Synergy MAC: A Cooperative MAC Protocol

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Synergy MAC: A Cooperative MAC Protocol

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Synergy MAC: A Cooperative MAC Protocol

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Vita

Santosh Kulkarni was born on the 1st of January, 1980 in Bijapur, India. He received his Bachelors degree in Computer Science Engineering from Visvesvaraya Technological University, India, in 2002. Following graduation he was employed by MindTree Limited, Bangalore, India, where he was involved with the development and maintenance of various communication products for the organization's R&D division. In the fall of 2006, he moved to Auburn, Alabama, to pursue his graduate studies at the department of Computer Science and Software Engineering, Auburn University.

During his sojourn in Auburn, Santosh was granted teaching as well as research assistantships. He was also awarded the Vodafone wireless research fellowship in January, 2008. He is presently a member of Dr. Prathima Agrawal's Wireless Research Group, pursuing his research interests in wireless networking, medium access control, routing protocols, quality of service and cooperative communications.

Thesis Abstract

Synergy MAC: A Cooperative MAC Protocol

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Since the advent of IEEE's 802.11 standard, Wireless Local Area Networks (WLAN) have gained widespread acceptance in providing broadband wireless access to portable devices. The performance of any WLAN depends largely on the nature of the wireless environment available to its participating nodes. This is because radio waves experiencing interference and fading effects severely affect the overall throughput achieved by the wireless network. Although spatial diversity is known to minimize the ill effects of channel fading, realizing this form of diversity generally requires incorporation of newer technologies such as Multiple Input Multiple Output (MIMO) systems. But it is impractical to equip every node in a WLAN with multiple antennas, primarily due to their size and energy constraints.

Recent research on cooperative communication demonstrates that spatial diversity can also be achieved by exploiting some unique properties of the underlying wireless medium. The inherent broadcast nature of the wireless channel suggests that any signal transmitted on the medium can be overheard by all nodes within the receiving range. If such nodes were to retransmit the overheard signal towards the destination rather than discarding it completely, they would effectively provide the destination with extra observations of the source signal. These observations at the destination are all dispersed in space and are akin to the observations resulting from MIMO systems. In short, one can think of a cooperative system as a virtual antenna array, where each antenna in the array corresponds to one of

the assisting neighbors. However, to exploit the spatial diversity realized at the physical layer, the idea of node cooperation needs to be extended to other layers of the protocol stack, especially the MAC sub-layer. Further, if such cooperation aware MAC sub-layer is designed to be backward compatible with 802.11b, then even devices with legacy hardware could potentially derive its benefits.

In addition to interference and fading effects, nodes in WLANs can also suffer from fairness problems resulting from multi-rate modulation scheme employed by IEEE's 802.11b standard. Studies have shown that when all nodes in a WLAN have uniform traffic to/from the access point (AP), the lower data rate nodes will use much more channel time than the higher data rate nodes resulting in two negatives: not only do the lower data rate nodes get poor service, they also reduce the bandwidth of the higher data rate nodes. This in turn reduces the effective throughput of the entire network. Researchers have proposed a multi-hop extension to IEEE's 802.11b infrastructure mode to mitigate such fairness problems.

In this work, we focus on the design of a new IEEE 802.11b compatible cooperative MAC protocol that also incorporates multi-hop techniques to counter fairness problems discussed above. With the studied protocol, labeled Synergy MAC, low data rate nodes transmit their packet first to an intermediate node which in turn forwards the packet to the destination at rates higher than otherwise possible. By ensuring that the destination receives two copies of the original transmission, Synergy MAC is able to realize spatial diversity. Performance of Synergy MAC is validated by means of extensive simulations using ns-2 network simulator. Results show that the proposed protocol is able to deliver a superior performance in comparison to IEEE's 802.11b.

Acknowledgments

This work would not have been possible without the help and support of many key individuals. First and foremost, I would like to thank my advisor, Dr. Prathima Agrawal, for a list that is perhaps too long to enumerate. Her insightful and open approach to research, her unwavering commitment towards her research team along with her willingness to let students tackle problems in their own style, were all instrumental in bringing this work to fruition.

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Style manual or journal used Journal of Approximation Theory (together with the style known as "aums"). Bibliograpy follows van Leunen's *A Handbook for Scholars.*

Computer software used The document preparation package TeX (specifically LaTeX) together with the departmental style-file `aums.sty`.

Table of Contents

List of Figures

Chapter 1

Introduction

The ability to communicate with people on the move has evolved remarkably since Guglielmo Marconi first demonstrated radio's ability to provide continuous contact with ships sailing the English Channel in 1897[1]. Since then, wireless communication methods and services have been enthusiastically adopted by people throughout the world. Particularly during the past ten years, the mobile radio communications industry has grown by orders of magnitude fueled by digital and radio frequency (RF) circuit fabrication improvements, new large-scale circuit integration and other miniaturization technologies which make portable radio equipment smaller, cheaper, and more reliable. Digital switching techniques have facilitated the large scale deployment of affordable easy-to-use radio communication networks. Scientists envision that these trends will continue at an even grater pace during the next decade [1].

1.1 Evolution of Mobile Radio Communications

The foundations of wireless communication were laid by Michael Faraday's work on electromagnetism, which established that electric and magnetic effects result from "lines of force" that surround conductors and magnets. Based on Faraday's work, James Maxwell derived mathematical equations that represented the "lines of force" that Faraday had explained. Maxwell published his work in a paper in 1855. Later, in 1861, Maxwell further developed his work showing that if an electric charge was applied to a (hypothetical) elastic fluid, it would result in the generation of waves that would travel through the medium. In effect, Maxwell predicted the existence of electromagnetic waves. Friedrich Kohlrausch and

[1]The actual invention of radio communications more properly should be attributed to Nikola Tesla, who gave a public demonstration in 1893. Marconi's patents were overturned in favor of Tesla in 1943 [2].

Wilhem Weber furthered Maxwell's work by calculating that these waves would travel at the speed of light. Up until 1888, the field of electromagnetism was that of pure theory. In that year, Heinrich Hertz discovered radio waves which are an example of electromagnetic radiation. Hertz did this by devising a transmitting oscillator and a "receiver". The "receiver" was basically a metal loop with a gap on one side. When this loop was placed within the transmitter's electromagnetic field, sparks were produced across the gap in the loop. This proved that electromagnetic waves could be sent out into space and remotely detected. In effect, Hertz showed that the elastic fluid that Maxwell had hypothesized could be the ether. The discovery of radio waves confirmed the ideas of Maxwell and other scientists who had worked on electromagnetism and sparked a greater interest in the field.

When Guglielmo Marconi learned about Hertz's work, he realized that if the radio waves could be transmitted over large distances, wireless telegraphy could be developed. Marconi started experimenting with this idea, and by 1894, managed to receive radio signals at a distance of over a mile. Marconi tried to develop his work further by taking the help of the Italian government. However, the Italian government was not interested. So, Marconi approached the British government. He was granted a patent for wireless telegraphy in 1897 and the world's first radio factory was setup at Chelmsford in 1898. Soon, radios started to be used commercially. The world of wireless telegraphy got another big boost in 1901 when Marconi and his associates were able to successfully receive a signal across the Atlantic. Recognizing his contribution to the field of wireless communication, Marconi was awarded the Nobel Prize in 1909 [3].

Radio technology has since advanced rapidly to enable transmissions over larger distances with better quality, less power and smaller, cheaper devices, thereby enabling public and private radio communications, television and wireless networking. While early radio systems transmitted analog signals, today most radio systems transmit digital signals composed of binary bits obtained either by digitizing an analog signal or by directly reading a digital stream. A digital radio can transmit a continuous bit stream or it can group the bits into packets. The latter type of radio is called a packet radio and is often characterized by bursty transmissions: the radio is idle except when it transmits a packet, although it may transmit packets continuously. The first network based on packet radio, ALOHANET, was developed at the University of Hawaii in 1971. This network enabled computer sites at seven campuses spread out over four islands to communicate with a central computer on Oahu island via radio transmissions. The ALOHANET network architecture used a star topology with the central computer at its hub. Any two computers could establish a bi-directional communications link with each other by going through the central hub. ALOHANET incorporated the first set of protocols for channel access and routing in packet radio systems and many of the underlying principles in those protocols are still in use today [4].

In 1985, the Federal Communications Commission (FCC) enabled the commercial development of wireless LANs by authorizing the public use of the Industrial, Scientific and Medical (ISM) frequency bands for wireless LAN products. The ISM band was attractive to wireless LAN vendors because they did not need to obtain an FCC license to operate in this band. By late 1990, vendors began introducing products based on wireless LAN technologies which operated in the 900 megahertz (MHz) frequency band. These solutions, which used non-standard, proprietary designs, provided data transfer rates of approximately 1 megabit per second (Mbps). This was significantly slower than the 10 Mbps speed provided by most wired local area networks (LAN) at that time. In 1992, vendors began selling wireless LAN (WLAN) products that used the 2.4 gigahertz (GHz) band. Although these products provided higher data transfer rates than 900 MHz band products, they also used proprietary designs. The need for interoperability among different brands of WLAN products led to several organizations developing wireless networking standards [5]. Subsection 1.1.1 briefly describes the IEEE 802.11 family of standards.

1.1.1 IEEE 802.11 Standards

In 1997, IEEE ratified the 802.11 standard [6] for wireless LANs. The IEEE 802.11 standard supports three transmission methods, including radio transmission within the 2.4 GHz band. In 1999, IEEE ratified two amendments to the 802.11 standard—802.11a

Table 1.1: Summary of IEEE 802.11 WLAN Technologies

IEEE Standard of amendment	Maximum Data Rate	Typical Range	Frequency Band	Comments
802.11	2 Mbps	50-100 meters	2.4 GHz	-
802.11a	54 Mbps	50-100 meters	5 GHz	Not compatible with 802.11b
802.11b	11 Mbps	50-100 meters	2.4 GHz	Most dominant WLAN technology
802.11g	54 Mbps	50-100 meters	2.4 GHz	Backward compatible with 802.11b

and 802.11b—that define radio transmission methods. Wireless LAN equipment based on IEEE 802.11b [7] quickly became the dominant wireless technology. IEEE 802.11b equipment transmits in the 2.4 GHz band, offering data rates of up to 11 Mbps. IEEE 802.11b was intended to provide performance, throughput, and security features comparable to wired LANs. In 2003, IEEE released the 802.11g amendment, which specifies a radio transmission method that uses the 2.4 GHz band and can support data rates of up to 54 Mbps. Additionally, IEEE 802.11g-compliant products are backward compatible with IEEE 802.11b-compliant products. Table 1.1 compares the basic characteristics of IEEE 802.11, 802.11a, 802.11b, and 802.11g. IEEE 802.11 wireless networking is also known as Wi-Fi.

Table 1.1 does not include all current and pending 802.11 amendments. For example, in November 2005, IEEE ratified IEEE 802.11e, which provides quality of service enhancements to IEEE 802.11 that improves the delivery of multimedia content. The IEEE 802.11n project is specifying IEEE 802.11 enhancements that will enable data throughput of at least 100 Mbps [5]. The publication of the final IEEE 802.11n spec is expected in April 2009. However products based on the draft 802.11n are already available in market.

1.2 Propagation Limitations

Since the advent of IEEE 802.11 standard, wireless local area networks have gained widespread acceptance in providing broadband wireless access to portable devices. However, like with any radio transmission, impairments in the propagation channel of wireless LANs can disturb the information carried by the transmitted signal. The resulting channel disturbance can be a combination of additive noise, multiplicative fading and distortion due to time dispersion. Among all these impairments that cause bit errors in wireless transmissions, fading is perhaps the most challenging one. We take a closer look at fading, its effects and available countermeasures in Chapter 2.

Chapter 2

Fading in Wireless Environment

Perhaps the most challenging technical problem facing communications system engineers is fading in the wireless environment. The term *fading* refers to the time variation of received signal power caused by changes in the transmission medium or path(s). In a fixed environment, fading is affected by changes in atmospheric conditions such as rainfall. But in a mobile environment, where one of the two antennas is moving relative to the other, the relative location of various obstacles changes over time, creating complex transmission effects.

2.1 Multipath Propagation

All three propagation mechanisms, illustrated in Figure 2.1 obtained from [8], contribute towards multi-path propagation. **Reflection** occurs when an electromagnetic signal encounters a surface that is large relative to the wavelength of the signal. For example, suppose a ground-reflected wave near the mobile unit is received. Because the ground-reflected wave has a 180 degree phase shift after reflection, the ground wave and the line-of-sight wave may tend to cancel, resulting in high signal loss[1]. Further, because the mobile antenna is lower than most human-made structures in the area, multi-path interference occurs. These reflected waves may interfere constructively or destructively at the receiver.

Diffraction occurs at the edge of an impenetrable body that is large compared to the wavelength of the radio wave. When a radio wave encounters such an edge, waves propagate in different directions with the edge as the source. Thus signals can be received even when there is no unobstructed line of sight (LOS) from the transmitter.

[1] On the other hand, the reflected signal has a longer path, which creates a phase shift due to delay relative to the un-reflected signal. When this delay is equivalent to half a wavelength, the two signals are back in phase

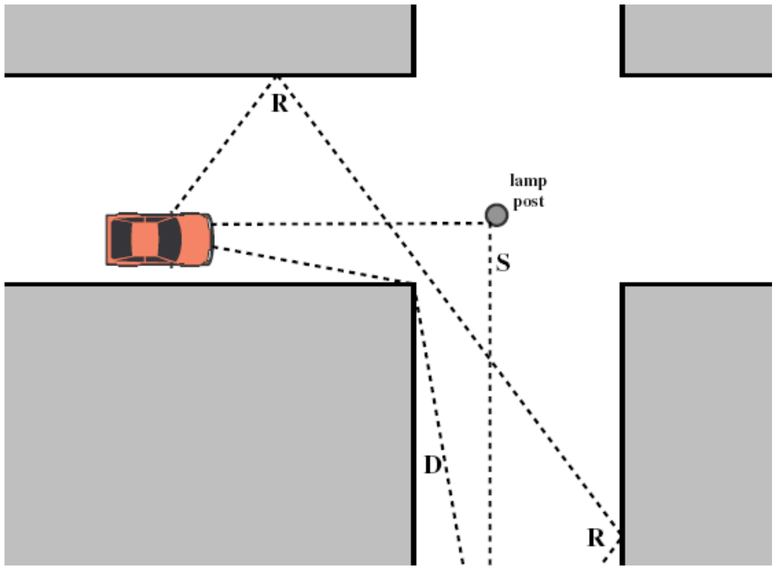

Figure 2.1: Propagation mechanisms — Reflection (R), Scattering (S), Diffraction (D)

If the size of an obstacle is on the order of the wavelength of the signal or less, **Scattering** occurs. An incoming signal is scattered into several weaker outgoing signals. At typical cellular microwave frequencies, there are numerous objects, such as lamp posts and traffic signs that can cause scattering. Thus scattering effects are difficult to predict.

These three propagation effects influence system performance in various ways depending on local conditions and as the mobile unit moves within a cell. If a mobile unit has a clear LOS to the transmitter, then diffraction and scattering are generally minor effects, although reflection may have a significant impact. If there is no clear LOS, such as in urban area at street level, then diffraction and scattering are the primary means of signal reception.

2.2 Effects of Multipath Propagation

As just noted, one unwanted effect of multi-path propagation is that multiple copies of a signal may arrive at different phases. If these phases add destructively, the signal level relative to noise declines, making signal detection at the receiver more difficult.

A second phenomenon, of particular importance for digital transmission, is inter-symbol interference (ISI). Consider that we are sending a narrow pulse at a given frequency across a link between a fixed antenna and a mobile unit. Figure 2.2 obtained from [8], shows what the channel may deliver to the receiver if the impulse is sent at two different times. The upper line shows two pulses at the time of transmission. The lower line shows the resulting pulses at the receiver. In each case the first received pulse is the desired LOS signal. The magnitude of that pulse may change because of changes in atmospheric attenuation. Further, as the mobile unit moves farther away from the fixed antenna, the amount of LOS attenuation increases. But in addition to this primary pulse, there may be multiple secondary pulses due to reflection, diffraction, and scattering. Now suppose that this pulse encodes one or more bits of data. In that case, one or more delayed copies of a pulse may arrive at the same time as the primary pulse for a subsequent bit. These delayed pulses act as a form of noise to the subsequent primary pulse, making recovery of the bit information at the receiver more difficult.

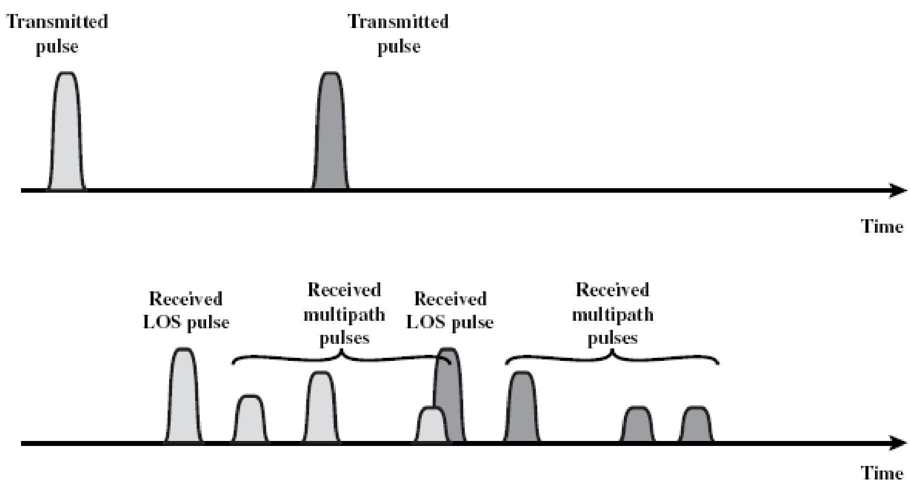

Figure 2.2: Two pulses in time-variant multipath

As the mobile antenna moves, the location of various obstacles changes; hence the number, magnitude and timing of the secondary pulses change. This makes it difficult to design signal processing techniques that will filter out multi-path effects so that the intended signal is recovered with fidelity.

2.3 Types of Fading

Fading effects in a wireless environment can be classified as either fast or slow. Referring to Figure 2.1 obtained from [8], as the mobile unit moves down a street in an urban environment, rapid variations in signal strength occur over distances of about one-half a wavelength. At a frequency of 900 MHz, which is typical for mobile cellular applications, a wavelength is 0.33m. The rapidly changing waveform in Figure 2.3 obtained from [8] shows an example of spatial variation of received signal amplitude at 900 MHz in an urban setting. Note that changes of amplitude can be as much as 20 or 30 db over a short distance. This type of rapidly changing fading phenomenon, known as **fast fading**, affects not only mobile phones in automobiles, but even a mobile phone user walking down an urban street.

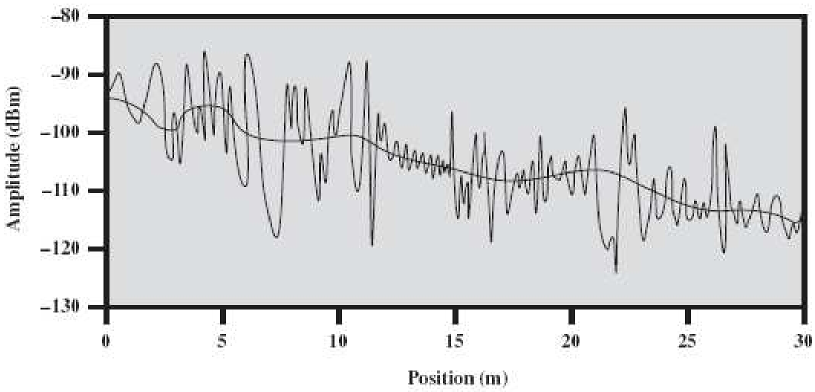

Figure 2.3: Typical slow and fast fading in an urban mobile environment

As the mobile user covers distances well in excess of a wavelength, the urban environment changes, as the user passes buildings of different heights, vacant lots, intersections and so forth. Over these longer distances, there is a change in the average received power level about which the rapid fluctuations occur. This is indicated by the slowly changing waveform in Figure 2.3 and is referred to as **slow fading**.

Fading effects can also be classified as flat or selective. **Flat fading**, or nonselective fading, is that type of fading in which all frequency components of the received signal fluctuate in the same proportions simultaneously. **Selective fading** affects unequally the different spectral components of a radio signal. The term *selective fading* is usually significant only relative to the bandwidth of the overall communications channel. If attenuation occurs over a portion of the bandwidth of the signal, the fading is considered to be selective; non-selective fading implies that the signal bandwidth of interest is narrower than and completely covered by the spectrum affected by the fading.

2.4 Fading Channel

In designing a communications system, the communications engineer needs to estimate the effects of multi-path fading and noise on the mobile channel. The simplest channel model, from the point of view of analysis is the **additive white Gaussian noise (AWGN)** channel. In this channel, the desired signal is degraded by the thermal noise associated with the physical channel itself as well as electronics at the transmitter and receiver (and any intermediate amplifiers or repeaters). This model is fairly accurate in some cases, such as space communications and some wire transmissions, such as coaxial cable. For terrestrial wireless transmission, particularly in the mobile station, AWGN is not a good guide for the designer.

Rayleigh fading occurs when there are multiple indirect paths between transmitter and receiver and no distinct dominant path, such as an LOS path. This represents a worst case scenario. Fortunately Rayleigh fading can be dealt with analytically, providing insights into performance characteristics that can be used in difficult environments, such as downtown urban settings.

Rician fading best characterizes a situation where there is a direct LOS path in addition to a number of indirect multi-path signals. The Rician model is often applicable in an indoor environment whereas the Rayleigh model characterizes outdoor settings. The Rician

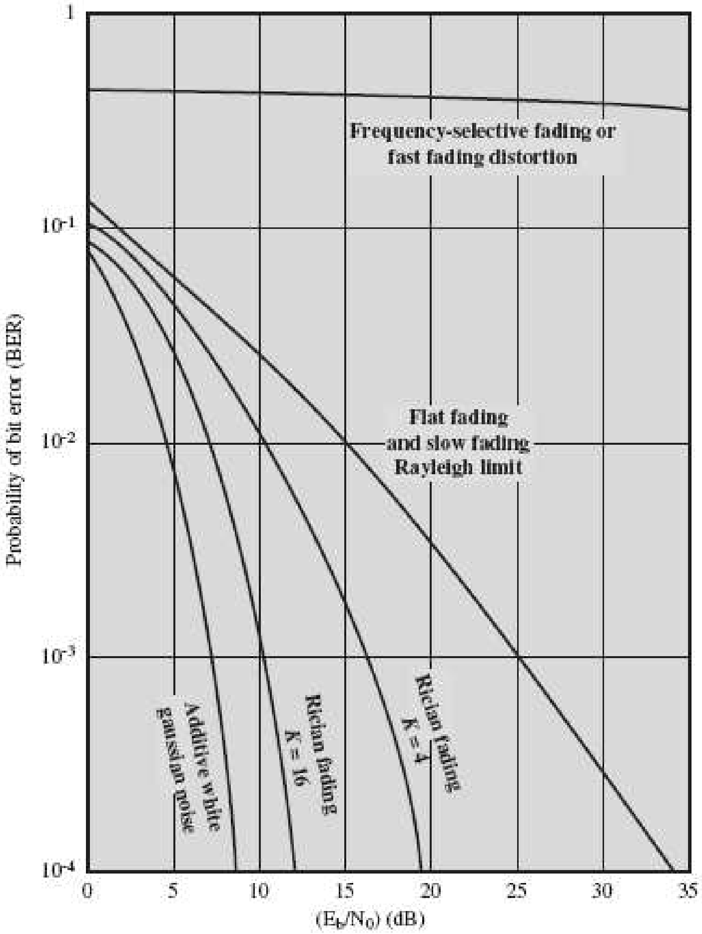

Figure 2.4: Theoretical Bit Error Rate for Various Fading Conditions

model also becomes more applicable in smaller cells or in more open outdoor environments. The channels can be characterized by a parameter K, as defined in the equation 2.1.

$$K = \frac{\text{power in the dominant path}}{\text{power in the scattered path}} \tag{2.1}$$

When $K = 0$ the channel is Rayleigh (i.e., numerator is zero) and when $K = \infty$, the channel is AWGN (i.e., denominator is zero). Figure 2.4 obtained from [8], shows system performance in the presence of noise. Here bit error rate is plotted as a function of the ratio $E_b/N_0{}^*$. Of course, as the ratio increases, the bit error rate drops. The figure shows

$^*E_b/N_0$ is the ratio of signal energy per bit to noise power density per Hertz. It is related to signal-to-noise ratio (SNR) and is more convenient for determining digital data rates and error rates.

that with a reasonably strong signal, relative to noise, an AWGN exhibit provides fairly good performance, as do Rician channels with larger values of K, roughly corresponding to micro cells or an open country environment. The performance would be adequate for digitized voice application, but for digital data transfer, efforts to compensate would be needed. The Rayleigh channel provides relatively poor performance; this is likely to be seen for flat fading and for slow fading; in these cases, error compensation mechanisms become more desirable. Finally, some environments produce fading effects worse than the so-called worst case Rayleigh. Examples are fast fading in an urban environment and the fading within the affected band of a selective fading channel. In these cases, no level of E_b/N_0 will help achieve the desired performance, and compensation mechanisms are mandatory.

2.5 Diversity for Error Compensation

Diversity is based on the fact that individual channels experience independent fading events. We can therefore compensate for error effects by providing multiple logical channels in some sense between transmitter and receiver and sending part of the signal over each channel. This technique does not eliminate errors but it does reduce the error rate, since we have spread the transmission out to avoid being subjected to the highest error rate that might occur. Other techniques like equalization and forward error correction can then cope with the reduced error rate.

Some diversity techniques involve the physical transmission path and are referred to as **space diversity**. For example, multiple nearby antennas may be used to receive the message, with the signals combined in some fashion to reconstruct the most likely transmitted signal. Another example is the use of collocated multiple directional antennas, each oriented to a different reception angle with the incoming signal again combined to reconstitute the transmitted signal.

More commonly, the term diversity refers to **frequency diversity** or time diversity techniques. With frequency diversity, the signal is spread out over a large frequency bandwidth or carried on multiple frequency carriers.

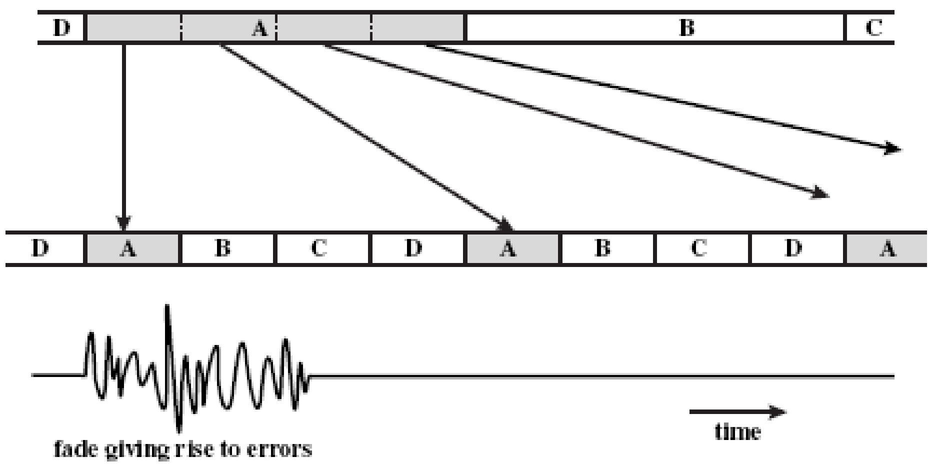

Figure 2.5: Interleaving in TDM Stream

Time diversity techniques aim to spread the data out over time so that a noise burst affects fewer bits. Time diversity can be quite effective in a region of slow fading. If a mobile unit is moving slowly, it may remain in a region of a high level of fading for a relatively long interval. The result will be a long burst of errors even though the local mean signal level is much higher than the interference. Even powerful error correction codes may be unable to cope with an extended error burst. If digital data is transmitted in a time division multiplex (TDM) structure, in which multiple users share the same physical channel by the use of time slots, then block interleaving can be used to provide time diversity. Figure 2.5 obtained from [8] illustrates the concept. Note that the same number of bits are still affected by the noise surge, but they are spread out over a number of logical channels. If each channel is protected by forward error correction, the error-correcting code may be able to cope with the fewer number of bits that are in error in a particular logical channel. If TDM is not used, time diversity can still be applied by viewing the stream of bits from the source as a sequence of blocks and then shuffling the blocks. In Figure 2.6 obtained from [8], blocks are shuffled in groups of four. Again, the same number of bits is in error, but the error correcting code is applied to sets of bits that are spread out in time. Even greater diversity is achieved by combining TDM interleaving with block shuffling.

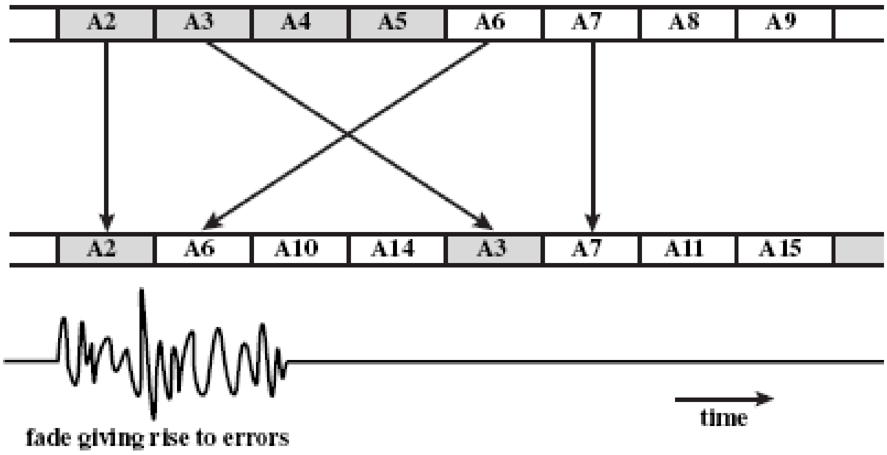

Figure 2.6: Interleaving without TDM

The tradeoff with time diversity is delay. The greater the degree of interleaving and shuffling used, the longer the delay in reconstructing the original sequence at the receiver [8].

2.5.1 Cooperative Diversity

When one examines all forms of diversity discussed in previous sections, spatial diversity emerges as the type that is most attractive. Spatial diversity relies on the principle that signals transmitted from geographically separated transmitters, and/or to geographically separated receivers, experience fading that is independent. Therefore, independent of whether other forms of diversity are being employed, having multiple transmit antennas is desirable due to the spatial diversity they provide [9]. However, this is impractical, if not infeasible, mostly due to the size and energy constraints of commonly found wireless devices.

Recent research on cooperative communication [9] [10] [11] [12] [13] [14] demonstrates that spatial diversity can also be achieved by exploiting some unique features of the underlying wireless medium. The inherent broadcast nature of the wireless channel suggests that any signal transmitted on the medium can be overheard by all nodes within the receiving range. If such nodes were to retransmit the overheard signal towards the destination rather than discarding it completely, they would effectively provide the destination with extra observations of the source signal. These observations at the destination are all dispersed in space and are akin to observations resulting from MIMO systems. In short, one can think of a cooperative system as a virtual antenna array, where each antenna in the array corresponds to one of the assisting neighbors [14]. Such spatial diversity resulting from nodal cooperation is called cooperative diversity. Chapter 3 describes the notion of physical layer cooperation and cooperative diversity in greater detail.

Chapter 3

Cooperative Communication

The burgeoning demand for mobile data networks has highlighted some constraints on its future growth. Wireless links have always had orders of magnitude less bandwidth than their wired counterparts. Mobile users have always chafed at this limitation, which essentially forces them to use applications in a manner reminiscent of wired networks of decades past, albeit freeing them from a desktop. Newer technologies such as multiple-input multiple-output (MIMO) systems are starting to increase the number of bits per second per hertz of bandwidth through spatial multiplexing, and to improve the robustness/range of the wireless link for a given data rate through space-time coding and beamforming. However, all these improvements come at the cost of multiple RF front ends at both the transmitter and the receiver. Furthermore, the size of the mobile devices may limit the number of antennas that can be deployed. Even when MIMO technology is feasible, wireless engineers are running into another roadblock: the inefficient way the electromagnetic spectrum has been allocated to different classes of users, mainly for historical or regulatory reasons. Thus, while large portions of the spectrum are grossly underused, the popular unlicensed bands are very crowded. Given this limitation, for unlicensed bands, the issue of interference from having too many users has become as important as how much bandwidth can be squeezed from it.

One way to address these problems is by using the notion of cooperation between wireless nodes. Consider the following analogy from everyday life that vividly portrays cooperative wireless communications.

> "Denise and her husband Mitch are at opposite ends of a living room at a crowded party. Denise tries to attract Mitch's attention and shouts something

> at him. All Mitch can hear is the word 'Let's.' Celine, in the middle of the room, who overhears Denise and notices their predicament, repeats to Mitch the part she hears: 'Go home.' This time, all Mitch hears is the word 'home.' Mitch finally figures out that his wife wants to go home."

The above analogy portrays the essential element of cooperative wireless communications, namely, utilizing information overheard by neighboring nodes to provide robust communication between a source and its destination. In cooperative communications, such neighboring nodes in a wireless network work together to form a virtual antenna array. Using cooperation, it is possible to exploit the spatial diversity of the traditional MIMO techniques without each node necessarily having multiple antennas. Multihop networks use some form of cooperation by enabling intermediate nodes to forward the message from source to destination. However, cooperative communication techniques described in this work are fundamentally different in that the relaying nodes can forward the information fully or in part. Also the destination receives multiple versions of the message from the source, and one or more relays and combines these to obtain a more reliable estimate of the transmitted signal as well as higher data rates.

3.1 Underlying Concepts

This section introduces some basic concepts that underlie cooperative communications. Cooperative techniques utilize the broadcast nature of wireless signals by observing that a source signal intended for a particular destination can be "overheard" at neighboring nodes. These nodes, called *relays*, *partners*, or *helpers*, process the signals they overhear and transmit towards the destination. The relay operations can consist of repetition of the overheard signal (obtained, for example, by decoding and then re-encoding the information or by simply amplifying the received signal and then forwarding), or can involve more sophisticated strategies such as forwarding only part of the information, compressing the overheard signal, and then forwarding. The destination combines the signals coming from the source and the relays, enabling higher transmission rates and robustness against channel variations due to fading. Such spatial diversity arising from cooperation is not exploited in current cellular, wireless LAN, or ad hoc systems; only one copy of the signal, whether it comes from the mobile directly or from a relay, is processed at the destination. Hence, cooperative relaying is substantially different than traditional multihop or infrastructure based methods.

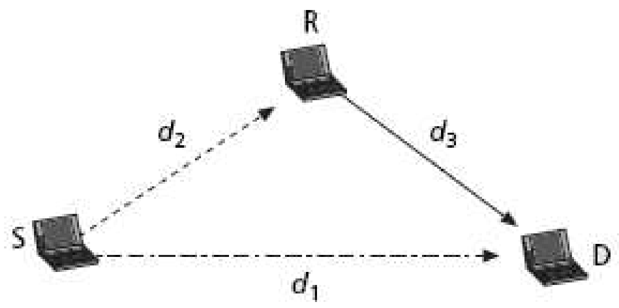

Figure 3.1: Cooperative system for an isolated link

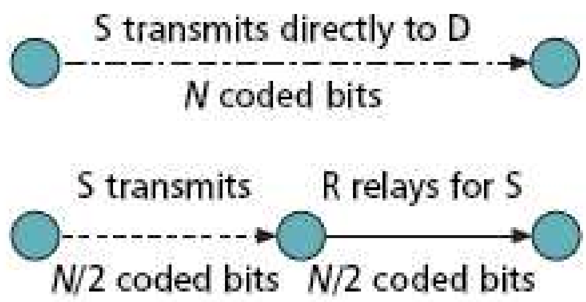

Figure 3.2: Time division in cooperative coding

This notion of cooperation dates back to the relay channel model in information theory extensively studied in the 1970s by Cover and El Gamal [15], but we owe the recent popularity to [9] [10] [11] [12] [13] [14], which showed the benefits of cooperative relaying in a wireless environment. In order to illustrate the idea of cooperation and cooperative diversity at the physical layer, let us consider the cooperative coding scheme used in [16] and [17]. Let us consider an isolated source S who wants to communicate with a destination

D with the help of a cooperative relay R, as illustrated in Figure 3.1 obtained from [19]. Here, d_i denotes the distances between the nodes.

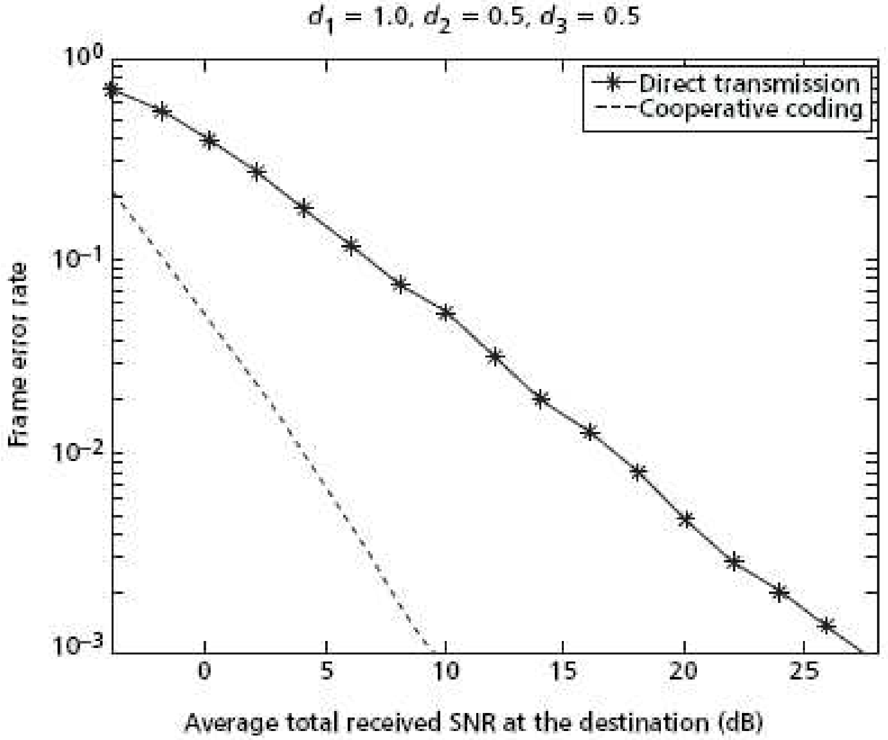

Figure 3.3: Two user cooperative coding performance for $d_1 = 1$, $d_2 = 0.5$ and $d_3 = 0.5$, (13, 15, 15, 17) convolutional code, 100-byte frame size

For direct transmission (i.e., if the relay R is not utilized), each channel block, or packet, contains B data bits and r parity bits for forward error correction (FEC), leading to a total of $N = B + r$ *coded bits*, as shown at the top of Figure 3.2 obtained from [19]. For ease of exposition, let us have $r >= B$. Let us assume that cyclic redundancy check (CRC) is employed for error detection. In order to cooperate, S divides its channel block into two and only transmits in the first half, as shown at the bottom of Figure 3.2. Hence, in the cooperative mode S ends up sending only half of its coded bits. These bits are received both by the destination D and by the relay R. The relay observes a higher coding rate and thus a weaker FEC. Nevertheless, it attempts to decode the underlying B data bits. If R has the correct information (which can be checked using the CRC), it re-encodes and sends the remaining $N/2$ parity bits in the second half of S's time slot. Otherwise, R informs S that there was a failure in decoding, and S continues transmission. Therefore, when R decodes correctly, the destination will receive half the coded bits from S and the remaining ones from R, thus creating spatial diversity. The question is how often this happens and how it affects the overall error performance.

Figure 3.3 obtained from [19], illustrates simulation results for frame error rate (FER) versus the total transmit signal-to-noise ratio (SNR) for the scenario where the relay is located halfway between the source and destination (i.e., d_1= 1.0, d_2 = 0.5, and d_3 = 0.5). Note that direct transmission and cooperative coding use the same total power and bandwidth (considering a low-mobility environment). Hence, along with path loss, the assumption is that all links experience independent slow Rayleigh fading that stays constant for the duration of each packet. The nodes use convolutional coding and each node has the same average power constraint. We observe from the figure that for an error rate of 10^{-3} we obtain about 18 dB improvement in SNR with cooperation. Also, the FER for cooperative coding decreases at a much faster rate than direct transmission; in fact, cooperation is able to achieve two full levels of diversity similar to a MIMO system with two transmit antennas and one receive antenna.

The above example considers one particular cooperative scheme to obtain diversity, yet it shows the potential of cooperation at the physical layer. Indeed, there is a rich literature on physical-layer cooperation that investigates many aspects, such as cooperative protocols for two or more users, performance bounds for cooperative systems, resource allocation for cooperation, and partner-choice strategies.

3.2 Benefits of Cooperative Networking

From the perspective of the network, cooperation can benefit not only the nodes involved, but the whole network in many different aspects. For illustration purposes, only a few potential benefits are explained below.

3.2.1 Higher Spatial Diversity

As a simple example, Figure 3.4 obtained from [19], shows a small network of four mobile nodes. If the channel quality between mobile nodes S and D degrades severely (e.g., due to shadow or small-scale fading), a direct transmission between these two nodes may experience an intolerable error rate, which in turn leads to retransmissions. Alternatively, S can exploit *spatial diversity* by having a relay R_1 overhear the transmissions and then forward the packet to D as discussed above. The source S may resort to yet another terminal R_2 for help in forwarding the information, or use R_1 and R_2 simultaneously [18]. Similar ideas apply to larger networks as well. Therefore, compared with direct transmission, the cooperative approach enjoys a higher successful transmission probability. We note here that cooperative communications has the ability to adapt and to mitigate the effects of shadow fading better than MIMO since, unlike MIMO, antenna elements of a cooperative virtual antenna array are separated in space and experience different shadow fading.

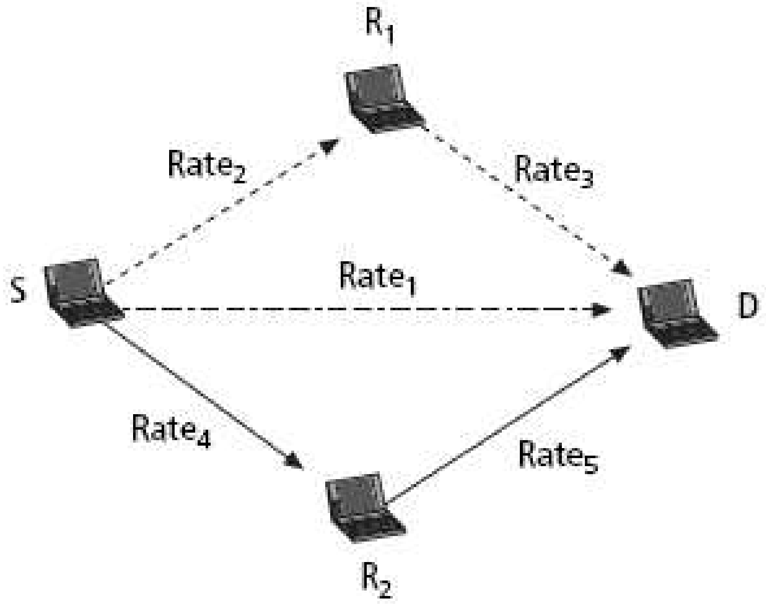

Figure 3.4: Cooperation in a network

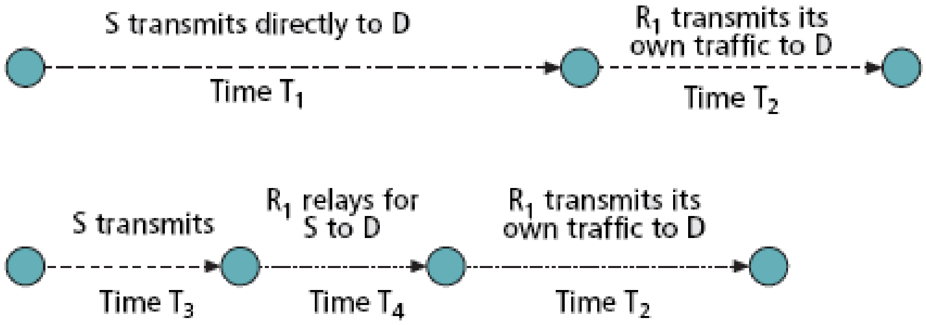

Figure 3.5: Illustration of the delay and throughput improvement achieved by cooperation in the time domain

3.2.2 Higher Throughput-Lower Delay

At the physical layer, rate adaptation is achieved through adaptive modulation and adaptive channel coding. Many MAC protocols have introduced rate adaptation to combat adverse channel conditions. For instance, when a high channel error rate is encountered due to a low average SNR, the wireless LAN standard IEEE 802.11 switches to a lower transmission rate so as to guarantee a certain error rate. The power of cooperation is evident when it is applied in conjunction with any rate adaptation algorithm. In Figure 3.4, specifically, if $Rate_2$ and $Rate_3$ are higher than $Rate_1$ such that the total transmission time for the two-hop case through R_2 is smaller than that of the direct transmission, cooperation readily outperforms the legacy direct transmission, in terms of both throughput and delay perceived by the source S. Furthermore, for relays such as R_1 and R_2, it turns out that their own individual self-interest can be best served by helping others. As further illustrated in Figure 3.5 obtained from [19], the intermediate node R_1 that cooperates enjoys the benefit of lower channel-access delay, which in turn can be translated into higher throughput.

3.2.3 Lower Power Consumption and Lower Interference

The diversity, error rate, and throughput gains obtained through cooperation can be traded in for power savings at the terminals. Alternatively, cooperation leads to an extended coverage area when the performance metric (error rate, throughput, etc.) is fixed.

The advantage of cooperation also leads to reduced interference when the network is deployed in a cellular fashion to reuse a limited bandwidth. With the improvement of throughput, we can reduce the average channel time used by each station to transfer a certain amount of traffic over the network. Therefore, the signal-to-interference ratio (SIR) between proximal cells using the same channel can be reduced, and a more uniform coverage can be achieved. As wireless network deployments become denser, a reduction of SIR will directly lead to a boost in network capacity. Indeed, the problem of dense deployment has already been reported for IEEE 802.11 b/g networks, which have only three non-overlapping channels.

3.2.4 Adaptability to Network Conditions

The cooperative communication paradigm allows wireless terminals to seamlessly adapt to changing channel and interference conditions. The choice of relays, cooperation strategy, and the amount of resources available for cooperation can be opportunistically decided. For example, in Figure 3.4, if the source S has some information about the current channel gains, packet-loss rates, traffic conditions, interference, or remaining battery energy of nodes in the network, it may choose to transmit its information directly to its destination D, using R_1 or R_2 or both in a cooperative fashion, depending on which transmission mode results in better performance (in terms of error rates, throughput, or power). This way, a surplus of resources such as battery energy or bandwidth at a particular node can be utilized by other nodes in the network in a manner that will benefit everyone, including the relay node itself.

Although originating from physical-layer cooperation, all the aforementioned benefits cannot be fully realized until proper mechanisms have been incorporated at higher protocol layers (e.g., MAC, network) and the necessary information is made available from the lower layer (e.g., PHY) [19]. Therefore it is imperative that the idea of node cooperation be extended to other layers of the protocol stack especially the medium access control (MAC) sub-layer. Further, if such re-designed, cooperation aware MAC sub-layer is compatible with IEEE 802.11b standard, a large number of devices despite their legacy hardware, could potentially derive the benefits of cooperation. Subsequent chapters shall discuss in detail the design and analysis of one such IEEE 802.11b compatible, cooperative MAC protocol, called the Synergy MAC.

Chapter 4

Overview of IEEE 802.11b

802.11 is a member of the IEEE 802 family, which is a series of specifications for local area network (LAN) technologies. Figure 4.1 obtained from [20], shows the relationship between the various components of the 802 family and their place in the OSI model. IEEE 802 specifications are focused on the two lowest layers of the OSI model because they incorporate both physical and data link components. Medium access control (MAC) in the link component, is a set of rules to determine how to access the medium and send data. The details of transmission and reception however, are left to the physical (PHY) component.

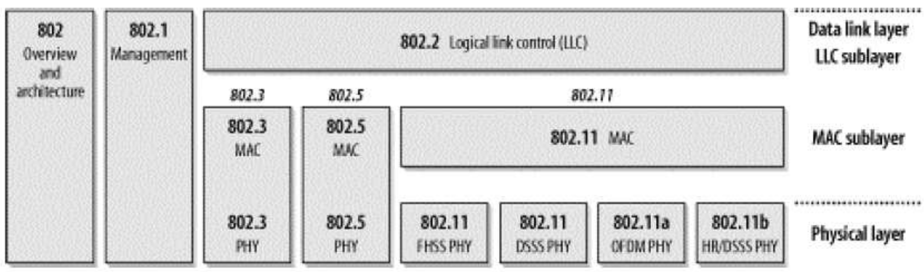

Figure 4.1: The IEEE 802 family and its relation to the OSI model

Individual specifications in the 802 series are identified by a second number. For example, 802.3 is the specification for a Carrier Sense Multiple Access network with Collision Detection (CSMA/CD). Similarly other specifications describe other parts of the 802 protocol stack. 802.2 specifies a common link layer, the Logical Link Control (LLC), which can be used by any lower-layer LAN technology. 802.11 on the other hand specifies a link layer for mobile networks that relies on 802.2/LLC encapsulation. The base 802.11 specification includes the 802.11 MAC and two physical layers: a frequency hopping spread-spectrum (FHSS) physical layer and a direct-sequence spread-spectrum (DSSS) link layer. Later revisions to 802.11 added additional physical layers. 802.11b specifies a high-rate direct-sequence layer (HR/DSSS) while 802.11a describes a physical layer based on orthogonal frequency division multiplexing (OFDM) [20].

4.1 802.11b PHY Layer

802.11b provides three variations for PHY layer. These include Direct Sequence Spread Spectrum (DSSS), Frequency Hopping Spread Spectrum (FHSS), and Infrared. In practice, only DSSS has any significant presence in the market.

802.11b DSSS operates in the 2.4 GHz ISM band which is allocated from 2400 to 2483 MHz. The channel assignments in North America are channels 1 to 11, starting at 2412 MHz and spaced at 5 MHz intervals to 2462 MHz. Each channel is about 22 MHz wide so there is substantial overlap. Therefore, channels 1, 6, and 11 can be used as non-overlapping channels. The DSSS system has different modulation modes for every transmission rate. These are: Differential Binary Phase Shift Keying (DBPSK) for 1Mbps, Differential Quaternary Phase Shift Keying (DQPSK) for 2Mbps and Complementary Code Keying (CCK) for 5.5Mbps and 11Mbps. The spreading is performed by multiplying binary data by a pseudo random (PN) binary waveform. At 1 and 2Mbps, the PN code is an 11-chip long Barker sequence. For the CCK modulation, 8-chip long Walsh codes are used. The transmitter divides the data into 4-bits or 8-bits. At 5.5Mbps, 2 of the 4 bits are used to select one of 4 complex spread sequences from a table of CCK sequences and then DQPSK modulates this sequence with the other two bits. At 11Mbps, 6 bits are used to select one of 64 sequences and the remaining 2 bits are used for modulation. For 5.5Mbps data rate, 4 bits are encoded into the 8-chip long codeword. So the processing gain is only 2. For the 11Mbps data rate, there's no processing gain because 8 bits are encoded into 8-chips.

Figure 4.2, obtained from [21], shows the Bit Error Rate (BER) vs. Signal to Noise Ratio (SNR) for different modulation schemes of 802.11b. While these curves can be derived theoretically as well, for the purpose of this paper and to achieve a solution closer to

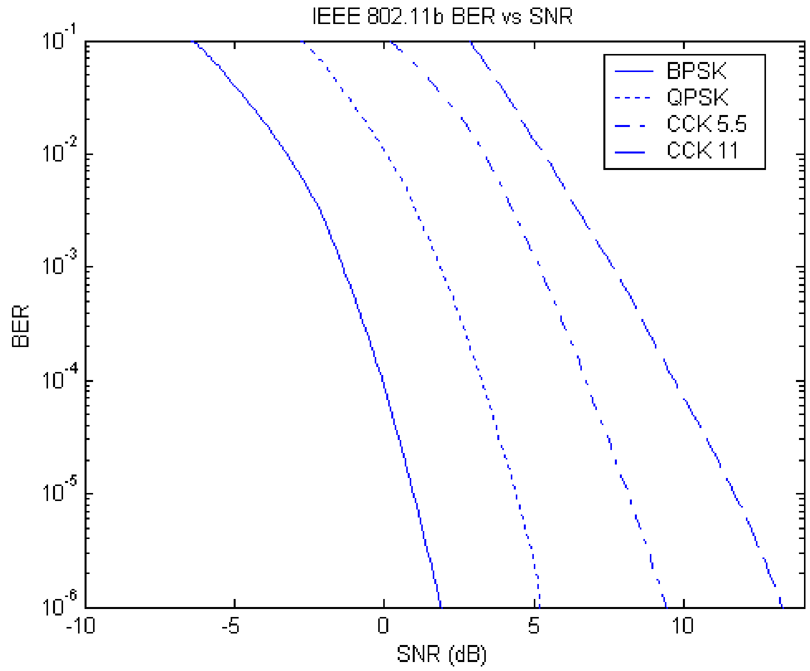

Figure 4.2: BER vs. SNR for different 802.11b modulation schemes

reality, we use these empirical curves provided by Intersil for its HFA3861B chip. From the figure we can derive that given a BER one can find the most suitable 802.11b modulation scheme to use based on the received SNR. Because path loss determines SNR, we can also derive that higher transmission rates are possible only when communicating nodes are sufficiently close by. This leads to the hypothesis that when the communicating nodes are far apart, it might be advantageous to utilize an intermediate relay for data transmission. This is because the source-relay and relay-destination transmissions can both employ better modulation schemes when compared to source-destination transmissions on account of high SNR resulting from physical proximity.

4.2 802.11b MAC Layer

In all IEEE 802.11 standards, access to the wireless medium is controlled by the MAC sub-layer's coordination functions. 802.11b's MAC sub-layer supports two such functions - distributed coordination function (DCF) for an Ethernet-like contention based CSMA/CA access and point coordination function (PCF) for contention free frame transfers. The two are explained below:

- The DCF is the basis of the standard CSMA/CA access mechanism. Like Ethernet, it first checks to see that the radio link is clear before transmitting. To avoid collisions, stations use a random backoff after each frame, with the first transmitter seizing the channel. In some circumstances, the DCF may use the CTS/RTS clearing technique to further reduce the possibility of collisions.

- Point coordination provides contention-free services. Special stations called *point coordinators* are used to ensure that the medium is provided without contention. Point coordinators reside in access points, so the PCF is restricted to infrastructure networks. To gain priority over standard contention-based services, the PCF allows stations to transmit frames after a shorter interval. The PCF is not widely implemented in 802.11b based products. Hence in this work, our focus will remain on DCF.

4.2.1 Carrier Sensing and Network Allocation Vector

Carrier sensing is used to determine if the medium is available. Two types of carrier sensing functions in 802.11b manage this process: the physical carrier-sensing and virtual carrier-sensing functions. If either carrier-sensing function indicates that the medium is busy, the MAC reports this to higher layers.

Physical carrier-sensing functions are provided by the physical layer in question and depend on the medium and modulation used. It is difficult (or, more to the point, expensive) to build physical carrier-sensing hardware for RF-based media, because transceivers can transmit and receive simultaneously only if they incorporate expensive electronics. Furthermore, with hidden nodes potentially lurking everywhere, physical carrier-sensing cannot provide all the necessary information.

Virtual carrier-sensing is provided by the Network Allocation Vector (NAV). Most 802.11b frames carry a duration field, which can be used to reserve the medium for a fixed time period. The NAV is a timer that indicates the amount of time the medium will be reserved. Stations set the NAV to the time for which they expect to use the medium, including any frames necessary to complete the current operation. Other stations count down from the NAV to 0. When the NAV is nonzero, the virtual carrier-sensing function indicates that the medium is busy; when the NAV reaches 0, the virtual carrier-sensing function indicates that the medium is idle.

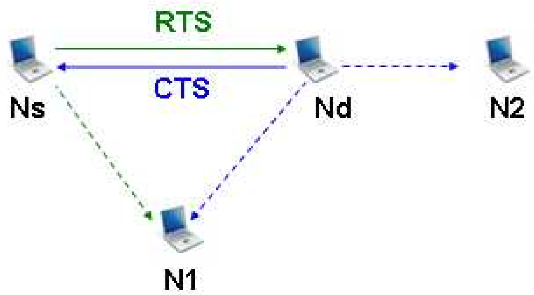

Figure 4.3: A sample 802.11b network

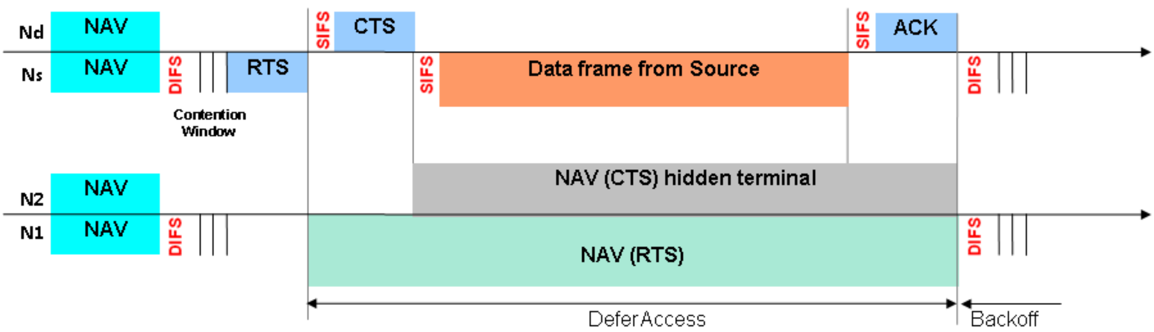

Figure 4.4: NAV propagation mechanism in 802.11b

By using the NAV, stations can ensure that atomic operations are not interrupted. For example, consider the wireless network depicted in Figure 4.3. To ensure that the sequence is not interrupted, node N_s sets the NAV in its RTS to block access to the medium while the RTS is being transmitted. All stations that hear the RTS defer access to the medium until the NAV elapses. RTS frames are not necessarily heard by every station in the network. Therefore, the recipient of the intended transmission, N_d responds with a CTS that includes a shorter NAV. This NAV prevents other stations from accessing the medium until the transmission completes. After the sequence completes, the medium can be used by any station after distributed interframe space (DIFS), which is depicted by the contention window in Figure 4.4.

4.2.2 Interframe Spacing

As with traditional Ethernet, the interframe spacing plays a large role in coordinating access to the transmission medium. Three of them are used to determine medium access; the relationship between them is shown in Figure 4.5 obtained from [21].

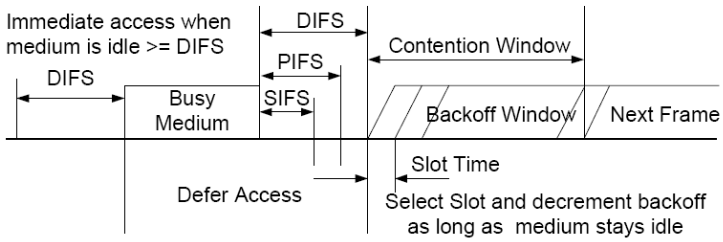

Figure 4.5: Interframe spacing in 802.11b

Varying interframe spacings create different priority levels for different types of traffic. The logic behind this is simple: high-priority traffic doesn't have to wait as long after the medium has become idle. To assist with interoperability between different data rates, the interframe space is a fixed amount of time, independent of the transmission speed.

The SIFS is used for the highest-priority transmissions, such as RTS/CTS frames and positive acknowledgments. High-priority transmissions can begin once the SIFS has elapsed. The PIFS is used by the PCF during contention-free operation. Stations with data to transmit in the contention-free period can transmit after the PIFS has elapsed and preempt any contention-based traffic. The DIFS is the minimum medium idle time for contention-based services. Stations may have immediate access to the medium if it has been free for a period longer than the DIFS.

Atomic operations start like regular transmissions: they must wait for the DIFS before they can begin. However, the second and any subsequent steps in an atomic operation take place using the SIFS, rather than during the DIFS. This means that the second (and subsequent) parts of an atomic operation will grab the medium before another type of frame can be transmitted. By using the SIFS and the NAV, stations can seize the medium for as long as necessary.

4.2.3 Contention Based Access

The DCF allows multiple independent stations to interact without central control, and thus may be used in either ad hoc networks or in infrastructure networks. Before attempting to transmit, each station checks whether the medium is idle. If the medium is not idle, stations defer to each other and employ an orderly exponential backoff algorithm to avoid collisions. In distilling the 802.11b MAC rules, there is a basic set of rules that are always used, and additional rules may be applied depending on the circumstances. Two basic rules apply to all transmissions using the DCF:

- If the medium has been idle for longer than the DIFS, transmission can begin immediately. Carrier sensing is performed using both a physical medium dependent method and the virtual (NAV) method.
  - If the previous frame was received without errors, the medium must be free for at least the DIFS.
  - If the previous transmission contained errors, the medium must be free for the amount of the EIFS.
- If the medium is busy, the station must wait for the channel to become idle. 802.11b refers to the wait as $access\ deferral$. If access is deferred, the station waits for

the medium to become idle for the DIFS and prepares for the exponential backoff procedure.

Additional rules may apply in certain situations. Many of these rules depend on the particular situation "on the wire" and are specific to the results of previous transmissions.

- Error recovery is the responsibility of the station sending a frame. Senders expect acknowledgments for each transmitted frame and are responsible for retrying the transmission until it is successful.
  - Positive acknowledgments are the only indication of success. Atomic exchanges must complete in their entirety to be successful. If an acknowledgment is expected and does not arrive, the sender considers the transmission lost and must retry.
  - All unicast data must be acknowledged.
  - Any failure increments a retry counter, and the transmission is retried. A failure can be due to a failure to gain access to the medium or a lack of an acknowledgment. However, there is a longer congestion window when transmissions are retried
- Multiframe sequences may update the NAV with each step in the transmission procedure. When a station receives a medium reservation that is longer than the current NAV, it updates the NAV. Setting the NAV is done on a frame-by-frame basis.
- The following types of frames can be transmitted after the SIFS and thus receive maximum priority: acknowledgments, the CTS in an RTS/CTS exchange sequence, and fragments in fragment sequences.
  - Once a station has transmitted the first frame in a sequence, it has gained control of the channel. Any additional frames and their acknowledgments can be sent using the short interframe space, which locks out any other stations.

– Additional frames in the sequence update the NAV for the expected additional time the medium will be used.

- Extended frame sequences are required for higher-level packets that are larger than configured thresholds.
  - Packets larger than the RTS threshold must have RTS/CTS exchange.
  - Packets larger than the fragmentation threshold must be fragmented.

4.3 802.11b Fairness Issues

The multi-rate modulation scheme employed by the 802.11b protocol is known to cause fairness problems within the wireless network as shown in [22]. If all the stations have uniform traffic to/from the access point (AP), then the low data rate stations will use much more channel time than the high data rate stations. This has two negative effects: not only do the low data rate stations get poor service, they also reduce the bandwidth of high data rate stations. This reduces the effective throughput of the network [23]. Other works like [24] too have demonstrated that the presence of a few low data rate stations will have an adverse effect on the overall throughput of the network.

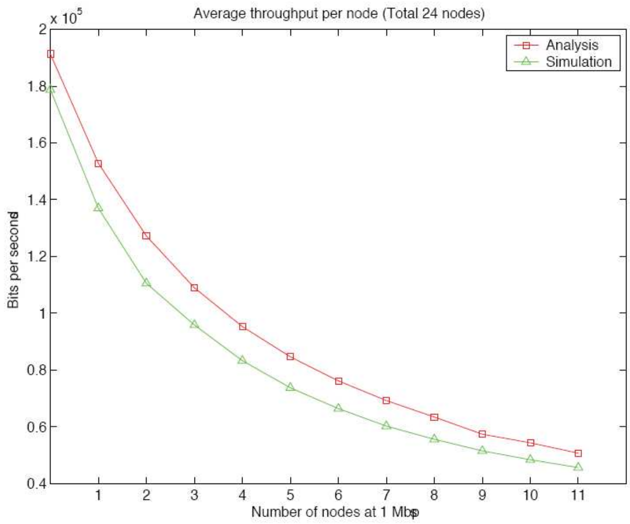

Figure 4.6: Effect of slow nodes in WLAN

The negative effect of stations operating at a lower data rate on the average throughput per node for an 802.11b system is shown in Figure 4.6 obtained from [25]. As can be seen from the figure, the presence of stations at 1 Mbps reduces the average throughput of all the stations in the network. This is because a 1 Mbps station takes roughly 11 times more transmission time than a 11 Mbps station to transmit the same number of bits [25].

In [26], the authors discuss the potential benefit of enabling a bridge like multi-hop transmission to mitigate the effects of slow stations. One of the goals of the proposed Synergy MAC protocol is to allow the high rate stations help those stations that can only sustain a low data rate to mitigate the unfairness effect. The design of Synergy MAC is described in great detail in Chapter 5

Chapter 5

Synergy MAC

The Medium Access Control (MAC) protocol described in this chapter is based on IEEE 802.11b's DCF mechanism. Synergy MAC can be described as a cooperative MAC protocol for infrastructure wireless LANs whose main aim is to combat the ill effects of channel fading by achieving spatial diversity through cooperation. The protocol also aims to mitigate 802.11b's unfairness issue arising from its multi-rate modulation scheme. The following are some of Synergy MAC's assumptions:

1. Transmission power for all nodes in the network is fixed.
2. Communication channel between any two nodes in the network is symmetrical.
3. Threshold SNR for each modulation scheme is predefined and stored in a *physical mode table* on every node in the network.
4. Transmitting nodes choose their data modulation scheme based on the received signal to noise ratio (SNR).
5. Control frames like RTS, CTS and ACK are overheard by other nodes besides the transmitter and the receiver.

The following sections shall now present the underlying details of Synergy MAC protocol.

5.1 The Synergy Table

After associating itself with an access point (AP), a node starts listening for control and data frames sent out by other nodes on the shared channel. This is required by 802.11b's

DCF mechanism as all nodes in the network need to correctly update their network allocation vector (NAV). In addition to this, Synergy MAC requires each node to maintain a $Synergy\ Table$ as shown in Table 5.1 to help determine its ability to volunteer as relay during cooperation. Each row in this table has five fields and is similar to the one maintained by [23]. The first field of this table stores the *ID* (MAC address) of the source followed by the $Time$ that the last packet from that node was heard. The third field is used to record the data rate that can be used to send data packets from the source to the current node and is denoted by R_{sr}. The fourth field stores the *ID* (MAC address) of the destination followed by R_{sd} which represents the data rate used between the source and the destination.

Source ID	Time	Src-Rly Rate	Destination ID	Src-Dst Rate
N_s	$Time$	R_{sr}	N_d	R_{sd}

Table 5.1: Synergy Table

Synergy Table on any node N_r gets updated in the following manner:

When any transmission between other nodes is overheard by the node (N_r), it will check if the transmitting node (N_s) is already in its *Synergy Table*. If not, a new row is added for the sender and is identified by the sender's *ID*. Then N_r computes the relative channel condition between the sender of that packet and itself by measuring the received power level (in dB). Path loss can be calculated by subtracting the transmission power (in dB), which is fixed for all nodes and the received power. By checking its *physical mode table*, N_r can find the data rate between N_s and itself and use this value to update the rate R_{sr} for N_s. If any data packet between source N_s and destination N_d is overheard by N_r, it will be able to detect the transmission rate used, by looking into the PHY header of the data frame, which is always transmitted at the base rate of 1 Mbps. This value along with the destination's *ID* is used to update the R_{sd} field for N_s. The $Time$ field is updated every time a packet from N_s is overheard by N_r.

5.2 The RTS frame

When a source node N_s wants to send L octets of data to destination N_d, it consults its *Synergy Table* and calculates the time needed to transmit all the octets using direct transmission. Following this, node N_s begins to sense the shared channel for any wireless activity. If the channel is found to be idle for distributed inter-frame space (DIFS) time and N_s has completed the required backoff procedure, an RTS frame is sent to the destination N_d, reserving the channel for the time needed for direct transmission. If the channel was sensed busy, node N_s waits until the channel is idle plus a DIFS interval and then sends its RTS frame to destination N_d.

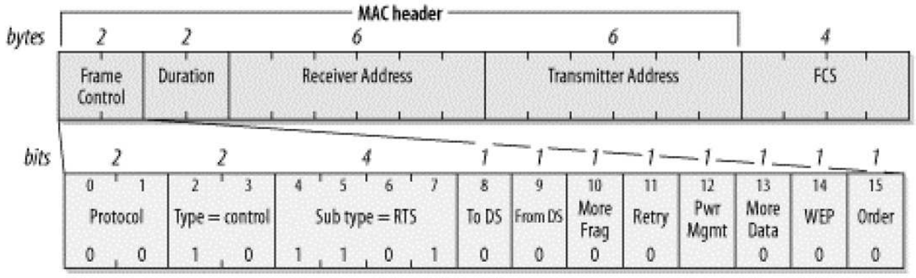

Figure 5.1: IEEE 802.11b RTS frame format

Figure 5.1 obtained from [20] shows the IEEE 802.11b RTS control frame format. According to [7], the *More Fragments* bit field in 802.11b frame header is set to 0 on all frames other than those data or management frames that have another fragment of their current MAC Service Data Unit (MSDU) or MAC Management Protocol Data Unit (MMPDU) to follow. This means that control frames in 802.11b never get fragmented and consequently always have their *More Fragments* bit set to 0.

It is therefore feasible for Synergy MAC to use this bit to distinguish its control frames from those of standard 802.11b's. Apart from setting its *More Fragments* bit to 1, Synergy MAC requires no other change to the legacy RTS frame format. An alternative strategy for Synergy MAC would have been to use a different protocol version in the *Protocol* field of the RTS control frame header, but doing so could have rendered it incompatible with existing versions of 802.11b implementations. Figure 5.2 shows the exchange of control frames in Synergy MAC protocol.

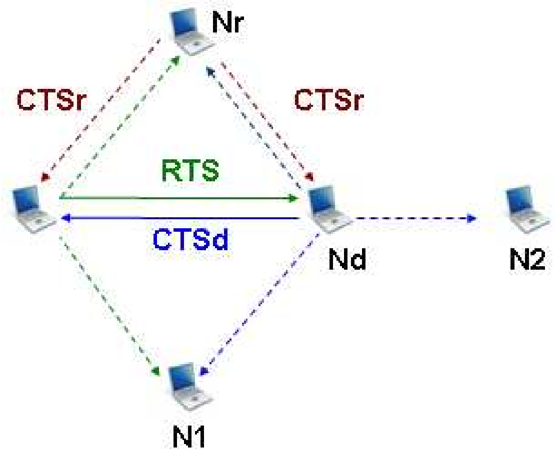

Figure 5.2: Synergy MAC Control Frame exchange

5.3 Relay Identification

When an intermediate node N_r, overhears an RTS transmission between source N_s and destination N_d, it estimates the length of the subsequent data frame based on the transmission duration obtained from the *Duration* field of the overheard frame and the rate of data transmission R_{sd}, between nodes N_s and N_d obtained from its *Synergy Table*. Next, N_r computes the time required to transmit the same data frame over two hops with itself acting as the relay. If the data frame is L octets long, the transmission time via N_r ignoring overhead and the contention time is $8L/R_{sr} + 8L/R_{rd}$ where, R_{sr} is the rate of data transmission between N_s and N_r and R_{rd} is the rate of data transmission between N_r and N_d. N_r obtains both R_{sr} and R_{rd} from its *Synergy Table*. Such two hop transmission via N_r is efficient only if $8L/R_{sr}+8L/R_{rd} < 8L/R_{sd}$. If this is indeed the case, node N_r will indicate its availability for cooperation by transmitting a self addressed CTS frame with *Duration* set to $8L/R_{sr} + 8L/R_{rd}$ after short inter-frame space (SIFS) time. Like with the overheard RTS, node N_r sets the *More Fragments* bit to 1 in its CTS-to-self frame header. To resolve potential collisions between many candidate relay nodes, the CTS-to-self frame from all eligible intermediate nodes are governed by a contention window. The contention window size used by candidate relays for transmitting their self addressed CTS frame is small when compared to that used by source nodes for transmitting their data frames. Moreover, candidate relays shall always choose their random slot time within [1, CW_r] for transmitting their self addressed CTS frames. The candidate that picks the lowest slot in the window wins while the remaining candidate relays update their NAV based on the *Duration* contained in the winning CTS-to-self frame. In an infrastructure basic service set (BSS), the value of CW_r can be announced by the AP in its beacon while in an ad hoc network, the nodes choose $CW_r = CW_{min}$.

Though the candidate nodes could have used any new frame format to announce their availability, using a self addressed CTS frame to accomplish this task has its benefits. Not only is the CTS-to-self frame compatible with 802.11b standard as mentioned in [**?**], it also serves the purpose of reserving the medium for the duration of cooperation. In addition to this, a CTS-to-self frame lets the source and the destination nodes know the identity of the assisting relay N_r. Figure 5.3 obtained from [20], shows the IEEE 802.11b CTS control frame format used for CTS-to-self frames.

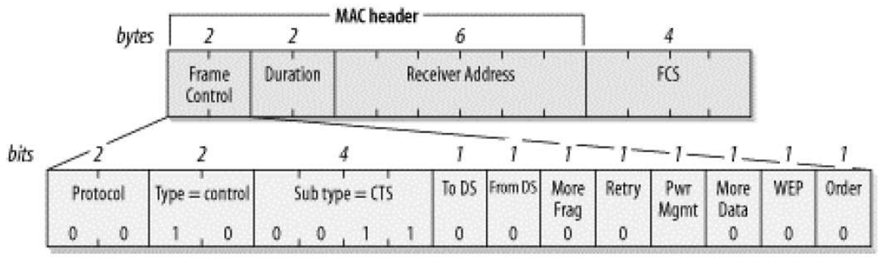

Figure 5.3: IEEE 802.11b CTS frame format

5.4 The CTS Frame

After receiving the initial RTS frame from source, the destination waits to overhear the CTS-to-self frame (CTS_r) transmitted by the winning relay. If the CTS_r from the relay N_r is overheard by the destination N_d, it sends out a CTS frame (CTS_d) to source N_s after

SIFS time, reserving the channel for the time needed to complete a two hop transmission via N_r. If a CTS_r is not overheard within a period of $CTS_{RelayTimeout}$, N_d still sends out a CTS_d frame to source, but this time reserving the channel for the time needed to complete a direct transmission. In case of the former, Synergy MAC sets the *More Fragments* bit in the CTS_d frame header to 1, requesting the source to use relay assisted transmission for its subsequent data frame. As the latter case is similar to that of legacy 802.11b, the *More Fragments* bit in the response header remains set to 0.

In situations where the destination is a legacy 802.11 device, a CTS response to a Synergy MAC RTS, is sent immediately after SIFS time. This is exactly the reason why the contention window for candidate relays is always in the interval [1, CW_r] and not in [0, CW_r]. Any random slot in [1, CW_r] ensures that all contending relays overhear the legacy device's response and update their NAV, behaving as if the destination had picked the lowest slot in the relay contention window. This results in 802.11b mode of operation for Synergy MAC. Thus Synergy MAC ensures that it is interoperable with legacy 802.11b devices without incurring any penalty.

5.5 Cooperative Communication

Once node N_s receives a CTS_d frame from destination N_d, it starts transmitting its data frame after SIFS time with the *Duration* field set to CTS_d's estimate duration. If CTS_d's *More Fragments* bit was set to 1, N_s sends the data frame to N_r using rate R_{sr}. Node N_r then checks the CRC field of the received data frame and if correct, forwards the frame to N_d, using rate R_{rd} after SIFS time. If CTS_d's *More Fragments* bit was set to 0, N_s sends the data frame directly to N_d using rate R_{sd}.

It is possible that node N_s does not overhear a CTS_r from the winning relay before receiving a CTS_d from N_d with its *More Fragments* bit set to 1. This might occur due to drastic change in channel condition between N_s and N_r during CTS_r frame exchange. But because N_d had overheard a CTS_r from relay, its *Duration* estimate in CTS_d would be far less than the *Duration* contained in the initial RTS frame. If this is the case, source

N_s resorts to fragmenting its data frame, based on CTS_d's *Duration* and its direct data transmission rate R_{sd} in order to maintain consistency of the NAV.

After receiving the data frame, destination N_d responds back to N_s with an ACK frame indicating a successful reception. Otherwise N_d stays idle in which case N_s notices the failure of transmission after a timeout period and starts backing off exponentially, which is the same as in the standard IEEE 802.11b MAC.

5.6 NAV Update Mechanism

According to [7], all nodes receiving a valid frame except the one whose MAC address is equal to the RA (Receiver Address) mentioned in the frame header, are required to update their NAV with the information received in the frame's *Duration* field. When compared to [7], Synergy MAC differs slightly in the way its NAV is calculated. The *Duration* carried in a Synergy MAC RTS header is the time in microseconds required to transmit the pending data frame using direct transmission from source N_s to destination N_d, plus a relay timeout[1], plus one CTS frame, one ACK frame, and three interleaving SIFS intervals as given in equation 5.1.

$$Duration_{RTS} = 3T_{SIFS} + CTS_{RelayTimeout} + T_{CTS} + 8L/R_{sd} + T_{ACK} \tag{5.1}$$

This ensures that even if there is no intermediate node to volunteer, the data frame can be sent to the destination by direct transmission using rate R_{sd}. The *Duration* field in subsequent CTS_r will be set according to equation 5.2 given below. As depicted in Figure 5.4, this duration reflects the time in microseconds required to transmit the pending data frame using node N_r as relay, plus one CTS frame, one ACK frame and four interleaving SIFS intervals.

$$Duration_{CTS_r} = 4T_{SIFS} + T_{CTS} + 8L/R_{sr} + 8L/R_{rd} + T_{ACK} \tag{5.2}$$

[1]Synergy MAC needs to consider a relay timeout for its RTS *Duration* in order to account for situations where a suitable relay was either not found or not identified.

The *Duration* in the CTS_d frame header is calculated based on whether or not the destination overheard a CTS_r from the winning relay. If the destination overheard a CTS_r, the value of the *Duration* via N_r is computed as shown in equation 5.3. This value represents the time in microseconds required to transmit the pending data frame using node N_r as relay, plus an ACK frame and three interleaving SIFS intervals as depicted in Figure 5.4.

$$Duration_{CTS_d} = 3T_{SIFS} + 8L/R_{sr} + 8L/R_{rd} + T_{ACK} \tag{5.3}$$

In cases where the destination does not overhear a CTS_r, the *Duration* in the CTS_d frame header is given by equation 5.4 which represents the time required to directly transmit the pending data frame from source N_s to destination N_d using transmission rate R_sd, plus an ACK frame and two interleaving SIFS intervals as shown in Figure 4.4.

$$Duration_{CTS_d} = 2T_{SIFS} + 8L/R_{sd} + T_{ACK} \tag{5.4}$$

Finally, the value of $CTS_{RelayTimeout}$ can be computed according to equation 5.5. This value reflects the length of contention window in microseconds plus the time required to transmit a CTS_r from the winning relay.

$$CTS_{RelayTimeout} = CW_r * SlotTime_{802.11b} + T_{CTS} \tag{5.5}$$

Figure 5.4 illustrates the NAV update mechanism in Synergy MAC. Nodes that can overhear both RTS and CTS_d frames (e.g. N_1) need to set their NAV duration according to the RTS frame first. Once the CTS_r or CTS_d frame is overheard, they need to reset the NAV according to the duration contained in the new frame. Hidden terminals that can only overhear N_d's transmissions (e.g. N_2) need to update their NAV on overhearing a CTS_d. Terminals that can only overhear N_s's transmissions set their NAV according to the initial RTS frame and update it when the subsequent Data frame is overheard.

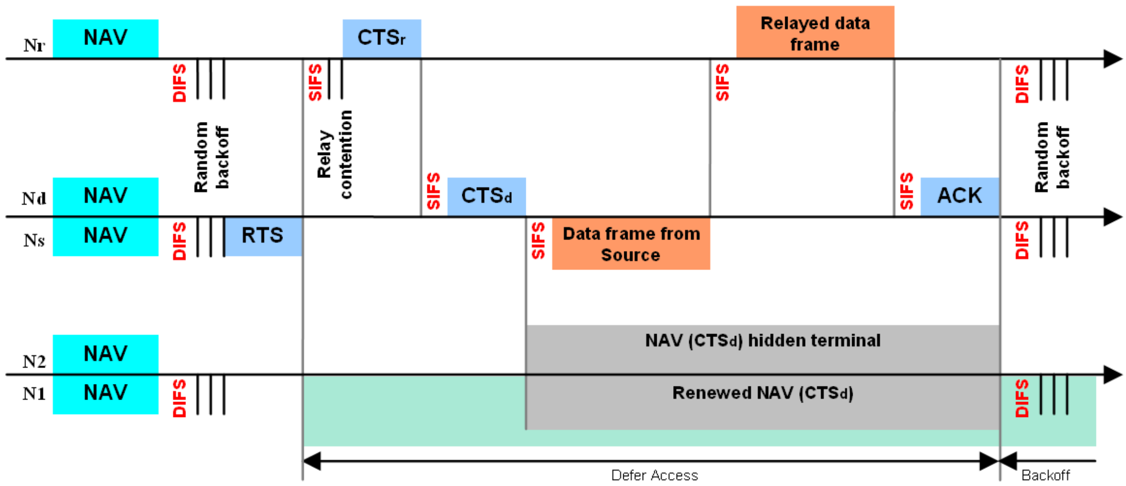

Figure 5.4: NAV update mechanism in Synergy MAC

The flow charts for nodes N_s (source), N_r (relay) and N_d (destination) are depicted in Figure 5.5, 5.6 and 5.7 respectively.

5.7 Comparing Cooperative MACs

Cooperation among nodes is a relatively new area of research in improving the performance of wireless networks. However, we are aware of other 802.11b based cooperative MAC protocols that have been proposed earlier. This section contrasts Synergy MAC against such protocols. In UTD MAC [27], the data frame transmitted by source is simultaneously made available at both the relay and the destination. It is only when the destination fails in its reception attempt that the relay intervenes to re-send the data frame after RIFS duration. Because the Duration in RTS and CTS remains unaltered, the protocol can lead to inconsistency in NAV propagation resulting in collisions. For example, nodes that can only overhear source node's transmissions would have a NAV value which does not account for the subsequent transmission by the relay.

Though Coop MAC I [23] employs similar techniques as Synergy MAC, it requires considerable changes in the frame formats of 802.11 rendering it incompatible with legacy implementations. For example, Coop MAC I requires addition of at least three new fields

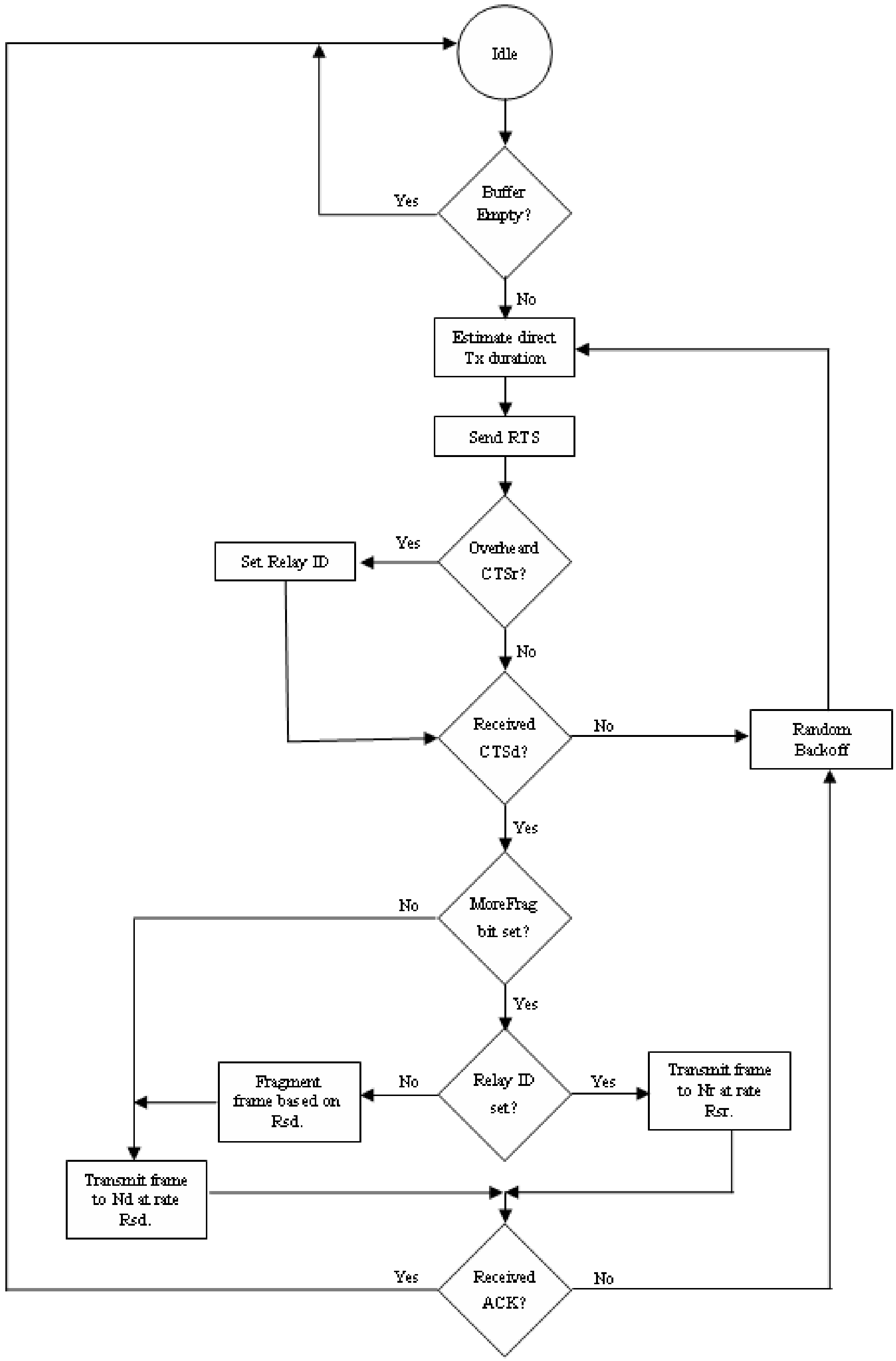

Figure 5.5: Flow chart at source node N_s

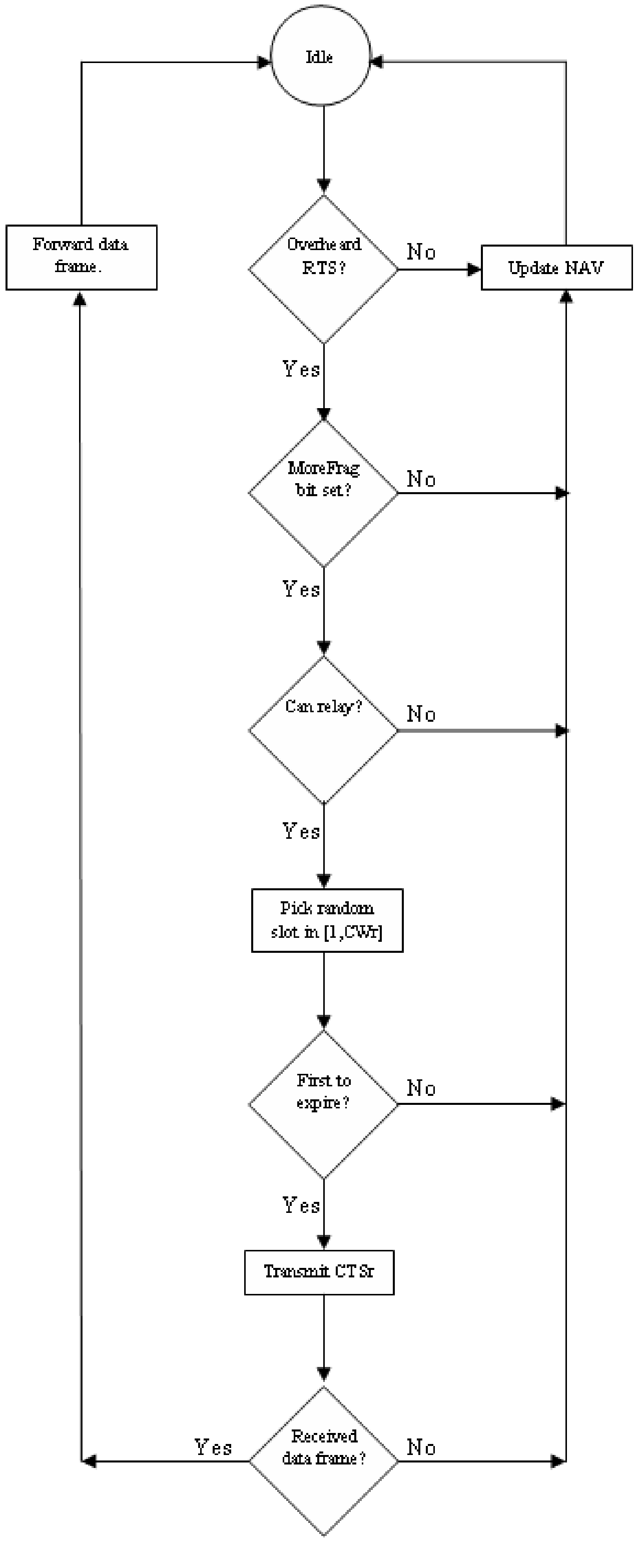

Figure 5.6: Flow chart at relay node N_r

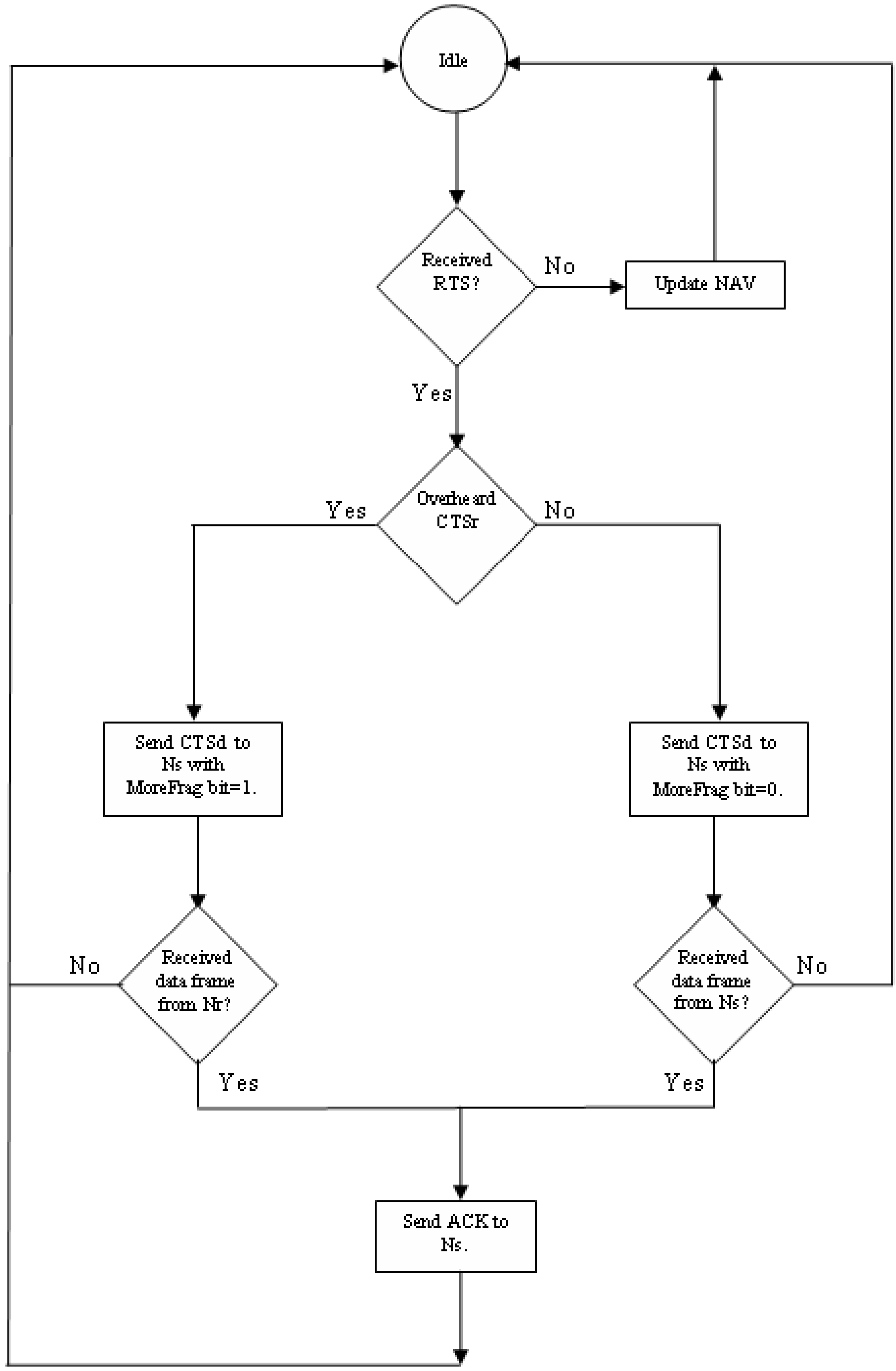

Figure 5.7: Flow chart at destination node N_d

Characteristic	Coop MAC I	Coop MAC II	UTD MAC	Synergy MAC
IEEE 802.11b based	✓	✓	✓	✓
Backward compatible with legacy 802.11	X	✓	✓	✓
Employs three-way handshake	✓	X	X	✓
Relay node identified on the fly	X	X	X	✓
Avoids collisions during cooperation	✓	X	X	✓
Handles multi-rate fairness	✓	✓	X	✓

Table 5.2: Comparison of Different Cooperative MAC Protocols

to the legacy 802.11b RTS frame header. The protocol also requires the relay node to transmit a new frame called 'HTS' to indicate its willingness to assist the source node during cooperation. Coop MAC II [23] on the other hand does not require any such changes to the 802.11b frame formats but because it employs only a 2-way handshake, it can lead to collisions at the relay node. Also both Coop MAC I and II identify their relay nodes beforehand at source and are vulnerable to change in its availability caused due to node mobility. The complete list of differences between these cooperative MAC schemes is given in Table 5.2.

5.8 Summary

In summary, Synergy MAC implements multi-hop extension proposed in [26] by allowing nodes with low SNR to their destination make use of intermediate relays, to transmit data at rates higher than otherwise possible. The protocol is also able to achieve spatial diversity by ensuring that the destination overhears multiple copies of the original frame (initial source-relay and later relay-destination transmissions).

Chapter 6

Simulations and Results

In this chapter, we describe our efforts to validate the performance of the proposed cooperative MAC protocol. Our verification strategy mainly relies on a detailed simulation study of the proposed protocol using ns-2 network simulator. Towards this end, ns-2's existing IEEE 802.11b source code was modified to implement Synergy MAC. This implementation was validated against the expected behavior of Synergy MAC by manually inspecting the log messages generated by ns-2. Other details regarding the experiments involved in this study are as explained below.

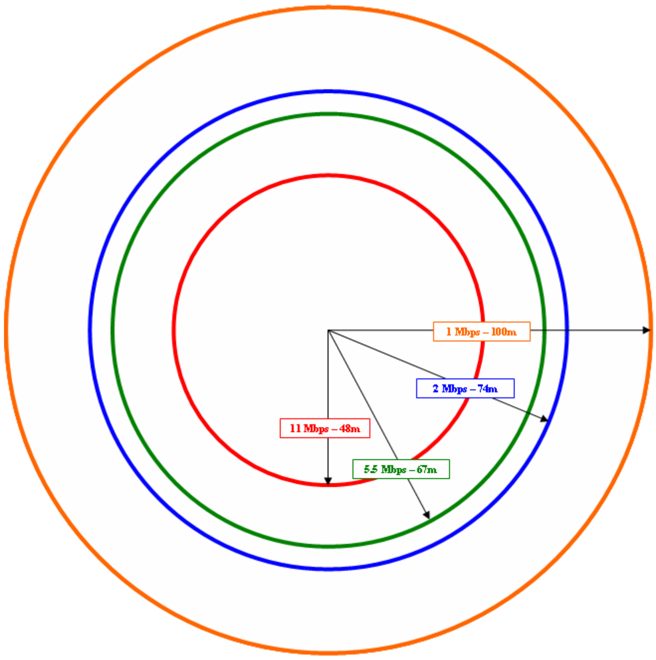

Figure 6.1: Transmission ranges for different data rates of IEEE 802.11b

All nodes in the experiments choose their modulation scheme based on the received SNR such that BER $\geq 10^{-5}$. From Figure 4.2, this translates to data rates of 11 Mbps if the node's distance from AP < 48m, 5.5 Mbps if the distance from AP ≥ 48m but < 67m, 2 Mbps if the distance from AP ≥ 67m but < 74m and 1 Mbps if the distance from AP ≥ 74m but < 100m. Nodes located farther than 100m from the AP are considered to be out of communication range. 802.11b's data rates and the corresponding transmission ranges are depicted in Figure 6.1.

We begin our first experiment with a basic setup of three nodes — one source, one destination and one relay as shown in Figure 6.2. The idea behind using such a basic setup is to accurately gauge the improvement in performance achieved by Synergy MAC protocol. The experiment has two parts to it. In the first part, the relay node is idle, i.e., it does not contribute to the traffic on the medium. We call this case the idle relay scenario. This scenario ensures that the source node does not have to contend with any other node to access the wireless medium. In the second part of the experiment, the relay node has some data that needs to be transferred to the destination. We call this case the active relay scenario. Here both, the source and the relay nodes contend with each other to gain access to medium.

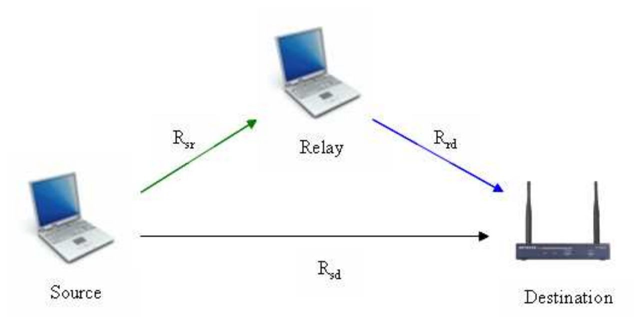

Figure 6.2: Basic setup consisting a source, a relay and a destination

In both the experiments, the source and the relay nodes are positioned in various data rate zones, as depicted in Figure 6.1, to achieve all possible data rate combinations (R_{sr} and R_{rd}) during cooperation. The same is then repeated with 802.11b to get a measure of the baseline performance. In all the trials, the source node transfers data to the destination via cbr traffic. At source, the data packets are all 1000 octets in length and arrive at a rate of 500 packets per second to keep the network heavily loaded. When active, the relay too has the same incoming traffic pattern.

The results for idle and active scenarios shown in Figure 6.3 and 6.4 respectively. In these figures the x-axis lists the coordinates for all the nodes involved in the trials. Distance from the destination is then used to compute the node's data rate. The y-axis in the graphs indicates the end-to-end throughput achieved by averaging all trials. Throughput was calculated by dividing the amount of data transferred in each frame by its corresponding transfer time. From the graphs it is clear that Synergy MAC is able to achieve better performance when compared to 802.11b. This is mainly because with the help of the relay node, a source with low SNR to destination is able to achieve much better transmission rates than otherwise possible. With improved data rates, more data is transferred to the destination which effectively improves the throughput achieved.

The next experimental scenario consists of a single access point (AP) servicing multiple end nodes in an infrastructure BSS. The end nodes are all randomly distributed in a circular area of radius 100 meters with the AP located right at the center of the circle. At each node, data packets of length 1000 octets arrive at a rate of 500 packets per second to keep the network heavily loaded. The experiment sets the minimum contention window size (CW_{min}) to 31 slots and uses a maximum of 6 backoff stages during retransmission.

Figure 6.5 shows the saturated throughput achieved by both 802.11b and Synergy MAC protocols. Each data point in the graph represents an average of 20 simulation runs. From the graph it is clear that the aggregate throughput achieved by both protocols is much less than 11 Mbps. This is because not all randomly distributed nodes are located within 48m of the AP to be able to use transmission rates of 11 Mbps. Collisions and protocol overheads further reduce the achievable throughput. When compared to 802.11b however, Synergy MAC is able to achieve much higher throughput. This is because Synergy MAC allows nodes with low data rates to the AP utilize intermediate nodes as relays to achieve higher transmission rates. By doing so, the protocol also minimizes the effects of fading through spatial diversity.

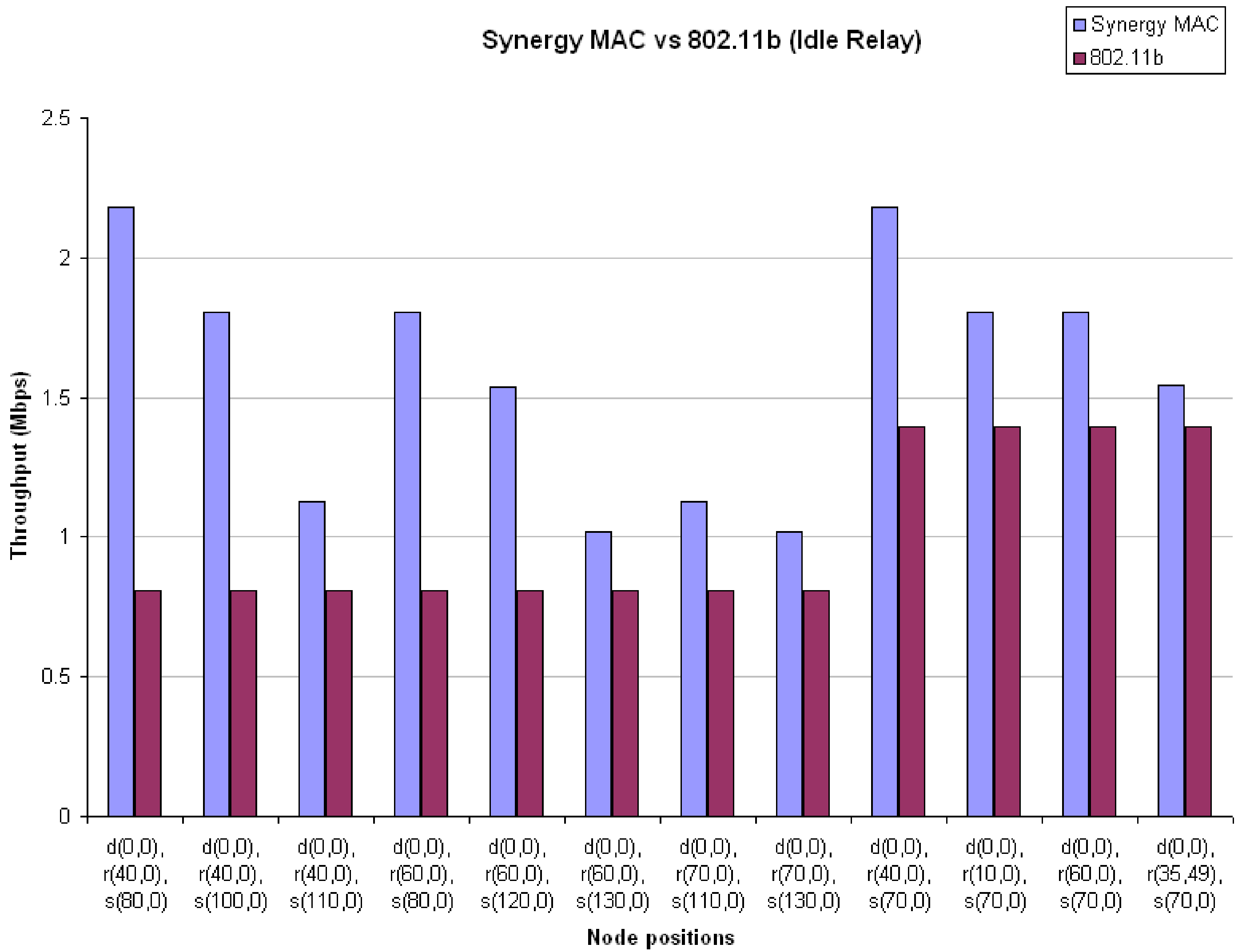

Figure 6.3: Synergy MAC vs. IEEE 802.11b with zero traffic at relay

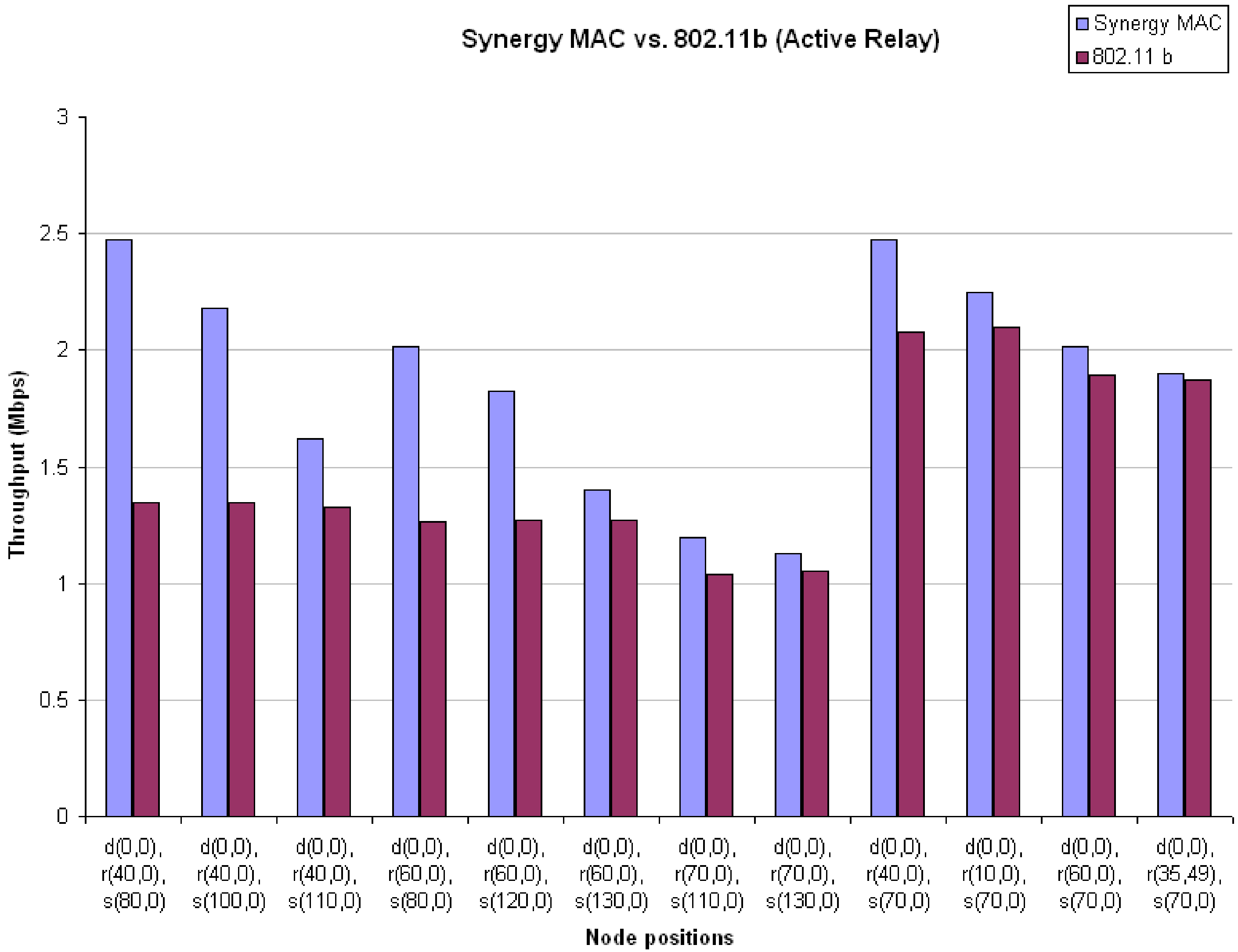

Figure 6.4: Synergy MAC vs. IEEE 802.11b with traffic at relay

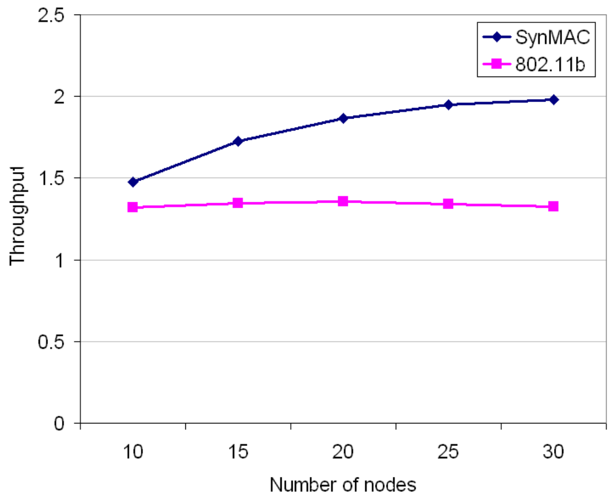

Figure 6.5: Throughput vs. Number of nodes in the network

Figure 6.5 also reveals that the throughput for 802.11b decreases with increase in the number of nodes on the network. This is mainly due to excessive collisions occurring on the shared channel. In case of Synergy MAC however, with more nodes in the network, there is a higher possibility for a node with low data rate to find an intermediate relay. This increased availability of relays not only offsets the degradation in performance caused by packet collisions but also leads to an increase in the overall throughput achieved by Synergy MAC. The relative gain in the throughput of Synergy MAC expressed as percentage versus number of nodes in the network is shown in Figure 6.6.

Our last experimental scenario tests the robustness of Synergy MAC in face of node mobility. Node mobility in network simulators are typically realized in two ways; by either using network traces or by using mathematical mobility models. To analyze the performance of Synergy MAC protocol in mobile environments, we employ the latter in our simulation study. Random Mobility Models [28] are widely used to model mobile networks in which some of the parameters responsible for mobility are indeterministic. Some of these parameters may be node attributes such as speed, direction, etc [29]. In our simulation study, we use two such random mobility models namely the Random Waypoint Model and the Random Walk model (Brownian motion). These are by far, the most commonly used mobility models in simulations involving non-static participants.

Random Waypoint mobility model [29] is the most frequently used mobility model in wireless network simulations. According to this model, nodes move independently to a randomly chosen destination with a randomly selected velocity. The destination, speed and direction are all chosen randomly and independently of other nodes. The simplicity of Random Waypoint model is the main reason for its widespread use in simulations [30].

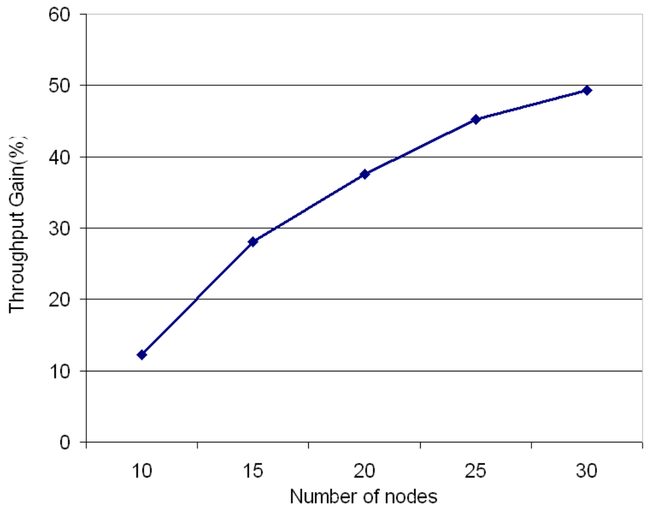

Figure 6.6: Throughput Gain(%) vs. Number of nodes in the network

However, Random Waypoint has been shown to have some inherent deficiencies such as speed decay and non-stationarity [31]. Stationarity means that the model's statistical properties remain constant at all times during simulation. The most important among them is the average speed of the nodes which has been shown to decrease consistently. In fact, over a large interval of time, speed decay will cause node velocity to become zero. With increasing simulation time, the speed of the nodes will have an exponential distribution [32] [33]. Hence what started off as a uniform distribution is changing with time and hence does not satisfy the condition of stationarity. Also, it suffers from border effect which means that nodes pass through the center of the simulation area with a greater probability than any other area. However, it is widely used since the decaying effects are only observed during long simulations.

The Random Walk model [34] has similarities with the Random Waypoint model because the node movement has strong randomness in both models. However, in the Random Walk model, the nodes change their speed and direction at each time interval. For every new simulation interval, t, each node randomly and uniformly chooses its new direction θ. Similarly, the new speed follows a uniform distribution or a Gaussian distribution. If the node moves according to the above rules and reaches the boundary of the simulation area, the exiting node is bounced back to the simulation field with the angle of $\pi - \theta$ respectively. This effect is called border effect. However, in our simulations, we have used Random Walk model with a *wrap around* effect which causes boundary exiting nodes to wrap around i.e., re-appear at the opposite boundary.

The experimental setup consists of a single access point (AP) servicing variable number of end nodes in an infrastructure BSS. The AP is located right at the center of a rectangular area of dimensions 250m X 250m. All client nodes are mobile and are randomly uniformly distributed in this area. Nodes in the network move according to Random Waypoint or Random Walk mobility models in the grid. Random Walk mobility model was simulated using [35]. All nodes travel at speeds of 5 meters/second with a pause time of 1 second. At each node, data packets of length 1000 octets arrive at a rate of 500 packets per second to keep the network heavily loaded. The experiment sets the minimum contention window size (CW_{min}) to 31 slots and uses a maximum of 6 back off stages during retransmission. Nodes select their data rates based on the received SNR as described above.

Figure 6.7 shows the the saturated throughput achieved by both 802.11b and Synergy MAC protocols for different mobility models. Data points in the graph represents the average throughput derived from 20 simulation runs for varying number of nodes in the network. From the graph it is clear that Synergy MAC is able to achieve much higher throughput than 802.11b despite node mobility. Part of the reason behind such impressive performance lies in the design of Synergy MAC, which enables the relay to be identified dynamically.

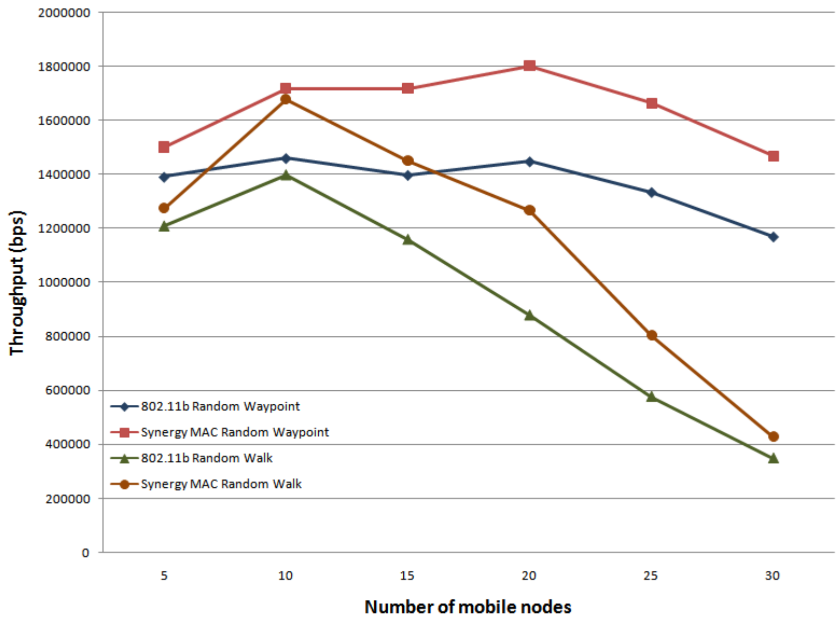

Figure 6.7: Throughput vs. Number of mobile nodes in the network

This design feature, allows the source node to solicit help from its ever changing neighbor set with little or no overhead costs. And because the source is able to solicit such help from its neighbors for every frame it transmits, it is able to reap the benefits of cooperation even when nodes in the network are mobile [36]. The relative gain in the throughput of Synergy MAC expressed as percentage versus number of mobile nodes in the network is shown in Figure 6.8.

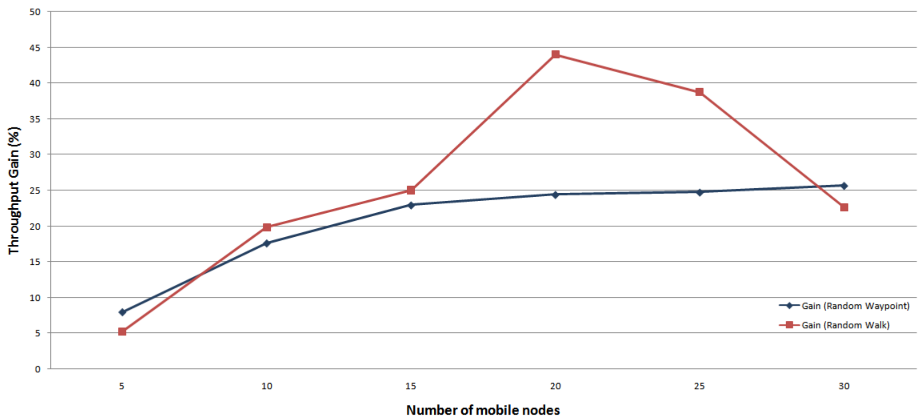

Figure 6.8: Throughput Gain(%) vs. Number of mobile nodes in the network

Chapter 7

Conclusion

In this work, we first looked at fading and its ill effects on radio communication. We then saw how diversity can help reduce the errors induced by fading via effectively transmitting or processing multiple (semi)independently fading copies of the original signal. We also discussed the concept of cooperative diversity, where nodes within the transmission range of source act as virtual antennas and retransmit the overheard signal to destination to achieve spatial diversity.

We then explored cooperation at the medium access control (MAC) layer and proposed a new 802.11b compatible, cooperative MAC protocol called Synergy MAC. With the proposed protocol, low data rate nodes transmit their packet first to an intermediate node which in turn forwards the packet to the destination at rates higher than otherwise possible. By ensuring that the destination overhears multiple copies of the original frame (initial source-relay and later relay-destination transmissions) the protocol is able to achieve spatial diversity. Also, by implementing the multi-hop transmission scheme suggested in [26], the protocol is able to minimize 802.11b's unfairness issue resulting from its multi-rate modulation scheme. As verified by extensive simulations, Synergy MAC is able to achieve substantial throughput improvements in comparison to 802.11b, without incurring significant overhead in system design. In fact the protocol's decreased sensitivity to channel variation is an advantage that warrants nodal cooperation even if there are no benefits of increased data rates. This is because some minimum data rate requiring real-time applications such as voice or video are better served by an improved QoS resulting from cooperation. Moreover for a given network throughput, Synergy MAC can reduce the interference experienced in proximal cells and thus can provide a more uniform coverage under dense deployment. Simulations also demonstrate that the proposed protocol's performance is resilient to node mobility.

Since the relay node simply forwards the source's data frame without looking into the contents of the MSDU, the confidentiality of the MSDU can be maintained by encrypting the content. Access fairness is not compromised in the new MAC, since the relaying node is allowed to access the network without utilizing its own transmission opportunities.

Also, Synergy MAC can be readily extended to other higher data rate extensions of 802.11, even though the current implementation is evaluated against IEEE's 802.11b only.

Chapter 8

Future Work

Following up on the results presented in this work, a number of additional research problems can be suggested. For example, in our study, we only consider infrastructure basic service sets. Although one can conjecture a similar result for single flows in ad hoc networks, the outcome needs to be demonstrated. Another interesting point that needs to be investigated in an environment of dense ad-hoc nodes is, whether spatial reuse via cooperation is beneficial or harmful. The issue is not straightforward as explained in the following example.

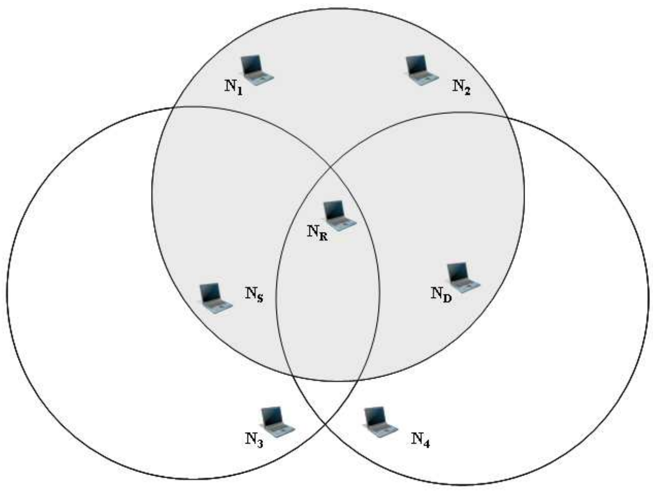

Figure 8.1: Spatial reuse in Synergy MAC

Consider an ad-hoc network deployment as depicted in Figure 8.1. When 802.11b is used for medium access control, the nodes that remain silent during an ongoing communication between N_s and N_d are N_3, N_r and N_4. On the other hand when Synergy MAC is used, the CTS_r frame also forces nodes N_1 and N_2 to defer their transmissions so as to not collide with the ongoing communication. The impact of silencing communication beyond immediate neighbors at the relay remains to be investigated.

Similarly other issues like identifying the right relay, rewarding an idle relay, estimating energy overhead at a relay, handling too many candidate relays as well as achieving communication integrity and confidentiality during cooperation are still wide open and remain to be addressed.

Bibliography

[1] Theodore S. Rappaport, “Wireless Communications: Principles and Practice,” IEEE Press, Piscataway, NJ, 1996.

[2] Richard Engelmann, “The Origins of Radio,” IEEE Potentials, November 2000.

[3] Praphul Chandra, “Bulletproof Wireless Security: GSM, UMTS, 802.11, and Ad Hoc Security (Communications Engineering),” Newnes, 2005.

[4] Andrea Goldsmith, “Wireless Communications,” Cambridge University Press, 2005.

[5] Sheila Frankel, Bernard Eydt, Les Owens, and Karen Scarfone, “Establishing wireless robust security networks: a guide to IEEE 802.11i,” National Institute of Standards and Technology, 2007.

[6] IEEE Computer Society, “IEEE Std. 802.11-1999 Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications,” IEEE Press, Piscataway, NJ, 1999.

[7] IEEE Computer Society, “IEEE Std. 802.11b-1999 Supplement to Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Higher-speed Physical Layer Extension in the 2.4 GHz Band,” IEEE Press, Piscataway, NJ, 1999.

[8] William Stallings, “Wireless Communication and Networks,” Pearson Prentice Hall, NJ, 2005.

[9] Andrew Sendonaris, Elza Erkip and Behnaam Aazhang, “User cooperation diversity-Part I: System Description,” IEEE Trans. Commun., vol. 51, no. 11, pp. 1927-1938, Nov. 2003.

[10] Andrew Sendonaris, Elza Erkip and Behnaam Aazhang, “User cooperation diversity-Part II: Implementation aspects and performance analysis,” IEEE Trans. Commun., vol. 51, no. 11, pp. 1939-1948, Nov. 2003.

[11] J. Nicholas Laneman, David N. C. Tse, and Gregory W. Wornell, “Cooperative Diversity in Wireless Networks: Efficient Protocols and Outage Behavior,” IEEE Trans. Inform. Theory, vol. 50, no. 12, pp. 3062-3080, Dec. 2004.

[12] Matthew C. Valenti and Neiyer Correal, “Exploiting Macrodiversity in Dense Multihop Networks and Relay channels,” in Proc. IEEE Wireless Commun. and Networking Conf. (WCNC), vol. 3, Mar. 2003, pp. 1877-1882.

[13] Ingmar Hammerstroem, Marc Kuhn, Boris Rankov, and Armin Wittneben, "Space-Time Processing for Cooperative Relay Networks," in Proc. of IEEE Vehicular Technology Conf. (VTC), Oct. 2003.

[14] Elza Erkip, Andrew Sendonaris, Andrej Stefanov and Behnaam Aazhang, "Cooperative Communication in Wireless Systems," Advances in Network Information Theory, AMS DIMACS Series, 2004.

[15] Thomas M. Cover and Abbas El Gamal, "Capacity Theorems for the Relay Channel," IEEE Trans. Info. Theory, vol. IT-25, Sept. 1979, pp. 57284.

[16] Andrej Stefanov and Elza Erkip, "Cooperative Coding for Wireless Networks," IEEE Trans. Commun., vol. 52, Sept. 2004, pp. 147076.

[17] Todd E. Hunter and Aria Nosratinia, "Diversity through Coded Cooperation," IEEE Trans. Wireless Commun., vol. 5, Feb. 2006, pp. 28389.

[18] J. Nicholas Laneman and Gregory W. Wornell, "Distributed Space-Time Coded Protocols for Exploiting Cooperative Diversity in Wireless Networks," IEEE Trans. Info. Theory, vol. 49, Oct. 2003, pp. 2415-25.

[19] Pei Liu, Zhifeng Tao, Zinan Lin, Elza Erkip and Shivendra Panwar, "Cooperative Wireless Communications: A Cross-Layer Approach," in IEEE Wireless Communications, vol. 13, Aug. 2006, pp. 84-92.

[20] Matthew Gast, "802.11 Wireless Networks: The Definitive Guide," O'Reilly Media, 2005.

[21] Javier Delprado and Sunghyun Choi, "Link Adaptation Strategy for IEEE 802.11 WLAN via Received Signal Strength Measurement," In Proc. IEEE ICC'03, Vol.2, pp.1108-1113, May 2003.

[22] Martin Heusse, Franck Rousseau, Gilles Berger-Sabbatel and Andrzej Duda, "Performance anomaly of 802.11b," in Proc. of IEEE INFOCOM, March 2003.

[23] Pei Liu, Zhifeng Tao and Shivendra S. Panwar, "A Co-operative MAC Protocol for Wireless Local Area Networks," in Proc. IEEE Int Conf. on Communications (ICC), Seol, Korea, May 2005, pp. 2962-2968.

[24] B. Sadeghi, V. Kanodia, A. Sabharwal, and E. Knightly, "Opportunistic Media Access for Multirate Ad Hoc Networks," in Proc. ACM MobiCom'02, Sept. 2002.

[25] Pei Liu, Zhifeng Tao, Sathya Narayanan, Thanasis Korakis, and Shivendra S. Panwar, "CoopMAC: A Cooperative MAC for Wireless LANs," IEEE Journal on Selected Areas in Communications, vol. 25, no. 2, Feb. 2007

[26] Sathya Narayanan, Pei Liu, and Shivendra S. Panwar, "On the advantages of multi-hop extensions to IEEE 802.11 infrastructure mode," in Proc. IEEE Wireless Commun. and Networking Conf. (WCNC), New Orleans, USA, March 2005.

[27] Niraj Agarwal, Divya ChanneGowda, Lakshmi Narasimhan Kannan, Marco Tacca and Andrea Fumagalli, "IEEE 802.11b Cooperative Protocols: A Performance Study," in IFIP/TC6 NETWORKING 2007, Atlanta, March 2003, pp. 415-426.

[28] T. Camp, J. Boleng and V. Davies, "A Survey of Mobility Models for Ad Hoc Network Research," in Wireless Communications and Mobile Computing, volume 2, 2002.

[29] David B. Johnson and David A. Maltz, "Dynamic Source Routing in Ad Hoc Wireless Networks," Mobile Computing, Kluwer Academic Publishers, 1996.

[30] C. Bettstetter and H. Hartenstein and X. Perez-Costa, "Stochastic Properties of the Random Waypoint Mobility Model," in ACM/Kluwer Wireless Networks, Special Issue on Modeling and Analysis of Mobile Networks, 2004. pp. 181-190.

[31] J. Yoon, M. Liu and B. Noble, "Random Waypoint Considered Harmful," in Proceedings of INFOCOM, 2003.

[32] T. Chu and I. Nikolaidis, "On the artifacts of random waypoint simulations," Proceedings of the 1st International Workshop on Wired/Wireless Internet Communications (WWIC2002), 2002.

[33] A. Jardosh, E. M. Belding-Royer, K. C. Almeroth and S. Suri, "Towards Realistic Mobility Models for Mobile Ad Hoc Networks," in ACM Mobicom, 2003.

[34] Michael McGuire, "Stationary distributions of random walk mobility models for wireless ad hoc networks," in Mobile ad hoc networking and computing, 2005.

[35] S. PalChaudhuri, J. Y. L. Boudec, and M. Vojnovic, "Perfect simulations for random trip mobility models," at 38th Annual Simulation Symposium, San Diego, CA, 2005.

[36] Santosh Kulkarni, Pratap Prasad and Prathima Agrawal, "Performance Enhancement of Mobile Ad Hoc Networks Using Nodal Cooperation," in Proceedings of 4th International Wireless Internet Conference (WICON), Maui, Nov. 2008.