rate and ED threshold that maximizes the throughput of these links. For our topology, we find routes for the same 200 flows as above using link length as a metric, restricting routing to use only links with length in the range 15 meters to 45 meters. Figure 3.19 compares the CDF of lengths of links used to carry traffic using link length as a routing metric to that using $ETT.N_B$ as the routing metric. It can be seen that the two distributions are very close to each other. We find the aggregate throughput that can be supported on the 200 flows using link length as the routing metric is 13.2 Mbps, only slightly lower than the 14.1 Mbps that can be supported when using $ETT.N_B$ as the routing metric. Thus, the "shortest possible range of link lengths" may be obtained using a simple metric such as length in networks where path loss between all pairs of nodes can be modeled as a function of distance with the same path loss exponent. In networks where that is not the case, a metric such as inverse of Shannon throughput ($\log_2(1 + SINR)$) for an appropriate value of interference $I$ may be used (note that as observed in figures 3.17 and 3.18, the interference experienced by links used is very similar).

While we have used $ETT.N_B$ for routing above, we now ask the question how important is it to account for $N_B$ in a topology with approximately uniform node density and with equal transmit power used on all links. $N_B$ for a link $i$ is the number of nodes at which the power received due to transmission on link $i$ alone exceeds the ED threshold. Thus, the value of $N_B$ for links depends on the transmit power used on links and the ED threshold used in the network. Figure 3.20 shows
3.7. JOINT OPTIMIZATION OF PHY PARAMETERS AND ROUTING

Figure 3.19: CDF of lengths of links carrying traffic using link length for routing vs. using $ETT.N_B$ for routing ($P = 29$ dBm, $R = 24$ Mbps, ED threshold = -80 dBm)

The CDF of number of nodes blocked $N_B$ for the links in the network at the optimum point of operation i.e., $P = 29$ dBm, ED threshold = -80 dBm. It can be seen that $N_B$ falls in the range of 42 to 48, with 90% of the links having a $N_B$ in the extremely narrow range of 44 to 48. Thus, since the value of $N_B$ for all links is almost similar, we expect that accounting for $N_B$ in the routing metric should not make a major difference in performance, and routing only based on $ETT$ suffices. Indeed, as seen from Table 3.4, the aggregate throughput for different sets of flows using $ETT$ for routing is only slightly less than that using $ETT.N_B$ for routing. However, if different transmit power is used on different links in the topology or if the density of nodes is not uniform throughout the network, it is important to account for $N_B$ in the routing metric - this accounts for the space resource used by a transmission on a link in the network, and helps distinguish between a link that blocks fewer nodes from one that blocks more nodes.
Figure 3.20: CDF of $N_B$ of links in the network ($P = 29$ dBm, ED threshold = -80 dBm)

<table>
<thead>
<tr>
<th>Flow set</th>
<th>Number of flows</th>
<th>Using $ETT$ for routing</th>
<th>Using $ETT.N_B$ for routing</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>200</td>
<td>12.76 Mbps</td>
<td>12.66 Mbps</td>
</tr>
<tr>
<td>6</td>
<td>200</td>
<td>13.3 Mbps</td>
<td>13.2 Mbps</td>
</tr>
<tr>
<td>7</td>
<td>200</td>
<td>12.9 Mbps</td>
<td>12.76 Mbps</td>
</tr>
</tbody>
</table>

Table 3.4: Aggregate throughput using $ETT$ for routing vs. using $ETT.N_B$ for routing, $P = 29$ dBm, $R = 24$ Mbps, ED threshold = -80 dBm

### 3.7.2 Adjustment of data rate, transmit power on a per-link basis

So far, we have considered that all links use the same transmit power and physical layer rate. Given that SINR is higher for shorter links, the question arises as to the possible improvement that one may get if shorter links were operated at either higher data rate, or lower power. A higher rate translates to a decrease in the transmission time of a packet on the medium. A decrease in transmit power translates to a decrease in $N_B$. The gain in either case, however, may be offset by an increase in packet error rate resulting from operating at higher data rate or with a lower power.
3.7. JOINT OPTIMIZATION OF PHY PARAMETERS AND ROUTING

Data rate adjustment

We address first the adjustment of data rates. We consider as a starting point the optimum operating point with \( P = 29 \text{ dBm}, \ R = 24 \text{ Mbps} \) on all links, ED threshold \( = -80 \text{ dBm} \), and the highest feasible traffic load for the set of 200 flows studied above. Since the range of link lengths used by routing is already the lowest possible, we claim that the ED threshold should be maintained at its optimum value. For each link, we evaluate the link metric \( ETT.N_B \) for all data rates based on the level of interference experienced as a result of the above traffic, and identify the data rate that minimizes the metric. The relationship between link length and optimum data rate is displayed in figure 3.21 in which we show the fraction of links of a certain length that have a given data rate as their optimum rate. As evident from the figure, almost all links in the range 25-45 meters have 24 Mbps as their optimum rate, almost all links in the range 15-25 meters have 48 Mbps, and links shorter than 15 m have 54 Mbps as their optimum rate. Given that 90% of the links used in the above scenario were longer than 25 m, the gain achieved by assigning the higher rates to the shorter links is expected to be low. This is indeed the case as seen from table 3.5. A notable difference with the base case, however, is the rise in the percentage of links shorter than 25 m that get used by routing (from 10% to over 20%) as can be seen from figure 3.22.

<table>
<thead>
<tr>
<th>Flow set</th>
<th>Number of flows</th>
<th>( P = 29\text{ dBm}, \ R = 24\text{ Mbps} ) on all links</th>
<th>With rate adjustment</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>200</td>
<td>12.76 Mbps</td>
<td>12.71 Mbps</td>
</tr>
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<td>200</td>
<td>13.3 Mbps</td>
<td>13.74 Mbps</td>
</tr>
<tr>
<td>7</td>
<td>200</td>
<td>12.9 Mbps</td>
<td>13.45 Mbps</td>
</tr>
</tbody>
</table>

Table 3.5: Aggregate throughput before and after rate adjustment, \( P = 29 \text{ dBm} \) on all links, ED threshold \( = -80 \text{ dBm} \)

Transmit power adjustment

We now address adjustment in transmit power. From figure 3.18, we see that shorter links have a higher SINR, which is also reflected in the low average PER of such
links in figure 3.16. This suggests that the transmit power of such short links may be reduced to some extent while still maintaining good performance. We perform the following test to investigate the improvement in network throughput that may be obtained by reducing the transmit power on shorter links. The transmit power of links shorter than a certain length $L$ is reduced such that the signal power received at the receiver of these links is the same as that at the receiver of a link of length $L$. The transmit power for links of length $\geq L$ is maintained at 29 dBm. The idea is to achieve the same SINR on these shorter links as that on links of length $L$ (Note that the level of interference experienced by the set of used links is approximately the same as observed in figure 3.18). We observe that with $R = 24$ Mbps, ED threshold = -80 dBm, the highest improvement in throughput is obtained when assigning transmit powers on links in this manner with $L = 35$ m. For the scenario consisting of 200 flows with 1528 byte packets for which results with equal transmit power and data rate were presented in figure 3.13, the aggregate throughput is improved to 16.33 Mbps (an improvement of 15% compared to 14.1 Mbps with $P = 29$ dBm on all
3.7. JOINT OPTIMIZATION OF PHY PARAMETERS AND ROUTING

![Figure 3.22: CDF of lengths of links carrying traffic before and after rate adjustment; $P = 29$ dBm, ED threshold = -80 dBm](image)

Figure 3.22: CDF of lengths of links carrying traffic before and after rate adjustment; $P = 29$ dBm, ED threshold = -80 dBm

links). Figure 3.23 shows the CCDF of interference experienced by transmissions on used links at capacity with such a transmit power assignment. It can be seen that shorter links now experience more interference as compared to when $P = 29$ dBm is used on all links, since they block fewer nodes with the reduction in their transmit power. This results in an increase in average PER of short links as shown in figure 3.24. However, shorter links become more attractive for routing due to the reduction in their $N_B$ as seen in figure 3.25. The distribution of link lengths carrying traffic is now skewed towards shorter links. With more shorter links used, the set of nodes blocked is smaller, leading to more concurrency and higher throughput despite the higher PER on short links. Note that our test is only to show that indeed adjusting transmit power has more influence than data rate. An even higher improvement in throughput than that demonstrated may be obtained by a more appropriate power assignment.
Figure 3.23: CCDF of interference experienced by used links with transmit power adjustment ($L = 35$ m), $R = 24$ Mbps, ED threshold = -80 dBm

Figure 3.24: Average PER of links with transmit power adjustment ($L = 35$ m), $R = 24$ Mbps, ED threshold = -80 dBm
3.7. JOINT OPTIMIZATION OF PHY PARAMETERS AND ROUTING

Figure 3.25: CDF of lengths of links carrying traffic with transmit power adjustment 
($L = 35$ m), $R = 24$ Mbps, ED threshold = -80 dBm
3.8 Conclusion

In this chapter, we have addressed the performance of CSMA-based wireless mesh networks with respect to physical layer parameter configuration and routing. We have presented heuristic algorithms for selection of transmit power and data rate on links in a mesh network, given a value for ED threshold. We have developed a link metric for shortest path routing that accounts for space-time resource usage of the link as well as the level of congestion experienced in the neighborhood blocked by transmissions on the link. Finally, we have shown that achieving the best performance in a mesh network requires joint optimization of the physical layer parameters and routes. We find that the best performance is achieved when the range of link lengths used by routing is the lowest possible, and physical layer parameters are optimized for this range of link lengths, as this leads to the highest degree of spatial reuse.
Chapter 4

Conclusion and Future Directions

We now summarize the work in this thesis and discuss some of the future directions for the work.

4.1 Conclusion

This thesis has addressed improvement of performance of CSMA-based wireless mesh networks. Owing to the high runtime and computation power requirement of simulation of large mesh networks, and lack of an adequate analytical model, we developed a novel analytical model for CSMA-based mesh networks in Chapter 2 as a tool for evaluating performance as a function of different operational parameters. For feasible traffic loads, our analytical model provides key performance measures for each link, viz. average packet error rate and fraction of time channel is sensed busy. Our model allows us to evaluate network capacity by starting from a low feasible load and scaling the load up in small steps until the traffic becomes infeasible due to fraction of time the channel is sensed busy reaching 1 at some link carrying traffic. The model identifies the bottleneck links that prevent the load from being able to be scaled up further. In contrast to previously proposed analytical models, our model satisfies all important requirements for being a highly useful tool - applicability to mesh networks with any configuration of physical layer parameters on links, scalability to large mesh networks, and accuracy in terms of results. As elaborated in Chapter 2, all previously
proposed analytical models fall short in one or more of these respects, limiting their applicability. Some other key features of our model include ability to accommodate multiple channels and technologies such as directional antennas and beamforming. Our analytical model fulfills a need for an analytical model that is general, accurate and scalable, and can serve as a very useful tool to researchers and network designers for addressing various research and design problems in the field of multihop wireless networks. Besides this thesis, the model has been used for performance evaluation of wireless mesh networks in another recent doctoral thesis [12].

Equipped with our analytical model, we addressed the performance of CSMA-based wireless mesh networks with respect to physical layer parameter configuration and routing in Chapter 3. We presented heuristic algorithms for configuration of physical layer parameters. We developed a routing metric that accounts for space-time resource usage of a link as well as the level of congestion in the neighborhood of the link. More importantly, we addressed joint optimization of physical layer parameters and routing so as to achieve the best performance in a mesh network. We presented tradeoffs between spatial reuse, performance of links, and distribution of link lengths used for carrying traffic that come into play in determination of end-to-end network capacity. It was observed that in an environment in which path loss between all pairs of nodes can be modeled to be a function of distance between nodes, best performance is achieved when the range of link lengths used for carrying traffic is the "shortest possible", and physical layer parameters are selected so as to optimize the performance of such links. Such a range of link lengths allows maximum possible spatial reuse in the network, resulting in the best performance.

4.2 Future Directions

While this thesis has addressed analytical modeling and performance optimization of CSMA-based wireless mesh networks and presented key insights, the work has been limited in some aspects. Some of the limitations of the work and possible future directions are summarized below:
4.2. FUTURE DIRECTIONS

4.2.1 Improvements to analytical model

The analytical model developed in Chapter 2 has proved immensely useful by allowing us to get numerical results regarding the performance of CSMA-based mesh networks for different values of operational parameters in a quick and efficient manner, with lower time and computational power requirements than simulations or experimentation. However, the model could be improved upon in the following respects to make it even more useful:

Accounting for channel variations due to small scale fading

In the analytical model presented, we considered static wireless mesh networks. Furthermore, we focused on the interactions between links, and assumed that propagation characteristics between a pair of nodes do not change with time. In reality, even in static wireless mesh networks wherein the nodes are stationary, propagation characteristics between nodes in a wireless network change with time due to multipath propagation effects as described in Chapter 1. The analytical model can be extended to account for these variations in two respects: (i) Blocking relationship between links - Each element $B_{ij}$ of our blocking matrix would become a random variable between 0 and 1 to account for the fraction of time during which received power at the source of link $j$ exceeds the ED threshold when there is an ongoing transmission on link $i$. (ii) Interference relationship between links - In evaluating the packet error rate on a link $i$ given overlap with a transmission on link $j$, we have only considered the strength of the received signal and the strength of the interfering signal. To account for multipath effects, one would need to evaluate the packet error rate averaged over two dimensions comprising of all possible fading realizations of the channel between the transmitter and receiver of the target link $i$, and all possible fading realizations of the channel between the transmitter of the interfering link $j$ and receiver of the target link $i$. 
CHAPTER 4. CONCLUSION AND FUTURE DIRECTIONS

Extension to accommodate TCP sources

Our analytical model is based on the assumption that the traffic load on each link is known and that packet arrivals follow a Poisson process with a known mean rate. This is useful in scenarios involving constant bit rate traffic sources like we have considered in this thesis. However, a large number of applications such as web access, file transfer, etc. use the transmission control protocol (TCP) in which the source adapts its traffic rate to the conditions of the path between itself and the destination with respect to throughput and round-trip delay. An analytical model for wireless mesh networks that can accommodate TCP traffic sources would be immensely useful to study the performance of such networks with respect to widely used TCP applications.

Extension to accommodate use of RTS/CTS

In the development of our analytical model in Chapter 2, we assumed that the RTS/CTS collision avoidance mechanism defined in the IEEE 802.11 standard is not used. It would be useful to extend the model to consider transmission of RTS/CTS control packets before actual data transmission. One simple motivation for doing so would be to study the effectiveness of RTS/CTS in a general topology, and the improvement in network throughput that it can provide.

4.2.2 Distributed algorithm for selection of physical layer parameters

In Chapter 3, we showed that the end-to-end capacity of a wireless mesh network can be maximized by using the maximum transmit power on all links, a certain physical layer data rate and a particular value of ED threshold that is optimum for this optimum data rate. Further improvement may be obtained, particularly by adjusting the transmit power on a per-link basis in accordance with the propagation characteristics of the link. However, the Chapter has not addressed selection of optimum physical layer parameters in a distributed manner. Development of a distributed algorithm for selection of optimum physical layer parameters is an avenue for future work. We discuss here some thoughts on one possible approach for a distributed algorithm that
4.2. FUTURE DIRECTIONS

aims to find the optimum equal physical layer data rate and ED threshold for use throughout the network, assuming use of maximum transmit power on all links.

The main challenge in such a distributed algorithm is that of identifying the links that could potentially be used for routing (i.e., the "shortest possible range of link lengths" as discussed in Chapter 3). We have hinted that in environments in which path loss between nodes is a function of distance alone, such links can be identified by using link length as a routing metric. If path loss cannot be modeled as a function of distance alone, a metric such as inverse of Shannon throughput may be used with an appropriate value of Interference power. Alternatively, links would potentially carry traffic may be identified by having the network go through a ranging phase in which all nodes send broadcast traffic at a high enough equal rate so as to fully utilize the wireless medium at each node. Each node can then measure the PER on its links compute routes to its neighbors that it hears beacons from using the $\displaystyle ETT.N_B$ routing metric, and identify those links that get used in routes to these neighbors. We refer to these links as the candidate links.

Having identified the candidate links for which physical layer parameter have to be tuned, the optimum physical layer rate and ED threshold may be found as follows - All nodes start by using the lowest physical layer data rate supported by the physical layer, and a very high value of ED threshold. Nodes gradually and uniformly increase traffic on its candidate links, until the channel utilization at some node in the network approaches one (a node that experiences channel utilization approaching one may broadcast a congestion notification to all other nodes, signaling that capacity has been reached for the current physical layer parameter settings). The nodes then decrease the value of ED threshold in a synchronized manner, finding the aggregate throughput of candidate links for each value of ED threshold. This is continued to find the optimum ED threshold $\Gamma_{ED}^*$ for the current rate beyond which a decrease in ED threshold results in a decrease in aggregate throughput of the candidate links. Nodes then increase the physical layer rate by one level and evaluate the aggregate throughput of candidate links for decreasing values of ED threshold starting at $\Gamma_{ED}^*$ for the previous rate. Again, the highest aggregate throughput possible for the new rate and the corresponding optimum ED threshold is found. This is continued until
the highest aggregate throughput for a data rate is found to be less than that for the lower data rate. This lower data rate is then the optimum physical layer data rate to use in the network, and the corresponding optimum value of ED threshold is the ED threshold to use in the network to achieve highest network throughput.

Note that the above approach requires synchronization between nodes so that nodes move to a different value of physical layer rate and/or ED threshold at the same time. The IEEE 802.11s mesh networking amendment includes support for time synchronization protocols. A default time synchronization protocol referred to as the Neighbor Offset Protocol is defined, and an extensible framework is supported, allowing implementation of any time synchronization protocol. Our requirement of having all nodes switch to a different value of physical layer rate and/or ED threshold at the same time can be met by using a time synchronization protocol in the mesh network.

### 4.2.3 Accounting for variations in channel conditions and traffic

Our analytical model in Chapter 2 and physical layer parameter selection in Chapter 3 has ignored variations in received signal power and received interference power with time due to multipath propagation effects. Our work has addressed selection of physical layer parameter and routes focusing on interactions between links, assuming that the average rate of traffic on links remains the same and propagation characteristics between pairs of nodes do not change. In reality, the performance on a link will vary with time due to variations in traffic, multipath propagation effects between the transmitter and receiver of the link, and multipath propagation effects between interfering nodes and the receiver of the link. It is important to account for such variations in both physical layer parameter selection and routing. Our analytical model can be extended to accommodate models for multipath fading between pairs of nodes as discussed above.
4.2. **FUTURE DIRECTIONS**

4.2.4 **Quality of Service in Wireless Mesh Networks: EDCA**

The work in this thesis has been limited to the DCF medium access protocol, which is a best-effort medium access protocol, with all traffic being treated equal. The IEEE 802.11 standard includes an optional medium access protocol with quality of service support, referred to as Enhanced Distributed Channel Access (EDCA). In essence, EDCA consists of multiple DCF instances at a node, one for each of four classes of service. The DCF instances for higher classes of service have lower values of contention window sizes and interframe spacing, allowing prioritized access to the channel for traffic corresponding to higher classes of service. While the performance of EDCA has been studied in single-hop Wireless LANs [90], it behooves us to study the performance of EDCA to provide quality of service in multihop environments.

4.2.5 **Development of admission control mechanisms**

Another important aspect of providing quality of service in wireless mesh networks besides prioritized channel access is that of admission control. In order to provide guaranteed bandwidth to a particular class of service, one needs to implement admission control mechanisms and admit flows requiring bandwidth guarantees only if adequate resources are available in the network to service the flow, given currently admitted traffic at the same and higher classes of service. Admission control mechanisms have been proposed for mesh networks in which medium access is based on reservations [91]. However, admission control in CSMA-based mesh networks poses several challenges due to random access to the medium. With the possibility of packet errors due to interference, the question arises as to how to estimate the amount of resources that a flow may require.

4.2.6 **Multichannel mesh networks**

We have considered single-channel wireless mesh networks in which each node is equipped with an omnidirectional antenna and analyzed the performance of such networks with respect to physical layer parameters comprising of transmit power, data rate rate and ED threshold. However, the capacity of a mesh network can be
tremendously improved by using more than one radio channel and more than one radio at each node. This adds another dimension to the problem of configuring the network, that of channel assignment. Ideally, one would want to assign operating channels to links such that the capacity of the network is maximized while still satisfying the constraint of the number of channels that can be used in the network, and the constraint of the number of radios at each node. Our analytical model is readily extensible to multichannel mesh networks by considering each set of links that share a radio channel independently. Thus, the model can be used as a tool for evaluating the capacity of a mesh network for different <channel, transmit power, rate, ED threshold> assignments, and for development of algorithms to select these parameters to maximize network capacity.

4.2.7 Performance comparison of MAC protocols

Apart from PHY parameters and routing, another aspect that influences the performance of wireless mesh networks is the MAC protocol. In this thesis, we have focused on CSMA-based mesh networks due to their widespread deployment. However, a number of MAC protocols based on dynamic reservations have been proposed, motivated by wanting to avoid collisions that are cited as a reason for significant loss in network throughput with the use of CSMA [26, 27, 28, 29]. The IEEE 802.11s amendment to the IEEE 802.11 standard also includes an optional media access control scheme based on distributed reservations, referred to as Mesh Coordinated Channel Access (MCCA). On the other hand, recently there has been work that shows for some simple topologies that the performance of CSMA is close to an optimal TDMA schedule [92, 93]. Our analytical model allows one to determine the network capacity for any general mesh network under a given traffic pattern. One can develop a model that determines the capacity of a reservation-based MAC - such a model only needs to track time reservations in the neighborhood of each node; capacity is reached when the fraction of time reserved in the neighborhood of a node including its own reservations exceeds 1. This capacity can then be compared to the capacity using CSMA.
Appendix A

Overview of the IEEE 802.11 Standard

The IEEE 802.11 standard was originally developed as a physical layer and media access control specification for single-hop wireless local area networks wherein multiple user stations communicate with a single access-point that has a connection to the wired infrastructure. With IEEE 802.11 based Wireless LANs becoming extremely popular and devices based on this standard available readily at low prices, the standard has been widely adopted for multihop wireless mesh networks as well. IEEE 802.11 task group ’s’ has been actively working on extensions to the standard for wireless mesh networks. At the time of this writing, these extensions are still work in progress and the latest version of these extensions is published as a draft amendment to the IEEE 802.11 standard [3]. Once this amendment is approved, it will be incorporated into the IEEE 802.11 standard.

We present here a brief overview of the functionality defined in the IEEE 802.11 standard and its mesh networking amendment at each of the layers:

A.1 IEEE 802.11 Physical Layer

The IEEE 802.11 standard defines the following physical layer specifications for transmission of bits on the wireless channel:
APPENDIX A. OVERVIEW OF THE IEEE 802.11 STANDARD

- Frequency-Hopping Spread Spectrum (FHSS) PHY specification for the 2.4 GHz ISM band, with support for data rates of 1 Mbps and 2 Mbps.

- Direct Sequence Spread Spectrum (DSSS) PHY specification for the 2.4 GHz ISM band, with support for data rates of 1 Mbps and 2 Mbps.

- High Rate Direct Sequence Spread Spectrum (HR/DSSS) PHY specification for the 2.4 GHz band, an extension of the DSSS PHY with support for data rates of 5.5 Mbps and 11 Mbps in addition to 1 Mbps and 2 Mbps rates supported by DSSS.

- Orthogonal Frequency Division Multiplexing (OFDM) PHY specification for the 5 GHz band, with support for data rates of 6, 9, 12, 18, 24, 26, 48 and 54 Mbps.

- Extended Rate PHY (ERP) specification for the 2.4 GHz band, with support for data rates of 1, 2, 5.5, 11, 6, 9, 12, 24, 36, 48, 54, 22 and 33 Mbps. Data rates of 1, 2, 5.5 and 11 Mbps use DSSS modulation, data rates of 6, 9, 12, 24, 36, 48 and 54 Mbps use OFDM, and data rates of 22 and 33 Mbps use DSSS with Packet Binary Convolutional Coding (PBCC).

- High Throughput (HT) PHY specification with extended range and support for data rates up to 600 Mbps using Multiple Input Multiple Output (MIMO) [94] and other technologies.

A.2 IEEE 802.11 MAC Layer

The IEEE 802.11 standard defines the following protocols for access to the medium by a node.
- **Distributed Coordination Function (DCF):** DCF is based on CSMA/CA, and is the fundamental method for channel access defined in IEEE 802.11. Its support is mandatory in all IEEE 802.11 devices, support for the other channel access protocols is optional.

- **Enhanced DCF Channel Access (EDCA):** EDCA is a QoS-aware channel access mechanism based on DCF. In a nutshell, EDCA comprises of four instances of DCF, one per traffic priority class. These DCF instances have different values for channel access parameters such as the contention window and various inter-frame spacings. These values are assigned such that a frame for a higher priority traffic class is guaranteed to be transmitted on the channel ahead of another frame corresponding to a lower priority traffic class.

- **Point Coordination Function (PCF):** PCF provides contention-free access to the medium based on polling. A central entity referred to as the Point Coordinator (usually the access point) accesses the channel with higher priority by using shorter inter-frame spacing, transmits polling requests to user stations and grants transmission opportunities to user stations based on their responses to polls.

- **Hybrid Coordination Function Channel Access (HCCA):** HCCA is based on PCF with QoS capabilities.

- **Mesh Coordinated Channel Access (MCCA):** MCCA is a new medium access control protocol introduced in the IEEE 802.11s amendment for mesh networks that allows mesh nodes to transmit during reserved times with lower contention than would otherwise be possible. MCCA uses a distributed mechanism to reserve time for transmissions on the medium on a first-come first-served basis. Reserved transmission times are referred to as MCCA opportunities. The
owner of a MCCAOP uses short inter-frame spacing times to gain prioritized access to the medium during the corresponding reserved time. If the MCCAOP owner does not initiate a transmission during its reserved time, other mesh nodes may contend for the channel using channel access parameters for their respective traffic categories.

Of the above channel access protocols, DCF, its QoS-aware extension in the form of EDCA and MCCA are relevant to wireless mesh networks while the other MAC protocols are for use in wireless LANs.

A.3 IEEE 802.11 Path Selection

The IEEE 802.11s mesh networking amendment includes an extensible framework to allow flexible implementation of path selection protocols and metrics. The standard defines a default mandatory path selection protocol called *Hybrid Wireless Mesh Protocol (HWMP)*, and a default mandatory path selection metric referred to as the *Airtime Link Metric* that corresponds to the time required on the link from the first transmission attempt to successful acknowledgement of a packet of a certain reference size. HWMP protocol primitives, message generation and processing rules are very similar to those of AODV [33]. Routes are selected to minimize the end-to-end sum of metric values of links along the route. However, while AODV is an on-demand routing protocol, HWMP supports two modes of operation:

- **Proactive tree building mode:** In this mode, routes are established between certain nodes configured as *root nodes* and all nodes in the network on a proactive basis and maintained at all times. Communication between a source-destination pair comprising of non-root nodes occurs via a root node over a suboptimal path comprising of the concatenation of the paths from the source to the root and the path from the root to the destination.

- **On-demand mode:** This mode allows for on-demand discovery of the optimal path between a pair of nodes in the network when such an optimal path is desired or when there is no root node configured.
These modes are not exclusive, and can be used concurrently.
Bibliography


