MAC-2: A MAC Protocol for Power Control in Mobile Ad Hoc Networks

by

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A thesis submitted in conformity with the requirements for the degree of Masters of Applied Science
Graduate Department of Electrical and Computer Engineering
University of Toronto

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Abstract

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Mobile ad hoc networks (MANETs) are multi-hop wireless networks where nodes cooperatively maintain network connectivity. These networks suffer from many problems, such as high power consumption, inefficient spatial reuse, and poor Quality of Service. These problems can be remedied by developing a medium access control (MAC) scheme which reduces power consumption by sending at the minimal power needed to reach the nodes involved in a connection, and which optimizes spatial reuse by allowing as many simultaneous exchanges as possible to occur in an area.

This thesis presents a comprehensive work that enhances the performance of MANETs through improvements at the MAC layer. This work is based on the IEEE 802.11a standard, which is not well suited yet for operation in MANETs. We propose a power efficient MAC layer protocol, with a physical layer extension, which makes the current IEEE 802.11a devices more suitable for operation in a MANET environment.
To Dad, Mom, Fadi, Chadi and Nagi

Your love is the wind beneath my wings
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To my best friends, your care was always a source of joy and comfort. Your thoughts always made me feel the special bond that unites us, and I am glad to say you were a part of my life every day.

I would like to address a very special thought to my late grandparents for their strong belief in my capabilities and their encouragements. I wish they were all here to share this special moment with me.

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Chapter 1

Introduction

1.1 MANET Overview

Wireless networks are generally classified into two categories: infrastructure (cellular) networks, and infrastructure-less (ad hoc) networks, as shown in Figure 1.1. Differences between the two can be summarized in Table 1.1. Ad hoc networks are expected to be useful in many applications where infrastructure is either not available, or not trusted, such as: military (e.g. soldiers in battlefield), scientific (e.g. sensors scattered in a city for biological detection), academic (e.g. notebook computers in a conference or campus), natural (e.g. rare animal tracking), maritime (e.g. undersea operations), business-related (e.g. temporary video conferencing), etc.

![Figure 1.1: Cellular vs. Ad Hoc Network Architecture](image-url)

1
A mobile ad hoc network (MANET) is a peer-to-peer network of communication devices that establish a connection between themselves on the fly, without the need for a fixed infrastructure, and maintain this connection without the need for a centralized controller. With the proliferation of inexpensive, widely available wireless devices, MANETs have received increasing interest recently. This trend was encouraged by the creation within the Internet Engineering Task Force (IETF) of the MANET working group.

Ad hoc networking is a multi-layer problem. Figure 1.2 shows the main layers of the protocol stack. The physical (PHY) layer carries information over the wireless medium. The multiple access control (MAC) layer allows and controls access to the shared wireless channels. The network layer exchanges information to find and configure efficient and reliable paths between any two nodes in the MANET. The transport layer maintains end-to-end connectivity by handling delays and packet losses. Finally, the application layer consists of applications which can cope with the frequent disconnections and reconnections of the peer-to-peer nodes.

To ensure interoperability of products, the IEEE finalized in June 1997 the initial 802.11 standard for WLANs [1]. Since then, this standard has been extended to the 802.11b (Direct Sequence in the 2.4 GHz band) and to the 802.11a (OFDM in the 5 GHz band) [2]. Table 1.2 summarizes the approved IEEE 802.11 standards. The IEEE 802.11 specification defines a set of requirements for the physical (PHY) layer and the medium access control (MAC) layer.
These standards are a potential framework for the operation of MANETs. The original 802.11b standard has received wide attention, but the emerging 802.11a OFDM based standard is gaining ground as the future standard of choice for WLANs. In this thesis, IEEE 802.11a is used as the basis for the proposed MAC layer protocol and the PHY layer enhancements in a MANET environment.

1.2 Motivation

Despite the growing attention MANETs have received recently, a number of problems still need to be solved in order to achieve satisfactory performance.

- Scalability: The network must provide an acceptable level of service even with a large number of nodes in the network.

- Power Efficiency: The network must conserve energy, as the individual mobile nodes have limited power sources.

- Quality of Service (QoS): The network must provide each node with its variable QoS requirements, while coping with potentially unpredictable changes in the wireless channel characteristics.
Chapter 1. Introduction

Table 1.2: Approved IEEE standards for WLANs

<table>
<thead>
<tr>
<th></th>
<th>802.11</th>
<th>802.11a</th>
<th>802.11b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Approved</td>
<td>July 1997</td>
<td>September 1999</td>
<td>September 1999</td>
</tr>
<tr>
<td>Available Bandwidth</td>
<td>83.5 MHz</td>
<td>300 MHz</td>
<td>83.5 MHz</td>
</tr>
<tr>
<td>Unlicensed Frequencies of Operation</td>
<td>2.4-2.4835 GHz</td>
<td>5.15-5.35 GHz 5.725-5.825 GHz</td>
<td>2.4-2.4835 GHz</td>
</tr>
<tr>
<td>Number of Non-Overlapping Channels</td>
<td>3 (Indoor/Outdoor)</td>
<td>4 (Indoor) 4 (Indoor/Outdoor)</td>
<td>3 (Indoor/Outdoor)</td>
</tr>
<tr>
<td>Data Rate per Channel</td>
<td>1, 2 Mbps</td>
<td>6, 9, 12, 18, 24 36, 48, 54 Mbps</td>
<td>1, 2, 5.5, 11 Mbps</td>
</tr>
<tr>
<td>Modulation Type</td>
<td>FHSS, DSSS</td>
<td>OFDM</td>
<td>DSSS</td>
</tr>
</tbody>
</table>

- Security: The network must be protected from Denial of Service (DoS) attacks which are hard to track due to the shared wireless medium and to the packet forwarding and routing by nodes.

- Mobility: The network must be able to quickly, and efficiently, recover from possible network partitions due to nodes moving out of range, hence modifying routing path and perturbing neighborhood discovery protocols.

One possible way to remedy to some of these problems is to consider improvements on lower layers of the protocol stack (PHY, MAC). This work attempts to do so by proposing a MAC layer protocol well adapted to a MANET environment. The proposed MAC protocol can take full advantage of PHY layer enhancements to further boost its performance.

For any MAC layer protocol in wireless networks to be efficient, two deficiencies need to be overcome, namely the hidden and exposed station problems. Those problems are due to the broadcast nature of the wireless medium and do not exist in wired counterparts.
The hidden station problem occurs when a node initiates a transmission which causes collision at the receiver of an ongoing exchange. Figure 1.3 shows such an occurrence. If node C initiates the T2 exchange while the T1 exchange is in progress, a collision occurs at node B, the receiver of the ongoing T1 exchange. One way to remedy to this problem is to reserve the channel prior to initiating an exchange.

![Figure 1.3: Hidden Station problem](image)

The exposed station problem occurs when a node reserves the channel for a particular exchange, precluding other exchanges which cause no collision at the receiver from simultaneously occurring. Figure 1.4 shows such an occurrence. If node C wants to initiate the T2 exchange while the T1 exchange is in progress, the channel reservation scheme of node B prevents the T2 exchange from occurring simultaneously, even though T2 does not cause a collision at node A, the receiver of the T1 exchange. Hence, the exposed station problem unnecessarily reduces the overall network throughput.

The original IEEE 802.11 MAC scheme uses the optional Request To Send/ Clear To Send (RTS/CTS) packets exchange to reserve the wireless medium by having neighboring nodes set their network allocation vector (NAV) for the duration of the data exchange and then proceeds to send the DATA packet which is acknowledged by the receiver using an ACK packet. Reserving the channel with the RTS/CTS handshake enables
collision avoidance, which is fundamental for wireless medium access, but precludes other concurrent transmissions in the region of the acquired floor. This reservation scheme creates the exposed station problem mentioned above, which is not solved by the IEEE 802.11 MAC protocol.

The need for new MAC layer protocols is further fuelled by the inability of the current IEEE 802.11 MAC protocol to deliver an acceptable performance in a MANET environment, due to several reasons, namely:

- Lack of power control
- Inefficient spatial reuse
- Inability to provide basic QoS

The IEEE 802.11 MAC protocol always sends packets at the same power, which is harmful for neighboring exchanges, as no flexibility due to topology can be used, i.e. all transmissions use the same energy even though some of them might need less energy than others due to distances. This translates into inefficient spatial reuse, as exchanges occurring at unnecessarily high powers reserve a greater area than that needed for a successful transmission. The topology in Figure 1.5 illustrates how unnecessarily
reserving floor area reduces the overall network throughput. The solid circles represent the transmission ranges for nodes A and B. In the IEEE 802.11 MAC protocol, if an exchange occurs between nodes A and B, node C will set its NAV for the duration of the A-B exchange. Hence the C-D exchange cannot occur simultaneously with the A-B exchange. In addition, the IEEE 802.11 MAC protocol does not offer any QoS guarantee (i.e. upper bound on delay, maximum packet error rate). The scheme is best-effort, hence vulnerable to changes in channel conditions and in network topology, both characteristics of a MANET environment.

![Figure 1.5: Effect of Power Control on Channel Reservation](image)

1.3 MAC-2: A Preview

These observations motivate the design of a new MAC protocol that enables power savings in addition to increased spatial reuse while providing basic QoS. The new MAC-2 protocol modifies the original IEEE 802.11 MAC protocol to achieve these goals.

Performing appropriate power control increases spatial reuse. In Figure 1.5, if the A-B exchange occurs at the minimum power with the transmission ranges of nodes A and B as shown in the light circles, then neither node C nor node D is reached, and
they are not affected by a possible channel reservation scheme, hence a simultaneous C-D exchange can occur while the A-B exchange is still occurring. Note that the C-D exchange is made possible by the power control in nodes A and B.

In the MAC-2 protocol, the nodes send the packets at the minimal power needed to reach the destination successfully. A successful transmission is defined as packets arriving with an acceptable PER, which corresponds to a required Signal to Interference plus Noise Ratio (SINR). Below this SINR, the packet is considered in error and has to be retransmitted again, causing further power consumption and delays.

In addition to the benefits just mentioned, the MAC-2 protocol has the potential to fully exploit power savings through enhancements in the PHY layer which permit the realization of the acceptable PER by sending the packets at a lower power. Such enhancements will be referred to as the IEEE 802.11a-STC design.

The IEEE 802.11a-STC design is a modification of the IEEE 802.11a PHY layer through the use of transmit and receive diversity, commonly referred to as space-time coding (STC). Recently, the use of multiple antenna elements at both the transmitter and the receiver to achieve diversity gains has received considerable attention. The pioneering work in [3] has sparked wide research on efficient space-time codes. In this regard, Alamouti [4] proposed a technique for a two-element array with remarkably simple encoding and decoding schemes. The development of STC in [4] assumes independent fading between any two pairs of transmitters and/or receivers. This assumption is only approximately valid. The finite spacing between the elements of the array and the nature of multipath both lead to partially correlated fading. In a MANET application, the element spacing is further constrained by the area of the mobile device. Two antenna elements will be used at both the transmitter and the receiver and, unlike previous attempts exploring the performance of IEEE 802.11a with STC [5,6], the spatial correlation is modelled by using the ”one-ring” model proposed by Jakes [7], and extended by Shiu et. al. [8].
Chapter 1. Introduction

The combined PHY-MAC design allows the use of a lower transmission power to achieve the desired PER. In case the desired PER is not achievable at the highest data rate, link adaptation can be used to switch this rate down to a level that guarantees the exchange to occur with the maximum allowed PER.

Our goal in this thesis is to develop and test MAC-2, a new MAC protocol based on the IEEE 802.11a standard MAC and PHY layers paradigm. The aim is to improve performance, mainly power consumption and overall network throughput, in a MANET environment. The proposed MAC-2 protocol fully benefits from PHY layer enhancements to achieve additional gains in both power consumption and overall network throughput. To increase the spatial reuse, a pair of nodes should only reserve the minimum floor area needed to complete data transmission. In addition, the MAC-2 protocol is designed to achieve basic QoS guarantees as the transmission power level is based on the minimum power needed to obtain a desired Packet Error Rate (PER) at the receiver. The MAC-2 protocol solves both the hidden station problem, and most important, the exposed station problem through the use of a dual-channel approach and of an efficient channel reservation scheme.

1.4 Contributions

The main contributions of this thesis can be summarized as follows:

- Providing energy savings in MANETs by implementing an efficient power control scheme at the MAC layer, which considerably saves energy when compared to the initial IEEE 802.11 standard.

- Increasing overall network throughput in MANETs by allowing more simultaneous exchanges to occur within a specific network area due to an appropriate channel reservation scheme.
• Achieving basic QoS in MANETs by adjusting the power to the minimum needed to achieve a desired PER, which can be dynamically set by the transmitter in the RTS packet for the forthcoming exchange.

• Presenting a comprehensive PHY-MAC approach to improve the performance of MANETs through a detailed study of PHY layer improvements and the compatibility of the proposed PHY layer design with the new MAC layer protocol, so as to further enhance its benefits. This cross-layer approach is, to our knowledge, one of the few studies aiming at combining benefits at multiple layers to boost the MANETs performance.

This thesis starts by reviewing the work done in the fields tackled throughout the MAC and PHY layers designs. The IEEE 802.11a standard is then reviewed and its PHY-MAC operation detailed. Next, the new MAC-2 protocol, the core of the work, is detailed, along with its performance analysis. Finally, one potential PHY layer enhancement, IEEE 802.11a-STC is explained, and its performance evaluated. The effect of combining MAC-2 and IEEE 802.11a-STC is explored.
Chapter 2

Related Work

This chapter presents a review of the existing literature in the various areas tackled by this thesis. The main previous works on power control MAC protocols, smart antenna based MAC protocols, space-time block codes (STBC) and spatial correlation, and link adaptation (LA) are summarized.

2.1 Power Control MAC Protocols

Recently, several power saving schemes have been proposed to minimize energy consumption in MANETs. These schemes fall under three main categories:

- Transmission Power Control
- Low Power Mode
- Power Saving Routing

The Power Saving Routing approach is implemented at the network layer, which is beyond the scope of this thesis, which is concerned with MAC layer schemes. Hence, only MAC layer mechanisms achieving power efficiency will be summarized.

In the first category of schemes, Transmission Power Control, power is adjusted according to a desired criterion. The main contributions in this area are presented next.
In a large part, the major drawback with these schemes is that they save power without changing the MAC protocol to exploit these savings for spatial reuse, i.e. energy is saved, but the overall network throughput is not increased.

The Power Controlled Multiple Access (PCMA) protocol [9] generalizes the transmitter-defer “ON/OFF” collision avoidance model to a more flexible “variable bounded power” collision suppression model, which adapts the transmission power according to an upper bound, which is not to be exceeded. This bound is determined on a packet-by-packet basis to ensure no collision with ongoing neighboring transmissions. The source-destination pairs can be more tightly packed into the network allowing a greater number of simultaneous transmissions. However, simulations show that PCMA does not perform well unless nodes are clustered. In addition, it uses busy tones on a busy tone channel, which increases power consumption. Finally, PCMA cannot avoid collision at the transmitter between the ACK packet returning from the receiver and other ongoing transmissions.

The use of different transmission powers and its effect on the average power consumption and end-to-end network throughput in a MANET environment are explored in [10]. The protocol first dynamically determines an optimal connectivity range where it adapts its transmission power so as to only reach a subset of the nodes in the network. The connectivity range is then dynamically changed in a distributed manner so as to achieve the near optimal throughput. However, the use of a signaling packet to advertise the local connectivity table, as well as the multiple measurements performed to obtain an average power value, can be source of unnecessary delays.

The Power Control MAC (PCM) protocol presented in [11] seeks to improve the BASIC [12,13] scheme of packet-by-packet power control. The PCM scheme periodically increases the transmission power during the transmission of data so that neighboring nodes can sense it and avoid collisions with the ACK packet. However, PCM only reduces power consumption, without any gains in the overall network throughput. In fact, PCM
only matches the performance of IEEE 802.11 MAC in terms of network throughput. In addition, PCM does not prevent collisions completely, due to the periodic nature of the increases in data transmission power.

The work in [14] explores the possibility of combining the concept of power control with the RTS/CTS and the busy-tone based protocols such as DBTMA [15] to further improve on channel utilization. The Dual Busy Tone Multiple Access (DBTMA) scheme was designed for MANETs, where the RTS/CTS optional packet exchange of the IEEE 802.11 MAC protocol is used to reserve the channel. In addition, two busy tones are employed to eliminate collisions between RTS/CTS control packets and DATA packet transmissions. The problems with these protocols are the use of the busy tone in [14], and of two out-of-band busy tones in [15], which causes additional power consumption, as well as implementation problems with the busy tone corrupting the incoming data.

In the second category of schemes, Low Power Mode, IDLE nodes shut themselves OFF, which saves power since adjacent exchanges are not unnecessarily overheard. Some of the works in this area are presented next.

PAMAS, an energy-conserving multi-access protocol for MANETs using busy tones is presented in [16, 17], where radios that are not actively transmitting or receiving a packet power themselves off in a manner that does not influence the delay or throughput characteristics of the protocol. This protocol only saves power without increasing the overall network throughput.

The Sensor-MAC (S-MAC) protocol [18] uses three novel techniques to reduce energy consumption and support self-configuration. Inspired by PAMAS, S-MAC sets the radio to sleep during transmissions of other nodes. However, S-MAC needs to maintain synchronization among neighboring nodes, and its updating period can be lengthy, which will affect the performance. Furthermore, as in the case of PAMAS, power is saved without changes to the overall network throughput.
Chapter 2. Related Work

In summary, the issue of power savings at the MAC layer has received a lot of attention in recent years. However, in general, the previous works have not provided a MAC protocol which both saves energy and increases overall network throughput, while solving both hidden and exposed station problems, all of which are desirable for the design of an efficient MAC protocol for MANETs.

2.2 MAC Protocols using Smart Antennas

In the last part of this thesis, the performance improvement of MANETs through the use of diversity processing by the smart antennas is studied. Here are various previous works using smart antennas to improve MAC protocols in wireless networks.

The use of smart antennas in centralized networks was studied by Okamoto et. al., who describe a smart wireless LAN (SWL) system that integrates SDMA (Space Division Multiple Access) with the IEEE 802.11 standard [19–22]. The beamforming algorithms, fading reduction, and diversity gain are detailed, but such work is only applicable at access points (AP).

The use of smart antennas in MANETs, on the other hand, has been mainly focused on designing protocols at higher layers (MAC, Network...) that can benefit from the enhancements that the use of smart antennas at the PHY layer brings. A MAC protocol suitable for ad hoc networks based on directional antennas is presented in [23]. The use of directional control packets is examined, but the basic assumption of the protocol is accurate location information that is assumed to be known at each mobile device through the use of GPS. Such an assumption is not very realistic nor cost-effective, hence the work is incomplete. Nasipuri et. al. [24] proposed a MAC protocol using directional antennas where the nodes have no location information. The location and tracking are done during random channel access, therefore have to be done as quickly as possible. The problem with this approach is that the accuracy of the location estimation depends on the length
A comprehensive PHY-MAC layer study by Balanis et. al. [25,26] describes the design and simulation of adaptive antenna arrays for MANETs in the 20-GHz band. The adaptive beamforming algorithm proposed uses training data for Direction of Arrival (DOA) estimation. Again, the limitations on complexity/accuracy of mobile devices especially in an indoor multipath fading environment, limit the applicability of this work.

Ohira et. al. [27–31] have suggested the use of Electronically Steerable Passive Array Radiator (ESPAR). Some gain in the Signal to Interference and Noise Ratio (SINR) is obtained due to the beamforming ability of ESPAR antennas [27]. In the adaptive MAC protocol of [30], each node keeps certain neighborhood information dynamically, so that each node can keep track of the direction of communication events going on in its neighborhood at any instant of time. The work in [31] contains a brief proposal for technologies at different layers in MANETs based on ESPAR antennas. A wireless ad hoc network community (WACNet) is presented, with a new routing scheme named Angle-SINR Table Routing, the concept of SDMA, and microwave signal processing for adaptive beamforming. Todd et. al. [32] use a relatively inexpensive circular antenna array configuration with a fairly modest number of elements. It improves spatial channel reuse by generating steerable beams at the source and destination, which point in the correct direction when array-mode transmission takes place. A new carrier sensing mechanism called DVCS (Directional Virtual Carrier Sensing) for MANETs using directional antennas is presented in [33]. DVCS only needs information on Angle of Arrival (AOA) and antenna gain for each signal from the underlying physical device, both of which are commonly used for the adaptation of antenna pattern. The limitation of the above mentioned works is the destructive effect that multipath has on the accuracy of the beamforming, which is always assumed to be accurate in the performance evaluation.

Ramanthan [34] considers a number of enhancements to a conventional MANET MAC protocol including “aggressive” and “conservative” channel access models for beamform-
ing antennas, link power control, and directional neighbor discovery. Koubaa [35] considers the link capacity achieved by a set of portable stations sharing the same medium and equipped with smart antennas, discussing the problem with the use of smart antennas in transmission based on the CSMA MAC protocols, principally beam selection and handoff. The CSMA MAC protocol has to interact with the physical layer to manage beam use. The work in [36] presents the analysis of CSMA/CA in a rural area MANET with and without adaptive antennas. An explanation of the system design with adaptive antennas is given as well as simulation results showing the expected performance gain. The effective use of smart antennas is integrally linked to the MAC protocol, so combined studies are indicated. Fixed beamforming is used, but the authors plan to study adaptive beamforming.

The trend in all the above mentioned works is to use adaptive beamforming for improved performance. However, adaptive beamforming is computationally intensive, and the devices which constitute MANETs are generally complexity limited for such operations. In addition, efficient adaptive beamforming needs high accuracy of the AOA information, which is difficult to achieve in indoor settings, most common for MANETs, due to multipath fading.

On the other hand, diversity schemes require less computationally intensive operations, and provide significantly lower error rates at high SNRs, which are likely to be the case in MANETs due to the distances between adjacent hops. However, the major drawback with diversity combining schemes is the need for channel estimation at the receiver. Nevertheless, such an estimation can still yield significant improvements in Packet Error Rate (PER) even if not ideal. A major advantage of using diversity schemes is that Space-Time Codes (STC) yield a good performance, even in a spatially correlated environment, while some AOA methods necessary for adaptive beamforming fail to operate correctly in a weakly correlated setting.
2.3 Space-Time Coding

Space-Time Coding (STC) is a relatively new however widely researched area to improve signal quality transmission and reception through the use of multiple antennas at the communication devices. The pioneering work in [3] has sparked wide research on efficient space-time codes. In this regard, Alamouti [4] proposed a technique for a two-element array with remarkably simple encoding and decoding schemes.

The previous studies have shown significant performance enhancement in applying STC to centralized networks with Access Points (AP). The performance results of Space-Time Trellis-Coded Modulation (STTCM) schemes in the two emerging WLAN standards (IEEE 802.11a and ETSI Hiperlan/2) is studied in [5]. The work in [6] uses two antennas at the Access Point (AP) with a single antenna at the Mobile Terminal (MT). The downlink improvement is achieved by using simple spatial transmit delay diversity, while the uplink improvement is achieved by using maximal ratio combining diversity. The use of space-time coding in OFDM-based systems is investigated in [37]. A design criterion for space-frequency coding (since coding is across OFDM tones) is derived. The performance of Space-Time Block Coding (STBC) in Hiperlan/2 is explored in [38], documenting the improvements in the Packet Error Rate (PER). However, all these studies are not adapted for a MANET environment with peer-to-peer nodes.

Most of the work on STC has been restricted to the idealistic case of uncorrelated spatial fading. This assumption is only approximately valid. The finite spacing between the elements of the array and the nature of the multipath both lead to partially correlated fading. The effects of spatial fading correlations in antenna arrays are studied for a cellular environment [8].

The impact of spatial fading correlation on the performance of space-time codes is studied in [39]. It is shown that the diversity order achieved in the correlated case is given by the product of the ranks of the transmit and receive correlation matrices. It also shows that transmit-side correlation has a severe impact on the performance of non-orthogonal
space-time codes. However, orthogonal space-time codes, such as the aforementioned Alamouti scheme [4] provide maximum robustness against correlation, as compared to trellis codes proposed by Tarokh et. al. [3]. A space-time vector channel model with realistic fading simulation for different scenarios is described in [40]. The mutual correlation between the fading coefficients is considered. The short study in [41] derives an analytical estimate for bit error probability when space-time codes are investigated over Rayleigh fading channels with spatially correlated fading between transmit antennas.

In summary, the use of STC in MANETs has received almost no attention despite the attention that these two subjects have received by themselves. Due to the constraints on the size/complexity of wireless handheld devices to be used in MANETs, the simple Alamouti coding scheme will be used in this work, while accounting for spatial correlation effects on the performance of this STC scheme.

2.4 Link Adaptation

The proposed MAC protocol is used with the IEEE 802.11a PHY scheme, which comprises eight possible data rates ranging from 6 to 54 Mbps. The capability to adapt the data rate to the channel conditions makes the proposed MAC protocol more scalable. Link Adaptation (LA) is an important technique to improve the signal transmission based on a variety of Link Quality Measurements (LQM), such as Packet Error Rate (PER), Received Signal Strength (RSS), Carrier over Interference (C/I) estimates, etc...

An algorithm to combine LA and transmit power control (TPC) in a cellular network is presented in [42]. The algorithm diminishes both Uplink (UL) and Downlink (DL) transmit powers significantly. The C/I estimate is used in [43] as the LQM for LA. The mean block error rate (BLER) for a system using minimum C/I estimate is significantly lower than that for using average C/I estimates. The work in [44] shows that updating the modulation and coding on a frame basis brings a 2.5dB gain over optimum long
term approach. Note that [42–44] were studied for the Hiperlan/2 standard, which is the European counterpart of IEEE 802.11a.

As concerns IEEE 802.11a, a system architecture to perform both dynamic fragmentation and PHY rate selection that depends on the wireless channel condition between transmitter and receiver is proposed in [45, 46]. The best throughput performance is achieved by selecting the optimal PHY mode and the fragment size to achieve the best data throughput possible at each time.

The problem of maximizing data throughput by adaptive modulation and power control while meeting PER requirements is proven in [47] to be NP-complete. An algorithm which divides terminals into groups, and periodically adapts transmission is proposed. Guidelines to help in the design of robust, low-complexity, and cost-effective algorithms for future wireless networks are suggested in [48].

The optimal frame size prediction to achieve maximal throughput under given channel quality is examined in [49, 50]. A Kalman filter is used to predict the size needed. A LA scheme based on the constellation error power per subcarrier for OFDM communication systems is used in [51].

Finally, a rate adaptive MAC protocol based on the RTS/CTS handshake, called the Receiver-Based AutoRate (RBAR) protocol, which is not specific to IEEE 802.11a, but to any pool of modulation schemes is presented in [52]. Rate selection and channel quality estimation are located at the receiver.

In summary, the study of efficient link adaptation techniques has led to various approaches being proposed to achieve better performance over changing wireless channels. Such studies are beyond the scope of this thesis, but we will use a simple SINR based link adaptation technique to add scalability to our proposed MAC-2 protocol.
2.5 Summary

This chapter has presented previous studies on power control MAC protocols. None of the proposed MAC protocols both reduces energy consumption and increases spatial reuse, while solving both the hidden and exposed station problems. The attempts to exploit PHY layer improvements through smart antennas processing have focused on beamforming, which is limited by the complexity of mobile handheld devices and the accuracy of AOA information in multipath fading channels. The use of space-time coding has received some attention, but not for a peer-to-peer environment, and in an idealistic spatially uncorrelated setting. Hence, an attempt is made in this thesis to design a power-efficient collision-free MAC protocol which saves power and increases overall network throughput, while solving the hidden and exposed station problems. The protocol would also take full advantage of STC at the PHY layer, with Alamouti’s scheme chosen as the code. The low complexity of this scheme makes it suitable for operation on small handheld devices. Spatial correlation will be taken into account, and link adaptation will be added as an extension to fully exploit the several data rates provided by future WLAN standards.
Chapter 3

IEEE 802.11a Overview

This chapter presents the IEEE 802.11a standard, which MAC layer scheme is used as a basis for the proposed MAC protocol, and which PHY layer scheme is used as a basis for space-time coding (STC) enhancements. The PHY-MAC layer interaction is explained first. OFDM, the modulation used for data transmission in IEEE 802.11a based devices, is reviewed next. The transmitter/receiver designs, and the channel model used in the simulations are then detailed.

3.1 IEEE 802.11a Frame Format

This section shows how the interaction between the MAC and PHY layers in IEEE 802.11a occur. The frame format is detailed, and its various fields are explained.

The primary purpose of the IEEE 802.11a PHY layer is to transmit media access control (MAC) protocol data units (MPDUs) as directed in the IEEE 802.11 MAC layer. The OFDM PHY layer is divided into two sub layers: the physical layer convergence protocol (PLCP) and the physical medium dependent (PMD). The PLCP sub layer minimizes the dependence of the MAC layer on the PMD sub layer by mapping MPDUs into a frame format suitable for transmission by the PMD, which provides actual transmission and reception of PHY entities between two stations through the wireless medium. The
frame format for an IEEE 802.11a frame is shown in Figure 3.1.

The receiver uses the PLCP preamble field to acquire an incoming OFDM signal and synchronize the demodulator. The preamble, shown in Figure 3.2, consists of 12 symbols, ten of which are short and used for establishing automatic gain control (AGC) and the coarse frequency estimate of the carrier signal. The two long symbols are used for fine-tuning. The signal field consists of 24 bits, defining the data rate and the frame length. The length field identifies the number of bytes in the frame. The PLCP preamble and signal field are convolutionally encoded and sent at 6 Mbps using BPSK no matter what data rate the signal field indicates. The parity field is one bit based on positive (even) parity, and the tail field consists of six bits (all zeros) appended to the symbol to bring the convolutional encoder to zero state. The service field consists of 16 bits, with the first seven bits as zeros to synchronize the descrambler in the receiver, and the remaining nine bits (all 0s) reserved for future use. The PLCP service data unit (PSDU) is the payload from the MAC layer being sent. The pad field contains at least six bits, but it is actually the number of bits that makes the data field a multiple of the number of coded bits in an OFDM symbol.
3.2 OFDM Overview and Benefits

Since the IEEE 802.11a PHY layer is based on the OFDM modulation, this section presents an overview of this scheme and of its benefits.

OFDM is a special case of multicarrier transmission, where a single bit stream is transmitted in parallel bit streams modulated on separate sub carriers. The aggregate throughput is the same but the data rate on each sub carrier is much lower than the single-carrier case. To reduce crosstalk between sub carriers, they are arranged so that the sidebands of the individual carriers overlap such that at the center frequency of each sub carrier, there is no crosstalk from other channels. Figure 3.3 shows the spectra for a conventional multicarrier signal and an OFDM sub carrier. For the IEEE 802.11a standard, Table 3.1 lists the different sub carriers modulations, while Table 3.2 summarizes the main physical layer parameters used.
### Table 3.1: Sub carrier Modulation Types used in IEEE 802.11a

<table>
<thead>
<tr>
<th>Data Rate (Mbps)</th>
<th>Modulation</th>
<th>Coding Rate (R)</th>
<th>Coded bits per sub carrier</th>
<th>Coded bits per OFDM symbol</th>
<th>Data bits per OFDM symbol</th>
</tr>
</thead>
<tbody>
<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>16QAM</td>
<td>1/2</td>
<td>4</td>
<td>192</td>
<td>96</td>
</tr>
<tr>
<td>36</td>
<td>16QAM</td>
<td>3/4</td>
<td>4</td>
<td>192</td>
<td>144</td>
</tr>
<tr>
<td>48</td>
<td>64QAM</td>
<td>2/3</td>
<td>6</td>
<td>288</td>
<td>192</td>
</tr>
<tr>
<td>54</td>
<td>64QAM</td>
<td>3/4</td>
<td>6</td>
<td>288</td>
<td>216</td>
</tr>
</tbody>
</table>

### Table 3.2: Physical Layer Parameters used in IEEE 802.11a

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling Rate</td>
<td>20 MHz</td>
</tr>
<tr>
<td>Useful Symbol Duration</td>
<td>3.2 µs</td>
</tr>
<tr>
<td>Guard Interval Duration</td>
<td>0.8 µs</td>
</tr>
<tr>
<td>Total Symbol Duration</td>
<td>4.0 µs</td>
</tr>
<tr>
<td>Number of Data Sub Carriers</td>
<td>48</td>
</tr>
<tr>
<td>Number of Pilot Sub Carriers</td>
<td>4</td>
</tr>
<tr>
<td>Total Number of Sub Carriers</td>
<td>52</td>
</tr>
<tr>
<td>FFT Size</td>
<td>64</td>
</tr>
<tr>
<td>Sub Carrier Spacing</td>
<td>0.3125 MHz (20 MHz/64)</td>
</tr>
<tr>
<td>Total Bandwidth</td>
<td>16.875 MHz</td>
</tr>
<tr>
<td>Short Training Sequence Duration</td>
<td>8 µs</td>
</tr>
<tr>
<td>Long Training Sequence Duration</td>
<td>8 µs</td>
</tr>
<tr>
<td>PLCP Preamble Duration</td>
<td>16 µs</td>
</tr>
<tr>
<td>Duration of the Signal BPSK-OFDM Symbol</td>
<td>4 µs</td>
</tr>
<tr>
<td>Training Symbol Guard Interval</td>
<td>4 µs</td>
</tr>
</tbody>
</table>
The IEEE 802.11a OFDM based scheme has some key advantages over the IEEE 802.11b spread-spectrum based standard:

- The 5-GHz band offers three times the operating bandwidth over the available spectrum in the 2.4-GHz band.

- The 5-GHz band is less susceptible to interference, unlike the 2.4-GHz band, which shares the spectrum with other wireless appliances such as Bluetooth devices.

- The 802.11a standard allows data rates up to 54 Mbps, as compared to 11 Mbps for the IEEE 802.11b standard.

- The use of OFDM increases robustness against narrowband interference because such interference affects only a small percentage of the sub carriers which can be corrected using error control coding.

- The orthogonal nature of OFDM allows subchannels to overlap, hence saving bandwidth and increasing the spectral efficiency.

- The use of OFDM achieves lower multipath distortion since a single bit stream is converted into N parallel bit streams, hence increasing symbol duration, therefore decreasing relative delay spread.

- In relatively slow time-varying channels, it is possible to significantly enhance the capacity by adapting the data rate per sub carrier according to the signal-to-noise ratio of that particular sub carrier.

- The use of OFDM with a guard time of 800 ns avoids intersymbol interference on channels with delay spreads up to 250 ns, which is the case for all channels but those in the harshest environments [53, 54].

On the other hand, OFDM also has some drawbacks compared to single-carrier modulation:
- The use of OFDM reduces the power efficiency of the RF amplifier due to the large peak-to-average power ratio (PAPR).

- The use of OFDM, which involves the IFFT/FFT operations, causes carrier frequency offset due to motion.

### 3.3 OFDM Mathematical Representation

This section presents the mathematical representation of an OFDM signal, in both the time and frequency domains.

An OFDM symbol is a sum of sub carriers that are individually modulated using phase shift keying (PSK) or quadrature amplitude modulation (QAM). Its equivalent complex baseband notation is given by:

\[
s(t) = \frac{A}{N} \sum_{i=-N/2}^{N/2-1} x_{i+N/2} \exp \left( j 2\pi \frac{i}{T} (t - t_s) \right), \quad \text{for} \quad t_s \leq t \leq t_s + T \tag{3.1}
\]

where \( A \) is the scaling factor, \( N \) is the total number of sub carriers, \( x_{i+N/2} \) are the coded bits on sub carrier \((i+N/2)\), and \( T \) is the OFDM symbol duration. Notice that the complex baseband OFDM symbol defined in Equation (3.1) is the inverse Fourier transform of the coded input symbols on the \( N \) sub carriers.

The received signal is given by:

\[
r(t) = s(t) * h(t) + n(t) \tag{3.2}
\]

where \( h(t) \) is the channel impulse response, and \( n(t) \) is the additive noise vector.

In the frequency domain, the received signal is given by:

\[
R[k] = S[k] H[k] + N[k] \tag{3.3}
\]

where \( R[k] \), \( S[k] \), \( H[k] \), and \( N[k] \) are the \( k \)-th FFT components of \( r(t) \), \( s(t) \), \( h(t) \), and \( n(t) \) respectively.
3.4 IEEE 802.11a Transmitter

The block diagram for the IEEE 802.11a transmitter is shown in Figure 3.4. Data bits are generated by the binary source, input to a convolutional encoder of rate 1/2, which can be punctured to 2/3 or 3/4 if needed for a particular data rate. The output is interleaved, then converted to BPSK, QPSK, 16-QAM or 64-QAM values depending on the modulation type of the data rate to be used. The resulting symbols are divided over the 48 data sub carriers, and 4 pilot sub carriers are added. An inverse Fast Fourier Transform (IFFT) converts the signal to time domain, the cyclic prefix is added and the preamble appended. The resulting signal is transmitted over the channel. More details on the design of the IEEE 802.11a transmitter are available in [55].

3.5 Channel Model

Since we will mostly be interested in indoor applications, the most plausible case for MANETs, the indoor channel model used in the rest of this thesis is explained.

The model shown in Figure 3.5 represents a realistic indoor scenario in which reflectors generate multipath components that impinge on the receiver. The channel model recommended in the IEEE 802.11 WLAN specification [56] is a simplified exponential
power delay profile where a fixed number of paths with equidistant delays have independent Rayleigh distributed amplitudes. The average power delay profile is shown in Figure 3.6. The power delay profile has the form:

\[
P(\tau) = \frac{1}{T_d} \exp\left(-\frac{\tau}{T_d}\right)
\]

(3.4)

For this exponential model, the mean excess delay is \(\overline{\tau} = T_d\), and the RMS delay spread is \(\sigma_r = T_d\). The exponential power delay profile has been extensively used in the literature to model indoor and some outdoor channels ([56–60]).

The characteristic values of the RMS delay spread in an indoor environment range from 30 ns to 250 ns. Therefore, since the 800 ns GI ensures that the OFDM symbol period is greater than the worst case delay spread, the received signal will not experience intersymbol interference (ISI).
Furthermore, since the signal bandwidth \( B \) (16.56 MHz) is approximately equal to the coherence bandwidth \( \left( \frac{1}{T_d} \right) \) (20 MHz), the channel behavior is somewhere between fast and slow fading [61]. In the rest of this work, the channel is assumed static for the duration of an OFDM packet, and is independent for each packet generated.

According to the model used, the channel impulse response is given by:

\[
h(t) = \sum_{k=1}^{L} h_k \delta(t - kT_s), \tag{3.5}\]

where \( h_k = N(0, \frac{\sigma_k^2}{2}) + jN(0, \frac{\sigma_k^2}{2}) \) \( \tag{3.6} \)

and \( \sigma_k^2 = \sigma_0^2 e^{-\frac{kT_s}{\sigma_r}}, \quad \sigma_0^2 = 1 - e^{-\frac{T_s}{\sigma_r}} \) \( \tag{3.7} \)

Note that \( T_s \) is the sampling time, \( L \) is the number of multipath components impinging on the receiver, and that the condition \( \sum_{k=1}^{L} \sigma_k^2 = 1 \) is satisfied to ensure the same (constant) average received power.

Note that in case the LOS component is much stronger than the other multipath components, the channel model is expected to yield a better performance than the NLOS case. To model such an occurrence, the power of all components \( k > 1 \) is halved, and the sum is added to the first LOS component so that a Ricean faded channel is approximated.
3.6 IEEE 802.11a Receiver

The block diagram for the IEEE 802.11a receiver is shown in Figure 3.7. The reverse operations of those performed at the transmitter are performed, with the addition of synchronization. Synchronization mainly consists of three steps: packet edge detection, frequency correction and symbol timing. The first step consists of finding the packet edge, followed by correction for frequency errors. The approach of [62] is used to implement these steps. Next, fine timing allows the detection of the precise moment when OFDM symbols start and end by using a simple cross correlation-based algorithm. The cyclic prefix is now removed, and a Fast Fourier Transform (FFT) for every symbol recovers the values on the sub carriers. Channel estimation is done using training symbols and pilot sub carriers. The decoded symbols are to be demodulated, deinterleaved and the Viterbi decoder identifies the data bits. More details on the design of the IEEE 802.11a receiver are available in [55].

3.7 IEEE 802.11a PHY Performance

This section presents the performance results of the IEEE 802.11a PHY layer design for the channel model described in Section 3.5. The accurate PHY layer simulations will
make the MAC-2 performance results more viable and realistic. Note that the channel characteristics used (Rayleigh faded with 50 ns delay spread) are a pessimistic scenario for an indoor channel, and that the use of channel estimation instead of assuming an ideal recovery at the receiver further degrades the performance.

Figure 3.8 shows the average PER vs. Signal to Noise Ratio (SNR) for all the modes (6, 9, 12, 18, 24, 36, 48 and 54 Mbps) in the IEEE 802.11a standard. Each packet comprises 1000 bytes. As expected, as the data rates increase, the PER increases for the same SNR. The simulations were performed using Matlab, with the IEEE 802.11a PHY design and the channel model described earlier in this chapter. These results will be later incorporated into the OPNET simulator to yield a realistic PHY layer model in the study of the proposed MAC protocol’s performance.
3.8 IEEE 802.11a MAC

This section summarizes the operation of the IEEE 802.11 MAC protocol, common to both the IEEE 802.11a/b standards, and classified as a random access MAC protocol, as the lack of a centralized controller causes wireless devices in MANETs to initiate exchanges when needed. More details can be found in the standard description [1, 2].

The basic access method in the IEEE 802.11a/b MAC protocol is the Distributed Coordination Function (DCF) [63], which is best described as the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). In addition to the DCF, 802.11 also incorporates an alternative access method known as the Point Coordination Function (PCF), which requires a central controller and is not suitable for MANETs.

When using DCF, a station, before initiating a transmission, senses the channel to determine if another station is transmitting. The station proceeds with its transmission if the medium is determined to be idle for an interval that exceeds the Distributed Inter Frame Space (DIFS). In case the medium is busy, the station backs off from the transmission until the end of the ongoing transmission. A random backoff interval is selected which is used to initialize the backoff timer. The backoff timer is decremented only when the medium is idle; it is frozen when the medium is busy. After a busy period, the decrementing of the backoff timer resumes only after the medium has been free longer than DIFS. A station initiates a transmission when the backoff timer reaches zero.

The scheme uses acknowledgements to determine the successful reception of each data frame. The receiver initiates the transmission of an acknowledgement frame after a time interval, Short Inter Frame Space (SIFS), that is less than DIFS, immediately following the reception of the data frame. Note that the acknowledgement is transmitted without the receiver sensing the state of the channel. In case an acknowledgement is not received, the data frame is presumed lost and a retransmission is scheduled (by the transmitter). After the ACK is successfully transmitted, the stations wait for a time interval DIFS, after which they contend again for channel access in the contention window (CW).
Chapter 3. IEEE 802.11a Overview

The DCF also provides an alternative way of transmitting data frames that involves transmission of RTS and CTS frames prior to the transmission of the actual data frame. A successful exchange of RTS and CTS frames reserves the channel for the duration needed to transfer the data frame under consideration. The rules for the transmission of an RTS frame are the same as those for a data frame under basic access. Upon receiving an RTS frame, the receiver responds with a CTS frame (the CTS frame acknowledges the successful reception of an RTS frame), which can be transmitted after the channel has been idle for a time interval exceeding SIFS. After the successful exchange of RTS and CTS frames the data frame can be sent by the transmitter after waiting for a time interval SIFS. In case a CTS frame is not received within a predetermined time interval, the RTS is retransmitted following the backoff rules specified in the basic access procedures outlined above.

The RTS and CTS frames contain a duration field that indicates the period the channel is to be reserved for transmission of the actual data frame. The stations that can hear either the transmitter or receiver update their Network Allocation Vector (NAV), a timer that is always decreasing if its value is non-zero. A station is not allowed to initiate a transmission if its NAV is non-zero. The use of NAV to determine the busy/idle status of the channel is referred to as the Virtual Carrier Sense mechanism.

Figure 3.9 illustrates the typical IEEE 802.11 MAC exchange sequence. Note that all packets are sent at the same power level. The RTS/CTS exchange reserves the floor area within the range of both the transmitter and the receiver.

3.9 Summary

This chapter has explored the design of the IEEE 802.11a standard. Since the standard is OFDM based, a brief overview of the OFDM modulation scheme and of its mathematical representation in both the time and frequency domains was mentioned.
The PHY layer transmitter and receiver designs, as well as the channel model used in the simulations, have been explained. The MAC layer protocol was also detailed and its exchange sequence presented.
Chapter 4

MAC Layer Design: MAC-2

This chapter details the operation of the new MAC layer protocol, MAC-2, the core contribution of this thesis. The need for new MAC protocols is mainly due to the fact that the IEEE 802.11 protocol for WLANs was not specifically designed for a MANET environment. The performance of IEEE 802.11 MAC in such networks was shown to be poor [64], mainly due to the hidden and exposed station problems detailed in Chapter 1. The problems with the IEEE 802.11 MAC approach are reviewed, then the MAC-2 protocol design is explained. Finally, some implementation issues are explored, and assumptions made during the course of this chapter are justified.

4.1 IEEE 802.11 MAC Problems

This section summarizes some of the key problems in the IEEE 802.11 MAC paradigm that the new MAC-2 protocol tries to solve.

The IEEE 802.11 MAC protocol deals with the hidden station problem through the use of the optional RTS/CTS packet exchange sequence. However, the exposed station problem, which reduces the overall network throughput, is not solved by the current IEEE 802.11 MAC, and by many of the MAC protocols proposed for use in MANETs.

The reason for the exposed station problem is that the nodes set their NAV upon
reception of the RTS packet from the transmitter. Since collisions only occur at the receiver, we believe that nodes should only set their NAV upon reception of the CTS packet. This observation led to a modification of the channel reservation scheme in the MAC-2 protocol, so that a more efficient scheme occurs.

The IEEE 802.11 MAC protocol sends all packets at the same power, which leads to unnecessary power consumption. The schemes that have been proposed to increase energy efficiency in MANETs can be divided into three main categories, as mentioned in Chapter 2:

- **Transmission Power Control**: These mechanisms adjust transmission power dynamically. The MAC-2 protocol falls under this category.

- **Power Saving Routing**: These mechanisms establish routing paths using energy consumption as the metric to minimize.

- **Low Power Mode**: These mechanisms put the nodes in the IDLE and SLEEP modes as often as possible to save power.

The ability to reduce transmission power leads to considerable energy savings, effective interference reduction, and greater spatial reuse. The design of the MAC-2 protocol tries to address these issues, and combines power reduction with an efficient channel reservation scheme to reserve the minimum area needed for a particular exchange to occur successfully.

The IEEE 802.11 MAC protocol provides no guarantees on Quality of Service (QoS) for any of the nodes in the MANET. QoS provision in MANETs is a major problem that is receiving considerable attention in the research community. Issues such as fairness and scheduling are easier to achieve in a centralized network than in a MANET. The new IEEE 802.11e draft [65] attempts to incorporate QoS guarantees in the MAC protocol, but is still under study.
The MAC-2 protocol adjusts the transmission power in order to achieve a desired packet error rate (PER) at the receiver, hence providing basic QoS guarantees. Furthermore, due to its efficient channel reservation scheme and to its collision free nature, simulations have shown an almost constant data packet end-to-end (ETE) delay. This observation supports the fact that MAC-2 can provide basic QoS, in addition to saving energy and increasing overall network throughput. Note that the focus of the MAC-2 protocol is not on QoS provisioning, but these observations can lay the ground for further work on this issue.

4.2 MAC-2 Protocol Design

This section details the packet exchange sequence of the MAC-2 protocol, and then summarizes the main assumptions made during the design of the MAC-2 protocol. A generic example is used to justify using an additional channel and using the new control packets. The new protocol is shown to solve both the hidden and exposed station problems. Finally, an extension to MAC-2 using link adaptation is proposed.

4.2.1 MAC-2 Protocol Packet Exchange Sequence

The MAC-2 protocol is based on using two channels, a control channel used to transmit the required control packets and a data channel used to transmit the data packets. The two channels are assumed not to interfere with each other. The MAC-2 protocol introduces two new control packets: a mandatory confirmation packet (CONF) to ensure a collision free protocol and an optional cancellation packet (CANCEL) to ensure no interference with on-going receptions. In addition, MAC-2 introduces a new inter-frame spacing called WIFS (Wait Inter Frame Spacing) after the CONF packet transmission. The need for the two channels and for the additional packets is justified in Sections 4.2.3 and 4.2.4 respectively. Note that the backoff and retransmissions mechanisms are similar
Chapter 4. MAC Layer Design: MAC-2

Table 4.1: Maximum Transmit Power in IEEE 802.11a

<table>
<thead>
<tr>
<th>Frequency Band (GHz)</th>
<th>Max Power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.15-5.25</td>
<td>40</td>
</tr>
<tr>
<td>5.25-5.35</td>
<td>200</td>
</tr>
<tr>
<td>5.725-5.825</td>
<td>800</td>
</tr>
</tbody>
</table>

Table 4.2: Inter Frame Spacing values in MAC-2

<table>
<thead>
<tr>
<th>Inter Frame Spacing</th>
<th>Duration (μs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIFS</td>
<td>34</td>
</tr>
<tr>
<td>SIFS</td>
<td>16</td>
</tr>
<tr>
<td>WIFS</td>
<td>9</td>
</tr>
</tbody>
</table>

to those for the IEEE 802.11a MAC protocol.

The MAC-2 protocol uses two network allocation vectors, one for the control channel (C-NAV) and the other for the data channel (NAV). Any non-zero C-NAV value implies that no control packets can be sent on the control channel. Any non-zero NAV value implies that no data packet can be sent on the data channel, and that no transmission can be initiated, i.e. no RTS packet can be sent on the control channel. Only CTS, CONF or ACK packets can be sent on the control channel in this case. The steps associated with the MAC-2 exchange sequence are:

1. The transmitter starts the exchange by sending the RTS packet on the control channel at the maximum power $P_{\text{max}}$ allowed in its frequency band. Table 4.1 shows the maximum allowed transmission power in the IEEE 802.11a for each possible band. These values will be used in this thesis, but this approach is valid for any frequency bands of interest. Nodes receiving this RTS packet set their C-NAV to the duration of the (CTS packet + CONF packet + 2*SIFS + propagation delay exchange sequence).

2. The receiver receives the RTS packet at power $P_{\text{recv}}$, but also noise and interference
summing to power $P_n$. The resulting SINR corresponds directly to a PER based on the modulation scheme used.

3. The receiver calculates the minimum required transmission power $P_{\text{min}\_\text{req}}$ at which the CTS packet should be sent so that it arrives at the transmitter at $P_{\text{thres}}$ corresponding to an acceptable threshold PER $\text{PER}_{\text{thres}}$. Once the required power level, $P_{\text{min\_req}}$, is established, all subsequent transmissions on both channels occur at $P_{\text{min\_req}}$.

4. The receiver sends the CTS packet on the control channel. Nodes hearing the CTS packet set their C-NAV to the duration of the (CONF packet + SIFS + propagation delay exchange sequence) and their NAV to the duration of the (CONF packet + DATA packet + SIFS + WIFS + propagation delay exchange sequence), where the WIFS duration will be explained shortly. Table 4.2.1 gives the inter frame spacings defined in the IEEE 802.11a standard, and used in the MAC-2 protocol. The CONF packet is assumed similar in structure to the RTS packet.

5. The transmitter sends the new confirmation control packet, CONF, on the control channel. The reason for this packet is to ensure that the MAC-2 protocol reserves the minimum area by preventing DATA packets collisions, which allows an increase in spatial reuse. The transmitter then waits for a short interval $\text{WIFS} < \text{SIFS}$. WIFS has to be large enough to allow for propagation delay and frame processing time. If a node within the range of the transmissions has an ongoing reception in progress with data transfer on the data channel and receives a CONF packet on the control channel, it sends a CANCEL packet on the control channel. As shown in Section 4.2.4, this CANCEL packet is needed to ensure a collision-free protocol. This cancellation causes any new exchange to be delayed until the ongoing transfer ends. The CANCEL packet is assumed similar in structure to the CTS packet.

6. If the transmitter does not receive the CANCEL packet during the WIFS duration,
it sends the DATA packet at the minimum required power, $P_{\text{min,req}}$, on the data channel. Note that the value of $P_{\text{min,req}}$ on the data channel is different than that on the control channel, since the control and data packet transmissions do not occur at the same rate. The value of $P_{\text{min,req}}$ on the data channel is also chosen so that the DATA packet is received at threshold PER. An inherent assumption is that the power loss on the control and data channels is the same. The receiver responds with an ACK packet on the control channel, and the exchange is successfully terminated.

![Figure 4.1: MAC-2 Protocol Exchange](image)

To determine $P_{\text{min,req}}$, the following model is used, where nodes A and B are exchanging information.

$$P_{\text{recv}} = P_{\text{max}} \cdot \gamma$$  \hspace{1cm} (4.1)

where $\gamma$ is the attenuation and loss from node A to node B.

$$P_{\text{thres}} = P_{\text{min,req}} \cdot \gamma$$  \hspace{1cm} (4.2)

where $P_{\text{min,req}}$ is the minimal power needed by node B to reply to node A so that node
A is reached at $P_{\text{thres}}$ corresponding to $\text{PER}_{\text{thres}}$.

$$P_{\text{min,req}} = \frac{P_{\text{max}} \cdot P_{\text{thres}}}{P_{\text{recv}}}$$ (4.3)

### 4.2.2 MAC-2 Protocol Assumptions

The aforementioned calculation of $P_{\text{min,req}}$ is based on a number of assumptions:

- The two channels do not interfere with each other: The spacing between the data and control channels is assumed large enough to have a perfect separation of packets sent on these two channels.

- The path loss is constant over the duration of a single exchange (control plus data packets): The MAC-2 protocol calculates $P_{\text{min,req}}$ based on the power level received $P_{\text{recv}}$ when an RTS packet arrives at the receiver. The remaining transmissions are performed at a power level derived from the path loss incurred by this initial exchange.

- The path loss is symmetric over a particular channel: The MAC-2 receiver assumes that the path loss in one direction (from the transmitter to the receiver) is the same as that in the other direction (from the receiver to the transmitter).

- The control and data channels suffer the same path loss: The MAC-2 protocol introduces a separate control channel for control packets transmission. To calculate $P_{\text{min,req}}$ for the data packet transmission, the transmitter assumes that both channels experience the same path loss.

These assumptions will be valid in some environments more than in others, but an attempt is made in Section 4.3 to justify some of them. An accurate physical layer modelling makes the obtained results more realistic.
4.2.3 Justification for Control Channel

One of the main problems related to using different transmission powers on a single channel is illustrated in Figure 4.2. If an A-B exchange is occurring at the minimum power, neither node C nor node D has knowledge of it since they are out of range of both nodes A and B. If either node C or node D initiates a transfer while the A-B exchange is still occurring, a collision will occur, requiring retransmission, thus causing delay and unnecessary power consumption.

![Figure 4.2: Need for Two Channels Justified](image)

To further illustrate the situation, assume node C sends RTS which reaches nodes A and B while the ongoing A-B exchange is occurring. This causes a collision, the A-B exchange is disrupted, and the C-D exchange cannot start. The use of a control channel helps to avoid this problem. Since the two channels are assumed to not interfere with each other, when the A-B data exchange is occurring on the data channel, the control packets sent on the control channel will guarantee that the data exchange is collision-free.
4.2.4 Justification for CONF and CANCEL Packets

The CONF packet is needed for two reasons: the fact that the collisions occur at the receiver, and the need to reserve the minimum area to ensure multiple simultaneous transmissions. A receiver of an ongoing exchange is notified upon the reception of CONF on the control channel that a new exchange that might cause collision is about to start. It can then delay this new exchange using the CANCEL packet. In addition, if the RTS packet reserves the floor area at the maximum power $P_{\text{max}}$, then the MAC-2 protocol would only save power, but would not increase the overall throughput. Therefore, with the introduction of the CONF packet and the modifications to the channel reservation schemes, MAC-2 becomes a collision-free protocol reserving the minimum area, hence increasing the overall network throughput in addition to saving power.

To justify the need for a CANCEL packet, we use an example scenario. This example scenario is based on four nodes (A to D) spaced by the following distances, illustrated in Figure 4.3:

A-B: $x$  B-C: $y > x$  C-D: $z > y$

Suppose T1, a transmission between nodes A and B starts first.

A sends the RTS packet at $P_{\text{max}}$ on the control channel. B replies with the CTS packet at $P_{\text{min,req}}$ on the control channel that covers $x$ (so it reaches only A, not C). All further transmissions are at this power level. A sends a CONF packet on the control channel that covers $x$ (so it reaches only B). A sends the DATA packet on the data channel that covers $x$ (so it reaches only B). B sends the ACK packet on the control channel that covers $x$ (so it reaches only A).

If C wants to transmit to D while the A-B exchange is ongoing, C sends the RTS packet at $P_{\text{max}}$ on the control channel. D sends the CTS packet at $P_{\text{min,req}}$ on the control channel that covers $z$ (so it reaches only C). All further transmissions are at this power level. C sends the CONF packet on the control channel that covers $z$ (so it reaches B and
D) and waits for WIFS. Since B is the receiver of an ongoing transmission on the DATA channel, it sends the CANCEL packet at the new $P_{\text{min req}}$ that covers $z$ on the control channel (so it reaches A and C). C was waiting for WIFS, and receives the CANCEL packet, so it delays its transmission, hence avoiding a collision at B.

4.2.5 Collision-Free Nature of the MAC-2 protocol

The MAC-2 protocol aims at avoiding collisions, which needlessly increase the power consumption and the delay in MANETs. The collision of DATA packets, due to their large size, is particularly harmful. These collisions are always avoided in MAC-2, due to the use of the CONF-CANCEL packets, which, as detailed in the previous section, will allow the new DATA packet transmission to occur only if no collisions with an ongoing exchange are guaranteed.

As for the collision of control packets, the issue needs further analysis. At the transmitter, when the RTS packet is sent at the maximum power $P_{\text{max}}$, all nodes hearing this packet will set their C-NAV for the duration of the CTS and CONF control packets exchange, hence, no new transmission can start, and no collisions can occur between an RTS packet from a new transmission and the CTS packet reception at the transmitter.
If a CANCEL packet is sent back to the transmitter by an ongoing exchange, no collisions occur as well, since after the CONF packet transmission, the duration till CANCEL is received (Maximum of WIFS + CANCEL = 9μs + 14μs = 23μs) is shorter than the DIFS time interval (34μs) and the contention window (CW) period that elapses before the RTS packet of a new exchange is transmitted (random value less than 7 time slots, i.e, 63μs). This scenario is illustrated in Figure 4.4.

The ACK packet reception at the transmitter will cause no control packets collisions if the nodes in the network are infinitely backlogged, since the duration of the RTS-CTS-CONF transfer on the control channel for a new exchange is 76μs, to which the DIFS time interval (34μs) and the contention window (random value less than 7 time slots, i.e, 63μs) are added, leading to a worst-case exchange on the control channel of 173μs, which is lower than the WIFS + DATA packet + SIFS duration of 177μs, that elapses before the ACK packet is sent. Therefore, by the time the ACK packet is sent back to the transmitter on the control channel, any neighboring exchange will have completed its control channel, which avoids collision between the ACK packet and other control packets on the transmitter side. This scenario is illustrated in Figure 4.5.

At the receiver, when the CTS packet is sent at the minimum required power $P_{\text{min, req}}$ to reach the transmitter, all nodes hearing this packet are prevented from sending DATA packets or RTS packets for the entire duration of the exchange at hand. Note that after the NAV duration ends, an ACK packet is sent after an SIFS time interval. But, due
Figure 4.5: No Collision with ACK packet at Transmitter

Figure 4.6: No Collision with ACK packet at Receiver

to the need for nodes where NAV has expired to wait for at least a DIFS time interval (34\(\mu s\)) which is longer than the time needed for the successful ACK packet transmission (SIFS + ACK = 30\(\mu s\)). Hence, no collisions can occur between the ACK packet and the control packets of any new exchange. This scenario is illustrated in Figure 4.6. The only potential collisions are between an RTS packet sent at the maximum power \(P_{\text{max}}\) from a node outside the range of the CTS packet, which corresponds to the minimum area around the receiver. Such a possibility exists, but is small enough not to considerably affect MAC-2’s performance.
4.2.6 Hidden and Exposed Station Solutions

The MAC-2 protocol described above solves two major problems with the IEEE 802.11 MAC protocol, namely the hidden station and most importantly, the exposed station problems.

Hidden Station:

The typical hidden station scenario is based on four nodes (A to D) spaced by the following distances, illustrated in Figure 4.7:

\[ A-B: x \quad B-C: y \leq x \quad C-D: z \]

Suppose T1, a transmission between nodes A and B starts first. Any distances \( x, y, z \) where \( y \leq x \), necessary to have a hidden station scenario, can be used. If \( y > x \), no hidden station problem occurs.

A sends the RTS packet at \( P_{\text{max}} \) on the control channel. B replies with the CTS packet at \( P_{\text{min,req}} \) that covers \( x \) (so it reaches both A and C) on the control channel. C sets its NAV so it cannot send neither an RTS nor a DATA packet for the duration of the (CONF packet + DATA packet + WIFS + SIFS exchange sequence). A sends the
CONF packet at $P_{\text{min,req}}$ on the control channel and then the DATA packet at $P_{\text{min,req}}$ on the data channel. B sends the ACK packet at $P_{\text{min,req}}$ on the control channel.

If C wants to transmit to D while the A-B exchange is ongoing, C cannot initiate any transmission until the A-B exchange is over due to its NAV setting, upon receipt of the CTS packet from B, which solves the hidden station problem.

Exposed Station:

The typical exposed station scenario also uses four nodes (A to D) spaced by the following distances, illustrated in Figure 4.8:

$$A-B: x \quad B-C: y \leq z \quad C-D: z$$

Suppose T1, an exchange between A and B, starts first. A similar analysis is valid if T2 starts first. Any distances $x, y, z$ where $y \leq z$, necessary to have an exposed station scenario, can be used. If $y > z$, no exposed station problem occurs.

B sends the RTS packet at $P_{\text{max}}$ on the control channel. A sends the CTS packet at $P_{\text{min,req}}$ that covers $x$ (so it reaches only B) on the control channel. B sends the CONF
packet at $P_{\text{min\_req}}$ on the control channel. No receiver of an ongoing transmission receives CONF, hence no CANCEL packet is sent. B sends the DATA packet at $P_{\text{min\_req}}$ on the data channel. A sends the ACK packet at $P_{\text{min\_req}}$ on the control channel.

If C wants to transmit to D while the A-B exchange is ongoing, C sends the RTS packet at $P_{\text{max}}$ on the control channel. D sends the CTS packet at $P_{\text{min\_req}}$ that covers $z$ (so it doesn’t reach A but reaches C) on the control channel. C sends the CONF packet at $P_{\text{min\_req}}$ on the control channel that covers $z$ (so it doesn’t reach A but reaches B and D). Since B and D are not the receivers of an ongoing transmission, then no CANCEL packet is sent. After waiting for WIFS, C sends the DATA packet at $P_{\text{min\_req}}$ on the data channel. D sends the ACK packet at $P_{\text{min\_req}}$ on the control channel. Hence the two transmissions can occur simultaneously, which solves the exposed station problem.

4.2.7 MAC-2 Link Adaptation

The MAC-2 protocol works at any data rate and its corresponding control rate which is specified by the IEEE 802.11a standard, as shown in Table 4.2. It is desirable to operate at the highest possible rate in order to benefit from the high speeds that IEEE 802.11a offers. However, due to distance and interference, it is sometimes impossible to operate at the highest possible rate. This occurs for instance, when the RTS packet is received by the receiver at power $P_{\text{recv}}$, with noise and interference summing to power $P_n$, hence corresponding to a SINR which achieves a PER below the threshold PER which conditions the subsequent packet exchanges. In this case, two solutions exist:

1. Increase the transmission power
2. Exchange the remaining packets at a lower rate

The first option is not possible, since it violates the limits set by the IEEE 802.11a standard on the transmission power $P_{\text{max}}$ allowed in each band of operation. On the other hand, the second option is more plausible. The key is to look for a lower rate that
Table 4.3: IEEE 802.11a control rates

<table>
<thead>
<tr>
<th>Data Rate (Mbps)</th>
<th>Control Rate (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6, 9</td>
<td>6</td>
</tr>
<tr>
<td>12, 18</td>
<td>12</td>
</tr>
<tr>
<td>24, 36, 48, 54</td>
<td>24</td>
</tr>
</tbody>
</table>

achieves the threshold PER at the SINR obtained at the receiver. The benefit of such an approach is to increase the range of operation of MAC-2. Since the 54 Mbps data rate and its corresponding 24 Mbps control rate are restricted by path losses, switching to lower rates gives MAC-2 the flexibility to operate over longer ranges, hence expanding its use to large indoor environments (conference rooms, malls...).

The steps associated with the new MAC-2 exchange sequence are similar to those described in Subsection 4.2.1, except for step 2, which becomes as follows:

- The receiver receives the RTS packet at power $P_{\text{recv}}$, with noise and interference summing to power $P_n$. The resulting SINR corresponds to a PER based on the modulation scheme used for control packets transfer (24 Mbps), which is below the desired PER threshold for the remaining packet exchanges. The receiver hence needs to lower the control rate to be able to achieve the threshold PER. Two other possibilities for the control rate are 6 Mbps and 12 Mbps as shown in Table 4.2. Hence, if the 12 Mbps control rate achieves the PER threshold at the resulting SINR, then the CTS packet will be sent back at this rate, while the DATA packet will be sent at the 18 Mbps rate (highest possible data rate for corresponding control rate). Similarly, if the 6 Mbps control rate works, the data rate will be 9 Mbps. This scheme allows transmission to occur at the highest possible rate, while achieving the power savings and the basic QoS requirements.

Another issue that can be brought to the MAC-2 protocol design is regarding the value of the threshold PER. In the initial description of Subsection 4.2.1, it is assumed
Table 4.4: Channel Base Frequencies for IEEE 802.11a standard

<table>
<thead>
<tr>
<th>Lower UNII Band</th>
<th>Middle UNII Band</th>
<th>Upper UNII Band</th>
</tr>
</thead>
<tbody>
<tr>
<td>5171.7, 5191.7,</td>
<td>5251.7, 5271.7,</td>
<td>5736.7, 5756.7,</td>
</tr>
<tr>
<td>5211.7, 5231.7 MHz</td>
<td>5291.7, 5311.7 MHz</td>
<td>5776.7, 5796.7 MHz</td>
</tr>
</tbody>
</table>

that the threshold PER is known by all nodes, and fixed to a particular value for each exchange sequence. An additional functionality is to include the desired PER information in the RTS packet. The steps associated with the new MAC-2 exchange sequence are similar to those described for MAC-2, except that the resulting SINR corresponds to a PER which is compared to the desired PER extracted from the RTS packet. The control rate and packet rate adjustments are done as previously described.

4.3 Implementation Issues

This section will try to justify some of the assumptions previously made while designing the MAC-2 protocol, by presenting practical ways to implement it while satisfying the constraints on the channel bandwidth and channel spacing. An effective way to convey QoS information is also proposed.

In implementing the power efficient MAC protocol of Section 4.2, an issue that needs some analysis is the choice of both the bandwidth and spacing of the control and data channels. The IEEE 802.11a standard defines 12 16.56 MHz channels in three bands, as shown in Table 4.3. We propose to assign part of this bandwidth for each channel. Ideally, the data is transmitted at 54 Mbps, hence the control information is transmitted at 24 Mbps. The simulations in this thesis use a data packet size of 1000 bytes, while the size of the control packets is 20 bytes for RTS/CONF and 14 bytes for CTS/CANCEL/ACK. With the addition of the 28-byte header, 16 μs are needed to send a control packet, and 152.3 μs are needed to send a data packet. It is a common practice to assume a narrowband channel for the control channel, and a wideband channel for the data
channel. However, frequency dependent fading [66] will cause the channel gains to be different in each channel. This problem can be overcome by ensuring that the data and control channels are within the channel coherence bandwidth.

The channel bandwidths are assigned to the data and control channels in the following manner: the time needed to send a control packet and the time needed to send a data packet are used to establish proportionality between BW1 and BW2, the bandwidth of the control and data channels respectively. Since the sum of BW1 and BW2 is 16.56 MHz, BW1 is set to 1.56 MHz and BW2 to 15 MHz.

The assumption of the path loss being constant over the packet exchange after RTS is received, i.e, the duration of the (CTS packet + CONF packet + ACK packet + DATA packet + 3*SIFS + WIFS + propagation delay exchange sequence), which is equal to 253\mu s at the highest rates possible (24 Mbps for control packets and 54 Mbps for data packets), means that the coherence time of the channels should be greater than 253\mu s. In the middle UNII band centered at around 5.3 GHz, the limiting speed of the mobile node for the assumption to be true is:

\[ v = f_m \times \lambda = \frac{1}{253 \times 10^{-6}} \times \frac{3 \times 10^8}{5.3 \times 10^9} = 223.73 m/s \] (4.4)

which is higher than the expected speed in indoor scenarios, and even in some outdoor scenarios.

Another issue that needs justification is the spacing between the two channels so inter-channel interference is avoided; yet, the control channel should be in the coherence

---

**Figure 4.9: Proposed UNII Middle Band Spectrum Allocation**

<table>
<thead>
<tr>
<th>1</th>
<th>1</th>
<th>2</th>
<th>2</th>
<th>3</th>
<th>3</th>
<th>4</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>5251.7 MHz</td>
<td>5261.7 MHz</td>
<td>5271.7 MHz</td>
<td>5281.7 MHz</td>
<td>5291.7 MHz</td>
<td>5301.7 MHz</td>
<td>5311.7 MHz</td>
<td>5321.7 MHz</td>
</tr>
</tbody>
</table>
bandwidth of the data channel. In the PHY layer design, a 50 ns rms delay spread was considered a realistic value commonly used for an indoor environment [54], which corresponds to a coherence bandwidth of 20 MHz. The spectrum shown in Figure 4.9 is proposed as a potential solution. It represents a way for the UNII Middle band to accommodate two channels with efficient guard bands. The initial center frequencies (5251.7, 5271.7, 5291.7 and 5311.7 MHz) are preserved for the data channels, so the changes are minimal. The center frequencies for the control channels will therefore be 5261.7, 5281.7, 5301.7 and 5321.7 MHz. Each device in the MANET will use a specific data channel and its corresponding control channel to communicate with the other devices. Both control and data channels are within 20 MHz; hence the control channel is in the coherence bandwidth of the data channel. In addition, the guard-band between the control and data channel is 1.75 MHz so inter-channel interference is minimal. A similar approach can be taken for the other two bands (Lower and Upper UNII).

Another issue that needs to be addressed is how to convey the information about the data rate and the desired Class of Service to the transmitter as the CTS packet is sent from the receiver when the adaptation has been made based on the control rate chosen. One way to do so is to use the reserved bits in the service field of the MAC Protocol Data Unit (MPDU) header field “Service”. As seen in Chapter 3, 9 bits are reserved in the “Service” field of the header. As concerns the data rate, 3 bits are needed to specify

### Table 4.5: Specifying data rates

<table>
<thead>
<tr>
<th>Bit Sequence</th>
<th>Data Rate (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>000</td>
<td>6</td>
</tr>
<tr>
<td>001</td>
<td>9</td>
</tr>
<tr>
<td>010</td>
<td>12</td>
</tr>
<tr>
<td>011</td>
<td>18</td>
</tr>
<tr>
<td>100</td>
<td>24</td>
</tr>
<tr>
<td>101</td>
<td>36</td>
</tr>
<tr>
<td>110</td>
<td>48</td>
</tr>
<tr>
<td>111</td>
<td>54</td>
</tr>
</tbody>
</table>


Table 4.6: Specifying Class of Service

<table>
<thead>
<tr>
<th>Bit Sequence</th>
<th>CoS</th>
<th>Desired PER</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>01</td>
<td>2</td>
<td>0.01</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>0.001</td>
</tr>
<tr>
<td>11</td>
<td>4</td>
<td>N/A</td>
</tr>
</tbody>
</table>

the 8 possible rates, as shown in Table 4.4. As concerns the Class of Service, 2 bits are needed to specify for example 4 different classes, as shown in Table 4.5. Note that we can have a bit sequence that disables the Class of Service option and allows this PER threshold to be specified by another method.

Another issue that needs to be looked at is how to convey duration information of both NAV and C-NAV to the nodes in the network. In order not to lengthen the RTS/CTS packet formats defined in the IEEE 802.11 MAC standard, it is suggested to use the 2-byte Duration field, which originally conveyed the NAV value, to transmit the higher of the NAV and C-NAV durations, and deduce the other value from it. Practically, the RTS packet will contain the C-NAV duration of the (CTS packet + CONF packet + 2*SIFS + propagation delay exchange sequence). The CTS packet will contain the NAV duration of the (CONF packet + DATA packet + SIFS + WIFS + propagation delay exchange sequence), from which the C-NAV duration is deduced, as the WIFS duration (known) and the DATA packet duration (can be easily found from the DATA packet length and data rate) are subtracted from the NAV value.

The MAC layer is made aware of the received power at the PHY layer through the Received Signal Strength Indicator (RSSI) field defined in the IEEE 802.11a standard. Note that the maximum transmission power in a particular UNII band is pre-defined in the standard as shown in Table 4.1. This explains how the calculation of $P_{\text{min,req}}$ at the receiver, described in Subsection 4.2.1, can be carried out, since $P_{\text{max}}$ is well-defined, $P_{\text{recv}}$ is provided by RSSI, and $P_{\text{thres}}$ can be extracted from the modulation table corresponding
to a particular channel’s data rate.

Since this work is mainly targeted towards indoor applications, the distance between the furthest nodes is always assumed to be less than the than the transmission range. Therefore, interference is accumulated from each transmission by all nodes in the network. This makes the carrier sensing range value unattainable, as the power received at each node is greater than the threshold power reception in commercial network cards, and this power is always added to the interference, yielding a signal to interference noise ratio (SINR) corresponding to a packet error rate (PER) which determines whether or not the packet is accepted.

The use of separate control and data channels requires simultaneous transmission and reception at two different center frequencies. This implies that two transceivers capable of operating in the 802.11a band are needed for an implementation of MAC-2. This is clearly an important implementation issue in terms of the additional cost and space needed. On a positive note, some state-of-the-art handheld devices have three transceivers at three different center frequencies, all of which can operate simultaneously [67]. Therefore, the assumption of two transceivers could become a reality in the next generation of wireless devices.

4.4 Summary

This chapter has explored the design of the MAC-2 protocol. A justification of the major design decisions of the MAC-2 protocol (use of two channels and of additional control packets), and a report of the main characteristics of the MAC-2 protocol (solution to both the hidden and exposed station problems) were shown. Finally, an explanation of some of the implementation issues was presented. This explanation justified some of the assumptions that were made in the design of the MAC-2 protocol.
Chapter 5

MAC-2 Performance Results

This chapter evaluates the MAC-2 protocol performance. The benefits of using the proposed protocol are illustrated using simulations. The simulations use OPNET Modeler version 7.0B [68] with its IEEE 802.11a extension [69]. Results show how the exposed station problem is solved, and how the MAC-2 protocol outperforms the IEEE 802.11a MAC protocol both in power consumption and in overall network throughput. Finally, the MAC-2 extension to include link adaptation is studied.

5.1 Simulation Model

This section presents the simulation model used throughout this chapter to analyze the MAC-2 protocol performance. Since MAC-2 is the first power efficient MAC protocol to be built on the IEEE 802.11a PHY layer, its performance cannot be compared with any existing MAC layer protocols.

For the MAC-2 protocol, the data and control channel rates are dynamically set, but the RTS packet rate is initially set to the highest possible control rate, namely 24 Mbps, with the data channel operating at 54 Mbps. The required QoS is assumed to be met below the PER threshold value specified in the RTS packet exchange.

Background white noise is added to the interference noise from other nodes to cal-
Chapter 5. MAC-2 Performance Results

calculate the SINR. The study is mostly based on a peer-to-peer video conferencing in an indoor environment, an application well suited for an ad-hoc application. In such an environment, the radio propagation model has a path loss where the signal would suffer from increased attenuation as it passes through the partitions, walls, floors, doors and ceilings. Studies show that a path loss exponent of 3.8 is realistic for indoor settings [70]. The results of the thorough PHY layer analysis done in Chapter 3 are integrated into OPNET.

The packet load is changed by varying the inter-frame spacing, the number of pixels and the resolution quality (Low or High). Unless stated otherwise, the packet size is fixed to 1000 bytes, so that the results generated for the PHY layer in Chapter 3 are more accurate.

5.2 Performance Metrics

This section proposes two metrics to evaluate the MAC-2 protocol performance versus the original IEEE 802.11 MAC protocol.

- Aggregate throughput over the entire network

- Total data delivered per unit of energy consumption (bits/J). The following formula is used to find the value of this performance metric:

\[
\frac{S}{E_c} = \frac{S}{\sum_{i=1}^{K} P_i T_i + \sum_{j=1}^{M} P_j T_j},
\]

where,

- \( S \): total number of successful data bits sent between source and destination
- \( E_c \): total energy consumption in the network
- \( K \): total number of packets sent (including control packets) for the duration of the simulation (from all nodes)
\( P_t^i \): transmission power of packet \( i \)
\( T_t^i \): time to transmit packet \( i \)

\( M \): total number of packets received (including control packets) for the duration of the simulation (from all nodes)

\( P_r^j \): reception power of packet \( j \)
\( T_r^j \): time to receive packet \( j \)

Note that this formula accounts for the power when the actual destination receives the packet and when any node hears a packet not destined for it.

### 5.3 MAC-2 vs. IEEE 802.11a Simulation Results

This section compares the performance of the new power-efficient MAC protocol (MAC-2) with the performance of the original IEEE 802.11a protocol. The class of service is 1, meaning that the threshold PER is 0.1. For a fair comparison with IEEE 802.11a, the threshold PER for correct reception is also set to 0.1. Since a 54 Mbps rate cannot be sustained for large distances [66], the simulation uses a typical distance of 20m over which such a rate is surely preserved in the MAC-2 protocol. This number is specified in both commercial products such as Cisco’s Aironet [71], and theoretical studies [5, 6]. When mobility is included in the simulations, the maximum spacing between any two nodes able to communicate at this rate is restrained by this limit.

The first example deals with the exposed station problem. Then, a comparison of the MAC-2 protocol vs. the IEEE 802.11a MAC protocol is shown for different packet loads and packet sizes. Control traffic throughput and the end-to-end (ETE) data packet delay are also compared to further illustrate the efficiency of the MAC-2 protocol. Finally, the effect of the different Classes of Service (CoS) in large indoor environments, using link adaptation to provide the desired QoS, is presented.
5.3.1 Exposed Station Problem

A typical chain topology, shown in Figure 5.1, is used to validate the claim that the MAC-2 protocol solves the exposed station problem. The 4 nodes are assumed to be equidistant. A video conferencing application was used, with the T1 2-way exchange starting at 20 sec, and the T2 2-way exchange starting at 25 sec.

![Figure 5.1: Simple Chain Topology for Exposed Station](image)

Figure 5.2 shows the aggregate throughput in the two cases: with the original IEEE 802.11a scheme, and with MAC-2. The 802.11a protocol allows only a single data exchange (T1) to occur at any time, while MAC-2 allows multiple transmissions (T1 and T2) to occur simultaneously. As can be seen from the figure, the MAC-2 protocol has an aggregate throughput almost twice that of the original IEEE 802.11a protocol, due to the use of two channels, the efficient power control, and the channel reservation scheme.

Figures 5.3 and 5.4 show the throughput at individual nodes. Clearly MAC-2 allows both nodes B and C to exchange data with nodes A and D respectively, i.e. the exposed station problem is solved.

5.3.2 Effect of Load

The effect of varying the network load on a random mobile topology is studied, where 10 nodes move in a 20m × 20m area. Each node randomly chooses its destination and initiates a transmission. Figure 5.5 shows the aggregate network throughput while Figure 5.6 shows the total data delivered per unit of energy consumption in Mbits/J.

Figure 5.5 shows the aggregate network throughput as the load increases. The figure
shows that the aggregate throughput for MAC-2 is significantly higher than that for IEEE 802.11a. Due to the efficient power control, more exchanges can occur when using MAC-2, and therefore a spatial reuse enhancement is obtained. In IEEE 802.11a, one or two predominant exchanges occurs; hence the aggregate throughput cannot exceed the data rate of two exchanges. Note that due to these multiple exchanges, the improvement increases with increasing network loads. This is because of the significantly fewer required retransmissions from the reduction in reserved area.

Figure 5.6 shows the total data delivered per unit of energy consumption for both MAC-2 and IEEE 802.11a as the network load increases. The figure shows that the total data delivered per unit of energy consumption (Mbits/J) increases with the network load for MAC-2, while remaining highly superior to IEEE 802.11a. The power savings, coupled with the additional aggregate throughput, resulting from the use of MAC-2 allow more data bits to be sent for the same amount of energy as compared to IEEE 802.11a.
Chapter 5. MAC-2 Performance Results

Figure 5.3: Throughput for Node B

Figure 5.4: Throughput for Node C
Chapter 5. MAC-2 Performance Results

Figure 5.5: Aggregate Throughput with various network loads

Figure 5.6: Total data delivered per unit of energy consumption (Mbits/J), with various network loads
5.3.3 Effect of Packet Size

The effect of varying the data packets size on a random mobile topology is studied, where 10 nodes move in the same 20m × 20m area. Each node randomly chooses its destination and initiates a transmission. Figure 5.7 shows the aggregate network throughput while Figure 5.8 shows the total data delivered per unit of energy consumption in Mbits/J. The load of each flow is 350 kframes/sec.

Figure 5.7 shows that the aggregate throughput for MAC-2 is greater than twice that of IEEE 802.11a for all packet sizes. As the packet size increases, the aggregate throughput increases for both MAC-2 and IEEE 802.11a, since the overhead due to the control packets is constant regardless of the packet size.

Figure 5.8 shows that the total data delivered per unit of energy consumption (Mbits/J) increases with the data packet size for MAC-2, while remaining highly superior to IEEE 802.11a. In using MAC-2, the power savings, coupled with the additional aggregate throughput allows many more data bits to be sent for the same amount of energy. Transfer of the data packet, the bulk of the transmission, occurs at the minimum required power, $P_{\text{min, req}}$. Hence as the packet size increases, the power savings increase.

5.3.4 Effect of Node Density

The effect of varying the node density on MAC-2 is studied next. A topology wherein 10 nodes move in a 20m × 20m area is compared to the same number of nodes in an area up to three times lower. Each node randomly chooses its destination and initiates a transmission. All exchanges occur with a rate of 350 kbps.

Table 5.1 shows that the aggregate throughput of MAC-2 is maintained when the node density increases, due to the efficient power control. However, the additional amount of interference, which causes SINR to decrease, prevents the throughput from increasing, hence limiting the performance of MAC-2.
Figure 5.7: Aggregate Throughput with various data packet sizes

Figure 5.8: Total data delivered per unit of energy consumption (Mbits/J), with various packet sizes
Table 5.1: Node Density Effect on MAC-2

<table>
<thead>
<tr>
<th>Density Factor</th>
<th>Aggregate Throughput (Mbps)</th>
<th>Bits delivered per Joule (Bits/J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>1.45</td>
<td>37,896,763</td>
</tr>
<tr>
<td>2D</td>
<td>1.47</td>
<td>37,413,711.2</td>
</tr>
<tr>
<td>3D</td>
<td>1.45</td>
<td>45,280,809.3</td>
</tr>
</tbody>
</table>

5.3.5 Control Traffic

By introducing two new packets, CONF and CANCEL, a possible problem with the new MAC-2 protocol is increased overhead due to greater control traffic. Such a statement is relative however, since the additional control packets are sometimes due to the additional exchanges which are allowed to simultaneously occur in the network. A comparison between the control traffic in both MAC-2 and IEEE 802.11a can only be made when an identical number of flows are occurring. Therefore, to illustrate this issue, a topology whereby 10 nodes initiate 10 exchanges of 350 kbps each at 20, 21, 30, 31, 35, 36, 40, 41, 50, and 51 seconds, is studied. The results for the total control traffic throughput in both cases are shown in Figure 5.9.

As the additional exchanges are starting, the control traffic in the MAC-2 based network is increasing, while the control traffic in the IEEE 802.11a based network drops to around 25 kbps and remains constant. The control throughput increases for the MAC-2 based network as more exchanges are simultaneously occurring, yielding an overall network throughput of 2.9 Mbps. The control throughput stabilizes for the IEEE 802.11a based network, yielding an overall network throughput of 735 kbps. Hence, it can be concluded that in case the same number of exchanges are occurring in the network, the control throughput is lower when MAC-2 is used. It only becomes higher as more simultaneous exchanges are accommodated, while less exchanges are occurring in case IEEE 802.11a is used, which leads to a lower control throughput. Therefore, overhead control traffic is not a problem in MAC-2 due to the efficient channel reservation scheme.
5.3.6 End-to-End Data Packet Delay

Another potential problem due to the additional control packets is the increase of the delay in the network, i.e. the time that elapses from the packet insertion in the queue at the transmitter to be sent until the packet correct reception at the receiver. The same network used to measure control throughput is used. The results for both MAC-2 based and IEEE 802.11a based networks are shown in Figure 5.10.

Again, in the case where the same number of exchanges are occurring in both networks, the end-to-end data packet delay for the MAC-2 based network is lower due to the efficient channel reservation and the lower amount of collisions. However, as more exchanges are starting, the MAC-2 network faces more contention on the control channel, which causes the delay to increase, yet remains almost constant. The price to pay for the additional exchanges is the increase in the ETE data packet delay, but the other benefits of the MAC-2 protocol, namely increased overall network throughput and decreased energy consumption outweigh this inconvenience.
5.3.7 Effect of Classes of Service

The performance of MAC-2 in a large indoor environment (mall, conference room...) is studied for different classes of service with link adaptation allowing the stringiest of desired PER constraints to be met. A random mobile topology is studied, with 10 nodes moving in a 50m × 50m area. Each node randomly chooses its destination and initiates a transmission. The total number of data bits delivered per unit of energy consumption (Mbits/J) is shown in Figure 5.11 for a load of 350 kbps per flow for the different classes of service.

Note that IEEE 802.11a cannot sustain reliable communication in this case, as the RTS packet is received at a high PER which fails to yield a desired PER of any significant value for a practical application (higher than 0.1). On the other hand, as expected, the performance of the MAC-2 protocol worsens as the desired PER decreases, which is expected since the same number of packets have to be sent at a higher power to achieve the tighter QoS constraints.
Chapter 5. MAC-2 Performance Results

5.4 Summary

This chapter has introduced the performance metrics used to judge the performance of the MAC-2 protocol. The proof that the MAC-2 protocol solved the exposed station was presented. The performance of the MAC-2 protocol versus that of the IEEE 802.11a MAC protocol was shown for various packet loads and packet sizes. The control traffic throughput and end-to-end (ETE) data packet delay were quantified to further prove the effectiveness of the MAC-2 protocol. An extension to the MAC-2 protocol including link adaptation was detailed and shown to add more scalability to the original MAC-2 protocol design.
Chapter 6

PHY Layer Enhancements:

IEEE 802.11a-STC

The MAC-2 protocol presented in Chapter 4 is shown in Chapter 5 to provide significant gains over the current 802.11a protocol. This chapter extends the protocol to account for possible enhancements in the PHY layer. In particular, the focus is on space-time coding based on the remarkably simple scheme of Alamouti [4]. The new IEEE 802.11a-STC design is explained, and its performance is evaluated. The transmitter/receiver design and the spatial correlation model used are described first. The following sections examine the spatial correlation effect on the IEEE 802.11a-STC design, and on the improvements it offers. The measure of performance considered is the packet error rate (PER). A received packet is considered to be in error if at least one bit is found in error after decoding. The number of transmit and receive antennas is set to two, as we believe that having more antenna elements on a handheld device would be impractical in terms of complexity, space and cost. The remaining sections present the IEEE 802.11a-STC benefits which the MAC-2 protocol can exploit, the effect of IEEE 802.11a-STC on the MAC-2 protocol, and of the channel model on the IEEE 802.11a-STC/MAC-2 combination.
6.1 IEEE 802.11a-STC Transmitter Design

The block diagram for the IEEE 802.11a-STC transmitter is shown in Figure 6.1. The operation of the blocks which are unchanged from the IEEE 802.11a transmitter design (bit generator, convolutional encoder, interleaver, modulator, pilot addition, IFFT, cyclic prefix and preamble addition) is similar to the previous explanations in Chapter 3, with additional details available in [55].

6.1.1 Alamouti Scheme

To implement Alamouti’s scheme in IEEE 802.11a, coding can be performed over the whole OFDM symbol $s[n]$ generated in the $n^{th}$ symbol period. If two consecutive OFDM symbols are referred to as $s[0]$ and $s[1]$, then at the first antenna $s[0]$ is transmitted in a symbol period, followed by $-s[1]^*$ in the next symbol period, while at the second antenna $s[1]$ is transmitted in the first symbol period followed by $s[0]^*$ in the second symbol period, as shown in Table 6.1. Details of the scheme are available in [4].
### 6.2 Spatial Correlation

This section will summarize the spatial correlation model used in the evaluation of the IEEE 802.11a-STC design. The purpose is to obtain a correlation matrix which modifies the channel impulse response derived from the channel model described in Section 3.5.

The assumption of independent and identically distributed i.i.d. fading channels has been made in previous works that explore the capacity of multi element antenna ([3–6]). However, in real propagation environments, the fades are not independent due to, for example, insufficient spacing between antenna elements. It has been observed that when the fades are correlated, the channel capacity is smaller than when the fades are i.i.d. ([37–41]). This issue becomes more important as terminal sizes shrink leaving less space for multiple elements.

To model multipath propagation and fading correlation, we use the “one-ring” model proposed by Jakes [7], and extended by Shiu et. al. [8]. The spatial fading correlation of a flat fading channel can be determined from the physical parameters of the model, which include antenna spacing, antenna arrangements, angle spread, and angle of arrival.

Figure 6.2 shows the parameters used to derive the spatial correlation matrix. The parameters in the model include the distance $D$ between the transmitter and receiver, the radius $R$ of the scatterer ring, the angle of arrival $\Theta$ at the receiver, and the geometrical arrangement of the antenna sets. As seen by a particular antenna element, the angles of incoming waves are confined within $[\Theta - \Delta, \Theta + \Delta]$. $\Delta$ is referred to as the angle spread. Since $D$ and $R$ are typically large compared to the antenna spacing $\Delta \approx \arcsin\left(\frac{R}{D}\right)$.

If $H$ is an $n_R \times n_T$ matrix, where $n_T$ is the number of antennas on the transmitter side and $n_R$ is the number of antennas on the receiver side, then we use $vec(H)$ to denote the $n_R n_T \times 1$ vector formed by stacking the columns of $H$ under each other; that is, if $H = (h_1, h_2, \ldots, h_{n_T})$, where $h_i$ is an $n_R \times 1$ vector for $i = 1, \ldots, n_T$, then:

$$h = vec(H) = (h_1^T, h_2^T, \ldots, h_{n_T}^T)^T$$  \hspace{1cm} (6.1)
where $^T$ denotes the matrix transpose.

The covariance matrix of $\mathbf{H}$ is defined as the covariance matrix of the vector $\text{vec}(\mathbf{H})$:

$$
cov(h) = E[hh^\dagger]$$

where $^\dagger$ denotes complex conjugate matrix transpose. Here, we model the fading as Rayleigh and the statistics of $\mathbf{h}$ are completely defined by $\text{cov}(\mathbf{h})$. The relation between $\mathbf{h}_{l;p}$ and $\mathbf{h}_{m;q}$ is:

$$
E[\mathbf{h}_{l;p}\mathbf{h}_{m;q}^*] = \frac{1}{2\pi} \int_0^{2\pi} \exp \left\{ -\frac{2\pi j}{\lambda} \left[ D_{TA_p} \rightarrow S(\Theta) - D_{TA_q} \rightarrow S(\Theta) \\
+ D_{S(\Theta) \rightarrow RA_i} - D_{S(\Theta) \rightarrow RA_m} \right] \right\} \, d\Theta.
$$  \hspace{1cm} (6.2)

where $D_X \rightarrow Y$ denotes the distance from object $X$ to object $Y$, and $S(\Theta)$ denotes the scatterer at angle $\Theta$.

In general, Equation (6.2) needs to be evaluated numerically. The approximation is derived using a notation illustrated in Figure 6.2. In a two-dimensional plane, let the $x$-axis be parallel to the line that connects the transmitter and receiver. Let $d^{T}(p,q)$ denote the displacement between the $p^{th}$ and $q^{th}$ transmitter, $d^{T}_{x}(p,q)$ and $d^{T}_{y}(p,q)$ denote the projections of $d^{T}(p,q)$ on the $x$- and $y$-axis, respectively. Similar notations, $d^{R}(l,m)$, $d^{R}_{x}(l,m)$, and $d^{R}_{y}(l,m)$, apply to the receiver side. Let $\Omega(\Theta)$ denote the angle at which $S(\Theta)$ is situated, as viewed from the center of the transmitter antenna relative to the

![Figure 6.2: “One-ring” Model Parameters](image-url)
- from one transmitter antenna element to two receiver antenna elements:

\[
\frac{d^R(l,m)}{R} \rightarrow 0, \quad E[H_{l,p}H^*_{m,q}] \approx J_0\left(\frac{2\pi}{\lambda} d^R(l,m)\right)
\]  

(6.3)

- from two transmitter antenna element to one receiver antenna element:

Assuming \(d_T^T(p,q) = 0\), \(E[H_{m,p}H^*_{m,q}] \approx J_0\left(\frac{\Delta}{\lambda} d_T^T(p,q)\right)\)  

(6.4)

- from two transmitter antenna elements to two receiver antenna elements:

Assuming \(d_T^T(p,q) = 0\) and \(d^R(l,m) = 0\),

\[
E[h_{m,p}h^*_{m,q}] \approx J_0\left(\sqrt{\left(\frac{2\pi}{\lambda} d_y^T(p,q)\right)^2 + \left(\frac{\Delta}{\lambda} d^R(l,m)\right)^2}\right)
\]

(6.5)

The above calculated correlations create an \((n_R \times n_T) \times (n_R \times n_T)\) correlation matrix that modifies the channel impulse response. In our proposed IEEE 802.11a-STC design, a \(4 \times 4\) correlation matrix is generated. Including this spatial fading correlation makes the results more realistic.

### 6.3 IEEE 802.11a-STC Receiver Design

The block diagram for the IEEE 802.11a-STC receiver is shown in Figure 6.3. The operation of the blocks which are unchanged from the IEEE 802.11a receiver design (synchronization, FFT, channel estimation, demodulator, deinterleaver and Viterbi decoder) is similar to the previous explanations in Chapter 3, with additional details available in [55].

### 6.3.1 Diversity Combining Scheme

Tables 6.2 and 6.3 indicate the notation to be used next. The encoding and transmission sequence of the information symbols for this configuration was shown in Table 6.1.
Figure 6.3: IEEE 802.11a Receiver Diversity

### Table 6.2: Definition of channels between the transmitter and receiver antennas

<table>
<thead>
<tr>
<th></th>
<th>rx antenna0</th>
<th>rx antenna1</th>
</tr>
</thead>
<tbody>
<tr>
<td>tx antenna 0</td>
<td>$h_{0,0}$</td>
<td>$h_{0,1}$</td>
</tr>
<tr>
<td>tx antenna 1</td>
<td>$h_{1,0}$</td>
<td>$h_{1,1}$</td>
</tr>
</tbody>
</table>

### Table 6.3: Received signals at the two receiver antennas

<table>
<thead>
<tr>
<th>Time</th>
<th>rx antenna0</th>
<th>rx antenna1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t$</td>
<td>$r[0,0]$</td>
<td>$r[0,1]$</td>
</tr>
<tr>
<td>$t+T$</td>
<td>$r[1,0]$</td>
<td>$r[1,1]$</td>
</tr>
</tbody>
</table>
Therefore,

\[
\begin{align*}
    r[0, 0] &= h_{0,0}s[0] + h_{0,1}s[1] + n[0, 0] \\
    r[1, 0] &= -h_{0,0}s[1]^* + h_{0,1}s[0]^* + n[1, 0] \\
    r[0, 1] &= h_{1,0}s[0] + h_{1,1}s[1] + n[0, 1] \\
    r[1, 1] &= -h_{1,0}s[1]^* + h_{1,1}s[0]^* + n[1, 1]
\end{align*}
\]

(6.6)

(6.7)

(6.8)

(6.9)

\(n[0, 0], n[1, 0], n[0, 1], n[1, 1]\) are complex random variables representing thermal noise and interference.

The combiner in Figure 6.4 builds the following two signals that are sent to the maximum likelihood detector:

\[
\begin{align*}
    \tilde{s}[0] &= h_{0,0}^*r[0, 0] + h_{0,1}^*r[1, 0]^* + h_{1,0}^*r[0, 1] + h_{1,1}r[1, 1]^* \\
    \tilde{s}[1] &= h_{0,1}^*r[0, 0] - h_{0,0}^*r[1, 0]^* + h_{1,1}^*r[0, 1] - h_{1,0}r[1, 1]^*
\end{align*}
\]

(6.10)

(6.11)

Substituting with the appropriate equations we have:

\[
\begin{align*}
    \tilde{s}[0] &= (|h_{0,0}|^2 + |h_{0,1}|^2 + |h_{1,0}|^2 + |h_{1,1}|^2)s[0] \\
    &+ h_{0,0}^*n[0, 0] + h_{0,1}^*n[1, 0]^* + h_{1,0}^*n[0, 1] + h_{1,1}n[1, 1]^* \\
    \tilde{s}[1] &= (|h_{0,0}|^2 + |h_{0,1}|^2 + |h_{1,0}|^2 + |h_{1,1}|^2)s[1] \\
    &- h_{0,0}^*n[1, 0]^* + h_{0,1}^*n[0, 0] - h_{1,0}n[1, 1]^* + h_{1,1}^*n[0, 1]
\end{align*}
\]

(6.12)

(6.13)

It is interesting to note that the combined signals from the two receiver antennas are the simple addition of the combined signals in the case with a single antenna.

### 6.4 Spatial Correlation Effect on IEEE 802.11a-STC

This section shows the effect of the correlation model used [8] on the performance of the IEEE 802.11a-STC design.
Figure 6.4: Alamouti’s space-time code
6.4.1 Antenna Spacing Effect on IEEE 802.11a-STC

Figure 6.5 quantifies the variation in average PER when the antenna spacing is varied at both the transmitter and the receiver for 1000 packets. Each packet comprises 100 bytes, sent over Rayleigh faded channels with 50 ns rms delay spread at 54 Mbps with a 20 dB SNR. The spatial correlation is calculated by varying the antenna elements spacing from 0.1λ to λ at both the transmitter and the receiver, with a fixed angular spread of 50°. As expected, the PER is the worse at smaller spacings, with a drop from a PER of 0.45 for 0.1λ spacing to a PER of 0.2 for 0.3λ spacing. Since the PER does not change considerably for spacing greater than 0.3λ, we can conclude that such a spacing is enough to achieve a good performance.

6.4.2 Angle Spread Effect on IEEE 802.11a-STC

Figure 6.6 quantifies the variation in average PER when the angle spread is varied for 1000 packets. Each packet comprises 100 bytes, sent over Rayleigh faded channels
with 50 ns rms delay spread at 54 Mbps with a 20 dB SNR. The spatial correlation is calculated by varying the angular spread from 5° to 85°, with a fixed antenna spacing of 0.5λ at both the transmitter and the receiver. As expected, the PER is the worst at low angle spread, with a drop from a PER of 0.65 for 5° angle spread, to a PER of 0.35 for 50° angle spread, and finally to a PER of 0.4 for 85° angle spread. We notice that for angular spreads exceeding 50°, the effects on the PER are negligible as the angular spread increases.

6.4.3 Correlation Effect on IEEE 802.11a-STC

Figure 6.7 quantifies the variation in average PER when the correlation coefficient is varied for 1000 packets. Each packet comprises 100 bytes, sent over Rayleigh faded channels with 50 ns rms delay spread at 54 Mbps with a 20 dB SNR. The correlation coefficient is calculated for various values of the antenna spacing at both the transmitter and the receiver and of the angle spread. The PER varies slightly with different correla-
6.4.4 Impact of Spatial Correlation on IEEE 802.11a-STC at 54Mbps

As seen in the previous subsections, the effect of spatial correlation on PER seems negligible when IEEE 802.11a-STC is used, however, for additional reliability and accuracy of results, it is beneficial to model such occurrence in studying the performance of the IEEE 802.11a-STC design.

The simulation is based on Rayleigh faded channels with a 50 ns rms delay spread. The spatial correlation is calculated for a $\lambda/2$ antenna element spacing at both the transmitter and the receiver, with an angular spread of $\Delta = 50^\circ$. As seen previously,
PER performance is not highly affected at these values, which we consider are realistic for a MANET in an indoor environment.

Figure 6.8 shows the average PER vs. Signal to Noise Ratio (SNR) for three cases: no diversity, STC without spatial correlation and STC with spatial correlation. As seen in the figure, the difference between the uncorrelated and correlated cases is minor. To obtain a 0.01 PER, an extra 1 dB is needed in the correlated STC case. In both the correlated and uncorrelated STC cases, the improvements compared to the no-diversity case are still considerable: around 11 dB for a PER of 0.1. For more realistic results, the spatial correlation will be accounted for when using IEEE 802.11a-STC in the remaining simulations.
This section shows the relative performance improvements of IEEE 802.11a-STC as compared to the original IEEE 802.11a standard at all data rates. The packet size is 100 bytes, sent over Rayleigh faded channels with a 50 ns rms delay spread.

Figure 6.9-6.16 show the average PER vs. Signal to Noise Ratio (SNR) for all the data rates supported by the IEEE 802.11a PHY layer. For all these cases, the gain obtained for a given PER from using STC is considerable.

6.5 IEEE 802.11a-STC improvements over IEEE 802.11a
Chapter 6. PHY Layer Enhancements: IEEE 802.11a-STC

Figure 6.13: PER vs. SNR 24 Mbps

Figure 6.14: PER vs. SNR 36 Mbps

Figure 6.15: PER vs. SNR 48 Mbps

Figure 6.16: PER vs. SNR 54 Mbps
6.6 IEEE 802.11a-STC Performance

This section shows the performance of IEEE 802.11a-STC in the correlated environment for the different IEEE 802.11a modes.

6.6.1 IEEE 802.11a-STC with 1000 bytes packets and Rayleigh Channel

Figure 6.17 shows the average PER vs. Signal to Noise Ratio (SNR) for the 4 highest modes (24, 36, 48 and 54 Mbps) in the IEEE 802.11a standard. Each packet comprises 1000 bytes, sent over Rayleigh faded channels with 50 ns rms delay spread. As expected, as the data rates increase, the PER increases for the same SNR.
6.6.2 IEEE 802.11a-STC with 1000 bytes packets and Ricean Channel

Figure 6.18 shows the average PER vs. Signal to Noise Ratio (SNR) for the 4 highest modes (24, 36, 48 and 54 Mbps) in the IEEE 802.11a standard. Each packet comprises 1000 bytes, sent over Ricean faded channels with 50 ns rms delay spread. As expected, as the data rates increase, the PER decreases for the same SNR.

6.7 IEEE 802.11a-STC Benefits

This section recaps the benefits of the IEEE 802.11a-STC which can be used in combination with the MAC-2 protocol benefits for better MANET performance.

The MAC-2 protocol proposed in this thesis is designed to maximally exploit any power savings due to improvements in the physical layer design, namely the IEEE 802.11a-STC design. For MANETs, the improvements brought by IEEE 802.11a-STC
seem realistic to achieve and are analyzed here.

The IEEE 802.11a-STC design has been shown to improve the performance of the IEEE 802.11a PHY layer protocol. An important characteristic of the MAC-2 protocol is its ability to fully exploit STC processing at the PHY layer. Due to the power savings resulting from STC, nodes using MAC-2 can send data at a lower threshold power $P_{\text{thres}}$ while maintaining the same maximum PER, i.e. power savings are enhanced by the IEEE 802.11a-STC design.

The use of space-time coding for IEEE 802.11a is a relatively new proposal [5,6]. In Sections 6.1 and 6.3, possible transmitter and receiver designs were shown. Note that $0.3\lambda$ spacing between antenna array elements, which for a device operating in the 5-GHz IEEE 802.11a band is around 2 cm, is shown sufficient for a significant performance improvement using the IEEE 802.11a-STC design. A spacing of $0.5\lambda$ is used in the remaining analysis.

According to the IEEE 802.11a standard, the control packets (RTS, CTS and ACK) are sent at one of the following three rates (6, 12 or 24 Mbps), depending on the data rate. A data packet size of 1000 bytes is assumed, while the control packet size is 48 bytes for RTS (actual size is 20 bytes and header size 28 bytes), 42 bytes for CTS/ACK (actual size is 14 bytes and header size 28 bytes). Figure 6.19 shows the results for 1000-bytes packets at a data rate of 54 Mbps. Figure 6.20 shows the results for 45-bytes (mean of RTS and CTS) packets at a control rate of 24 Mbps. The use of STC results in power savings of as much as 10dB for a given PER.

6.8 Effect of IEEE 802.11a-STC on MAC-2

This section quantifies the power consumption and overall network throughput benefits which the IEEE 802.11a-STC design adds to the MAC-2 protocol.

The combination of IEEE 802.11a-STC and MAC-2 can improve the performance of
Figure 6.19: PER vs. SNR at 54 Mbps for 1000 bytes packets

Figure 6.20: PER vs. SNR at 24 Mbps for 45 bytes packets
Figure 6.21: Total data delivered per unit of energy consumption (Mbits/J), with various network loads

MAC-2 as compared to the results shown in Chapter 5. A random mobile topology is studied, where 10 nodes move in a 20m x 20m area. Each node randomly chooses its destination and initiates a transmission. The total number of data bits delivered per unit of energy consumption (Mbits/J) is shown in Figure 6.21 for MAC-2 with and without STC.

The results clearly show that the use of IEEE 802.11a-STC yields further power savings, hence improving the performance of MAC-2 to a great extent. The power savings due to the physical layer enhancements contribute towards the reduction of the energy consumption, while the overall network throughput remains constant. This results in an increase in the total number of data bits delivered by unit of energy consumed.

To show another effect of STC on the performance of MAC-2, the same mobile topology is studied, where 10 nodes move in a 20m x 20m area. Each node randomly chooses its destination and initiates a transmission. The 10 exchanges of 350 kbps each start
at 20, 21, 30, 31, 35, 36, 40, 41, 50, and 51 seconds. The aggregate throughput of the network is shown in Figure 6.22 for MAC-2 with and without STC.

The results clearly show that the use of STC yields further spatial reuse, hence improving the performance of MAC-2 to a great extent. In a dense environment, the use of STC causes the transmission power to be lower, hence the interference level decreases, and the SINR at the receiver is higher, allowing the desired PER to be attained for more simultaneous exchanges. This results in an increase of the total network throughput as more data flows may be possible. In the case STC is not used, the additional flows would cause further interference and the performance of MAC-2 without STC is lower than that of MAC-2 with STC.
6.9 Effect of Channel Model on IEEE 802.11a-STC and MAC-2

This section studies the effect that the channel model, whether Rayleigh or Ricean, has on the IEEE 802.11a-STC/MAC-2 combination, in terms of power consumption for the same overall network throughput. A Ricean channel model yields a slightly better performance due to the strong LOS component.

Figure 6.23 shows the average PER vs. Signal to Noise Ratio (SNR) for the 24 Mbps data rate in the IEEE 802.11a standard. Each packet comprises 45 bytes, sent over Ricean faded channels with 50 ns rms delay spread.

Figure 6.24 shows the average PER vs. Signal to Noise Ratio (SNR) for the 54 Mbps data rate in the IEEE 802.11a standard. Each packet comprises 1000 bytes, sent over Ricean faded channels with 50 ns rms delay spread.

Figure 6.25 shows the average PER vs. Signal to Noise Ratio (SNR) for the 24
Mbps mode defined in the IEEE 802.11a standard for two channel models: Rayleigh and Ricean. Each packet comprises 45 bytes, sent with 50 ns rms delay spread. Results show a very slight improvement in performance when channel is Ricean, which is expected as the LOS component is stronger and contributes to the performance improvement.

Figure 6.26 shows the average PER vs. Signal to Noise Ratio (SNR) for the 54 Mbps mode defined in the IEEE 802.11a standard for two channel models: Rayleigh and Ricean. Each packet comprises 1000 bytes, sent with 50 ns rms delay spread. Results show a slight improvement in performance when the channel is Ricean, which is expected as the LOS component is stronger and contributes to the performance improvement.

For illustrative purposes, the effect of the channel model on the joint IEEE 802.11a-STC with MAC-2 design is studied for a mobile topology, where 4 nodes move in a 10m x 10m area. Each node randomly chooses its destination and initiates a transmission. Half of the flows start at 35 sec and the other half starts at 40 sec. The aggregate throughput of the network is the same for both the Rayleigh and Ricean channel, but the 1-dB gain
Figure 6.25: PER vs. SNR for Rayleigh and Ricean Channel at 24 Mbps

Figure 6.26: PER vs. SNR for Rayleigh and Ricean Channel at 54 Mbps
Figure 6.27: Total data delivered per unit of energy consumption (Mbits/J), with various network loads
due to a less pessimistic channel model can further improve the performance of the joint PHY-MAC design in a Ricean environment.

Figure 6.27 shows the total data delivered per unit of energy consumption for IEEE 802.11a-STC as the network load increases for both channel models. As expected, the figure shows that the total data delivered per unit of energy consumption (Mbits/J) slightly increases when the IEEE 802.11a-STC is used in a Ricean channel.

6.10 Summary

This chapter has explained the IEEE 802.11a-STC PHY layer extension to the MAC-2 protocol. The transmitter and receiver designs were shown for the 2-transmitter 2-receiver Alamouti scheme applied to the OFDM modulation, in which case it is more appropriately called space frequency coding, as the transmission and reception diversity schemes are
performed on the whole OFDM subcarriers. Spatial correlation, neglected in some of the previous works on space time codes, was taken into account. The performance of the IEEE 802.11a-STC scheme in a spatially correlated environment was studied in provision of its use in combination with the MAC-2 protocol. The benefits of IEEE 802.11a-STC which can be used by the MAC-2 protocol were summarized. The effect of IEEE 802.11a-STC on the MAC-2 protocol was shown. The gains in both power consumption and overall network throughput were quantified. The effect of using a different channel model (Ricean) for the combined IEEE 802.11a-STC/MAC-2 PHY-MAC protocols on power consumption for a fixed overall network throughput was studied in order to show that additional gains are obtained when a less constraining channel model is used.
Chapter 7

Conclusion and Future Work

7.1 Conclusions

In this thesis, performance improvements at the lower layers of the protocol stack, mainly at the MAC layer, have opened the door for power-efficient MANETs to increase the overall network throughput, and to achieve basic QoS guarantees. The use of diversity at the PHY layer, with the STBC proposed by Alamouti [4], chosen for its simple encoding and decoding scheme, as well as its robustness to spatial correlation effects [8], allows further gains in power, which is critical in the mobile, handheld devices that will form the future MANETs.

To our knowledge, this thesis is one of the few works that presented a cross-layer comprehensive PHY-MAC layer design to improve MANETs’ performance. The accurate modelling of the wireless environment’s characteristics makes the obtained results more realistic.

As a result of this research, the following conclusions can be drawn:

- The MAC-2 protocol solves the exposed station problem instead of avoiding it, while being power-efficient, which is to our knowledge the first MAC protocol for MANETs to do so.
The MAC-2 protocol highly outperforms the IEEE 802.11a MAC both as concerns power consumption and overall network throughput with various loads, packet sizes and node densities.

The MAC-2 protocol reduces the control traffic throughput as compared to the IEEE 802.11a MAC due to its collision-free nature and to the efficient channel reservation which reduces control packets retransmissions.

The MAC-2 protocol almost stabilizes the data packet end-to-end (ETE) delay due to its collision-free nature since fewer retransmissions are needed prior to the successful exchange.

Link adaptation allows the MAC-2 protocol to operate over longer ranges while saving power and achieving basic QoS guarantees. This flexibility makes MAC-2 a solid candidate for being an effective MAC layer protocol in future MANETs.

The spatial correlation effect on IEEE 802.11a-STC is small, but was included in all simulations performed.

The Rayleigh-faded channel model is a worst case assumption for the performance of the MAC-2 protocol, which is better when the wireless channel is Ricean-faded.

The gain in SNR due to the use of IEEE 802.11a-STC versus IEEE 802.11a at the PHY layer is on average 13 dB, which is conformal to expectations.

Finally, the ability of the MAC-2 protocol to fully exploit the benefits due to IEEE 802.11a-STC at the PHY layer further contributes to the already numerous advantages. With smart antennas on wireless handheld devices becoming more of a reality due to advancements in digital signal processing and RF components manufacturing, the MAC-2 protocol will allow MANETs to fully benefit from the properties of the new hardware technologies.
The proposed MAC-2/IEEE 802.11a-STC design can be regarded as a PHY-MAC standard for future MANETs, due to its high performance in such environments. The use of a dual-channel approach does not however make a MAC-2/IEEE 802.11a-STC device non compatible with the IEEE 802.11a based Access Points (APs) which are becoming increasingly popular in infrastructure networks. In fact, the proposed spectrum allocation in Section 4.3 has kept the center frequencies of the MAC-2/IEEE 802.11a-STC data channels similar to those of the IEEE 802.11a channels, but with a slightly smaller bandwidth. Hence, we can argue that a MAC-2/IEEE 802.11a-STC node would be able to switch to the normal IEEE 802.11a mode when operating in an infrastructure network, and to the proposed MAC-2/IEEE 802.11a-STC mode when operating in an ad hoc network. Since the MAC layer is actually a program that runs on a processor, and since the RF hardware circuitry is suitable for both modes of operation, we claim that the MAC-2/IEEE 802.11a-STC design can play a significant role in next generation wireless communication networks which might have a hybrid ad-hoc/infrastructure architecture.

7.2 Future Work

The MAC-2 protocol lays the ground for more sophisticated MAC protocols yielding more QoS guarantees to MANETs. A traffic-based, user-based, or location-based class of service assignment is possible through the use of MAC-2. A more elaborate link adaptation technique can be added to further boost performance.

An additional degree of flexibility can be incorporated by adapting the MAC-2 protocol operation to the varying wireless environment. Constant measurement and feedback of the PER vs. SNR curves at the PHY layer makes the results even more realistic. Such a step is however limited in part by the capabilities of current wireless networks simulators available which for the most part, make abstraction of the PHY layer properties.

On the PHY layer, other STC codes can be used and compared to the Alamouti
scheme used in this thesis. However, the complexity and limitations in MANET devices should always be taken into account when looking at the different possibilities for additional power savings using PHY layer enhancements.

In addition, the interference power is a major problem for correct packet reception and high network throughput [72], especially in MANETs. Performing efficient interference cancellation at the PHY layer can help improving the performance of several MAC protocols, and the MAC-2 protocol’s performance will surely benefit from such an approach, since MAC-2 in its current version is interference-limited due to its need to achieve a particular desired PER for packet reception to be considered successful.

Finally, higher layer protocols can also be designed based on the MAC-2 protocol and its improvements in both power consumption and overall network throughput. Note that in wireless networks, the interaction of the different layers is more pronounced than in wired networks, as enhancements at lower layers can be used efficiently in multi-layer designs for better MANET performance.
Bibliography


