Adaptive Cross Layer Design and Implementation for Gigabit Multimedia Applications Using 60 GHz Wireless Links

by

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ABSTRACT

Demands in file size and transfer rates for consumer-orientated products have escalated in recent times. This is primarily due to the emergence of high definition video content. Now factor in the consumer desire for convenience, and we find that wireless service is the most desired approach for inter-connectivity. Consumers expect wireless service to emulate wired service with little to virtually no difference in quality of service (QoS). The background section of this document examines the QoS requirements for wireless connectivity of high definition video applications. I then proceed to look at proposed solutions at the physical (PHY) and the media access control (MAC) layers as well as cross-layer schemes. These schemes are subsequently are evaluated in terms of usefulness in a multi-gigabit, 60 GHz wireless multimedia system targeting the average consumer. It is determined that a substantial gap in published literature exists pertinent to this application. Specifically, little or no work has been found that shows how an adaptive PHY-MAC cross-layer solution that provides real-time compensation for varying channel conditions might be actually implemented. Further, no work has been found that shows results of such a model. This research proposes, develops and implements in Matlab code an alternate cross-layer solution that will provide acceptable QoS service for multimedia applications. Simulations using actual high definition video sequences are used to test the proposed solution. Results based on the average PSNR metric show that a quasi-adaptive algorithm provides greater than 7 dB of improvement over a non-adaptive approach while a fully adaptive algorithm provides over 18 dB of improvement. The fully adaptive implementation has been conclusively shown to be superior to non-adaptive techniques and sufficiently superior to even quasi-adaptive algorithms.

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TABLE OF CONTENTS

Page

CHAPTER Page

APPENDIX

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

Figure Page

Chapter 1

INTRODUCTION

Background and Motivation

The home theater market is offering significant opportunities as well as considerable challenge for wireless connectivity. Digital television is the force behind this opportunity due to recent advances in high definition and flat panel technology, along with the FCC requirement that digital signals replace analog transmissions by July 2007 - actually implemented by full-power broadcasters on August 12, 2009. The tremendous interest by consumers in these televisions in conjunction with fierce competition has resulted in substantial reduction in the cost of large, high definition sets. Even more dramatic are the recently released and emerging standard and specifications such as High-Definition Multimedia Interface (HDMI), Digital Visual Interface (DVI) and Display Port that define interfaces for uncompressed high definition (HD) transmission between devices through cables or wires (wired links). These interfaces demand one to several Gb/s bandwidth capacity which cannot be provided by existing consumer wireless products. For example, a single uncompressed 1080p HDMI link is capable of transferring up to 24 bits of data at 2.07 Mega-pixels per second resulting in a bandwidth requirement of 3.986 Gb/s. Note that this is for raw data and does not include addition bandwidth needed for blanking and Transition Minimized Differential Signaling (TMDS). With these requirements, the data rates are at about 4.5 Gb/s. Furthermore, HDMI recently released specifications for HDMI versions 1.3a and 1.3b that require a video bandwidth of 10.2Gb/s [6].

Additional anticipated consumer/home applications include digital video camcorder downloading, gaming, printing and scanning applications, photography and various other applications requiring transfer of large amounts of data in a short period of time. For example, a digital camcorder can hold 24 Gigabytes of data which can be transferred in a little over 3 minutes at 1 Gb/s while the same download would take nearly 1 hour using WiFI (802.11g) at 24 Mb/s.

A number of outside the home, consumer-orientated applications are also emerging. These include wireless synchronization of hand-held devices, such as a handset. Content may include audio video (AV) files, data files, secure financial transactions and other applications requiring high bandwidth over a relatively short distance. For example, a consumer could carry his/her handset into a mall or store and download a large AV file nearly instantaneously. This file or information could be used immediately or downloaded through wireless access to another device, either in a vehicle, or when they return home. Finally, payment for these services could be done via this wireless medium in a very secure manner.

Many business and enterprise use cases have been identified as well. Some of the perceived early adopters include ad hoc networking such as in a conference room environment, wireless gigabit Ethernet and other similar applications. Public safety uses such as secure transfer of video files is another likely market. Other industries that have expressed interest in this technology includes the aircraft industry – for distribution of multimedia content wirelessly to the planes passengers. Similar scenarios can be envisioned for ships, trains and buses. In fact, an early demonstration system was set up in Japan on one of their bullet trains. The idea was to enable users to upload and download data and so on to an on-board server while the train was in route. When the train pulled into a station, the huge amount of data stored could be transferred very quickly using the 60 GHz technology and at multi-gigabit data rates [7].

Other applications requiring very high data rates are emerging. Examples of these include virtual reality, real-time high-quality video conferencing and many others . High data rate applications also requiring secure links could take advantage of the propagation characteristics at these frequencies. These could include military, emergency services, homeland security and other secure applications. Outdoor wireless mesh networks with relatively short range links on the order of 100m may have significant potential for moving data at multi-gigabit rates [49].

Why 60 GHz?

A promising approach for addressing the need for short-range, multi-gigabit wireless networking is the potential use of the unlicensed spectrum that is available at 60 GHz. The use of the 60 GHz band gained worldwide interest in the wireless arena over the last decade specifically for low cost, consumer and commercial applications. A primary reason for this interest is the fact that at least 3.5 GHz of contiguous spectrum is available in this frequency band worldwide as depicted in Fig. 1.1. Europe has allocated 59-66 GHz for mobile broadband systems (MBS) and wireless local area networks (WLAN). In the United States 57-64 GHz is allocated for general unlicensed applications. Japan has allocated 59-66 GHz for high speed data communications. Most other countries and regions have similar bands assigned [30]. The near universal availability of unlicensed spectrum allocation essentially eliminates regulatory delays and conflicts. This factor is critical for two reasons: it promotes rapid deployment of low cost, consumer and/or commercial networks, and the overlapping nature of the international allocations will permit large-volume production with perhaps some very minor modifications for alignment with the region of intended operation. This should ultimately lead to low cost of device and/or system implementation for the end user [56].

The 60 GHz band has several other positive attributes as well. Antennas, which typically must be several wavelengths in size, are very small at 60 GHz. These antennas can easily be integrated into small form factor products, even into handheld devices. Other components such as microwave integrated circuits (MMIC) are also proportionally smaller at these high frequencies. High gain antennas with corresponding narrow beam widths are required to overcome the increased path loss. This factor can be viewed as advantageous in that multiple users on the channel could be networking in close proximity. Narrow beam width – or equivalently, high directivity- is beneficial for spatial reuse scenarios such as spatial multiplexing.

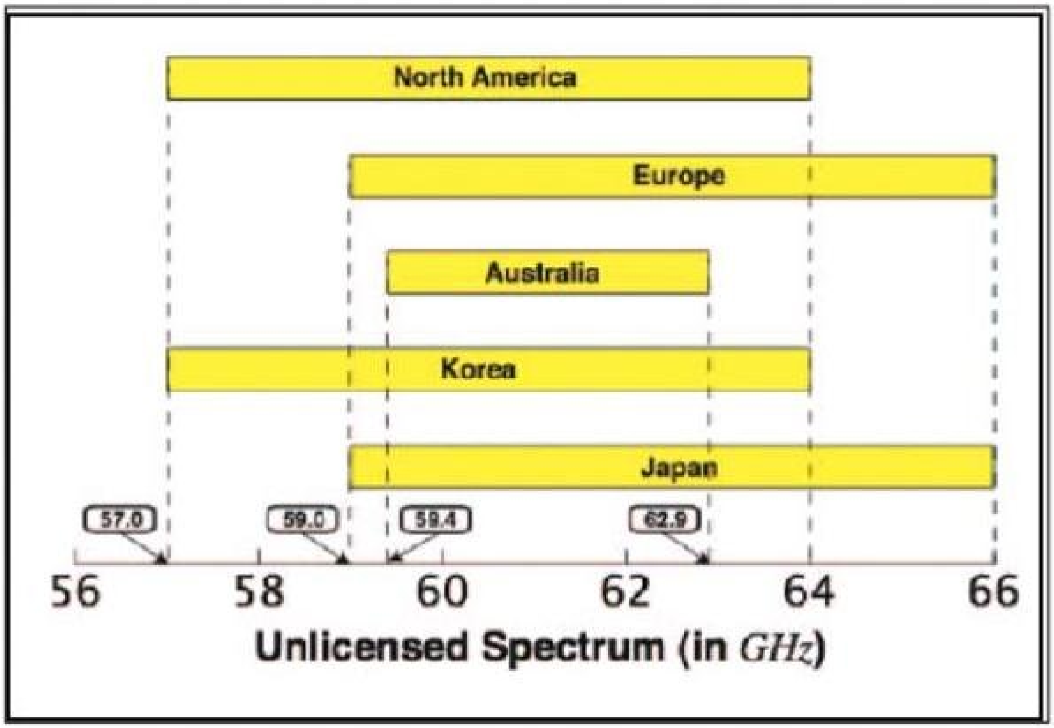


Figure 1.1: Worldwide available spectrum in the 60 GHz millimeter wave band [30].

Wireless systems using the 60 GHz band have actually been in place for several years. These systems however are long range backhaul networks and are typically used as wireless extensions for wired or fiber systems. These systems are very much point to point systems, typically located such that interference – and communication– with other systems is very unlikely and are very costly. Ranges of operation for 60 GHz band backhaul can exceed 1 km with data rates up to 1.25 Gb/s – capable of supporting gigabit Ethernet for example [20]. The motivation to use these systems is primarily financial. Though they are relatively expensive, their costs often are an order of magnitude or less than the cost to establish a fiber link. For example, very densely populated areas such as large urban centers are prime candidate for wireless extensions. College and corporate campuses are also actively employing these last-mile solutions. Conversely, very remote or difficult areas, technologically emerging areas and so on are also employing these wireless types of systems. The kinds of systems that this research is concerned with are much smaller in range, much cheaper, but also much more flexible and portable. These systems were until recently targeted towards enterprise applications but now focus primarily on use cases that target early high-end consumer adopters [10]. A wireless personal area network (WPAN) is traditionally defined as a network that extends about 10m in every direction from a user. One alternate definition distinguishes WPAN from other networks in that for WPAN the focus is inward toward a single user. In other networks, such as wireless local area networks (WLAN), the focus is outward toward the rest of the information world. This is not to say that the WPAN cannot access via WLAN or other means, this world of communication and information. Indeed such networks are clearly established as viable use case scenarios. For example, an ad-hoc network of laptop users could communicate in a conference room setting via the WPAN and also be tied in to an access point providing a link to a WLAN and ultimately, the ubiquitous Internet [15].

Characteristics of 60 GHz WPAN Channels

The wireless channel at millimeter-wave frequencies, such as at the 60 GHz band has intrinsic characteristics unlike those at lower microwave frequencies, for example, at the 5 GHz carrier frequency used for WiFi (802.11n). Fundamentally, the path loss is proportional to the frequency of the carrier squared. For example, in order to maintain the same link budget at 60 GHz as at 5 GHz, the antenna gain (of the system, that is, both transmit and receive) must be scaled by a factor of 144, or 21.5 dB. This high gain equates to a highly directional beam. Further, the60 GHz line of sight (LOS) channel clearly dominates any additional propagating waves [31]. Any scattered waves will be severely attenuated in all but low-loss material situations, for example, in the inside of a metal cylinder. Edge-scattering and other phenomena normally associated with optics begin to play a role in the channel model. Fading due to shadowing effects can dominate. This is not an easy environment in which to attempt to establish a wireless network. Now, factor in the requirement for 1 Gb/s plus data rates, and the challenges increase drastically. At 60 GHz, attenuation due to fixed objects is very large. Various common wall construction types can introduce considerable attenuation. A simple 5/8 inch plasterboard wall with no studs in the path of propagation can introduce about 4 dB of attenuation while walls with metallic studs in the signal path can introduce over 36 dB of attenuation [37]. Therefore, most use case scenarios are for a single room or area such as a conference room or a factory floor. However, through the use of repeaters or other multi-hop techniques, a multi-room or whole-house/office scenario could possibly be realized [66].

Motivation

The motivation for this research is the tremendous commercialization potential as can be deduced from the number of recently released and emerging international standards organizations and industrial associations looking at gigabit plus data rates using wireless networks. IEEE 802.11 TGad [4] is probably the standard that has the most potential for large scale commercial and consumer deployment. This standard is attempting to provide multi-gigabit data rates in a WLAN environment in conjunction with existing 802.11x products and services . If successful, an enormous market can be envisioned. Recently released IEEE 802.15.3c [1] and ECMA TC48 [2], which both address WPAN using the 60 GHz band, are also relevant to this research.

On the hardware side, numerous examples of CMOS and SiGe Heterojunction Bipolar Transistor (HBT) circuits and sub-systems operating at 60 GHz – and beyond - have been reported [45], [59].

This is a critical step towards developing consumer products since the alternatives, namely Gallium Arsenide (GaAs) and Indium Phosphide (InP) (InP) – based processes are prohibitively expensive [32]. Perhaps

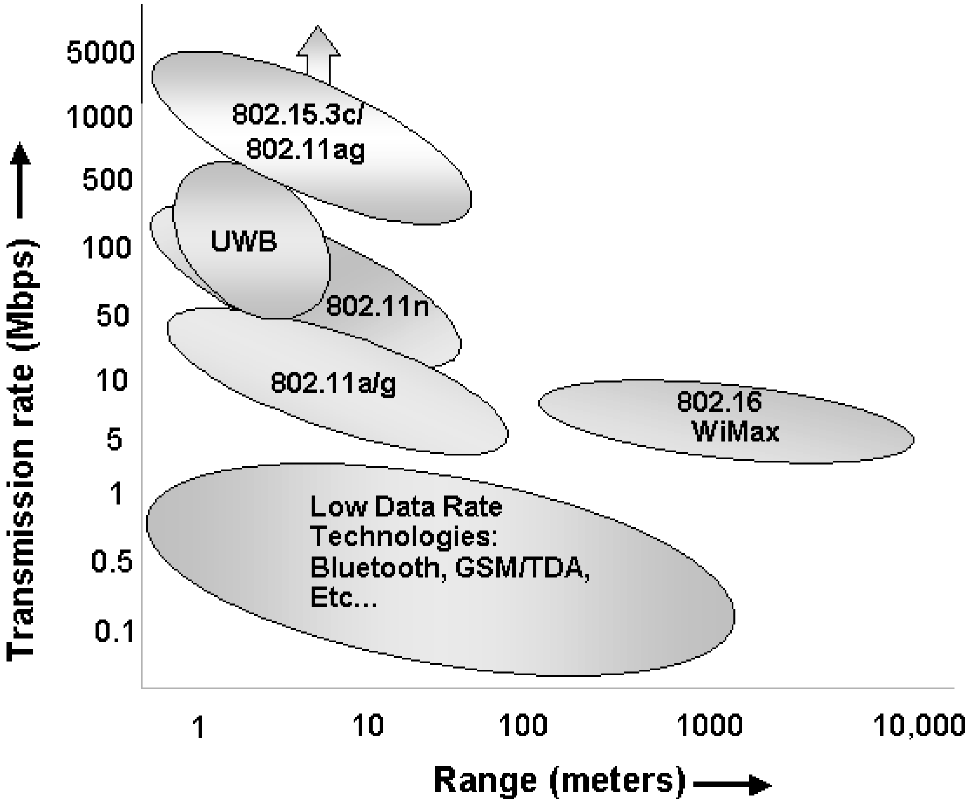


Figure 1.2: Wireless standards landscape snapshot as of 2011 [76].

equally if not more important is the fact that these technologies do not lend themselves well to high levels of integration, such as is available in silicon processes such as CMOS. Advances in complimentary circuitry such as steerable and smart antennas, ultra-miniaturization, high frequency-enabled low-cost packaging as well as advanced automated manufacturing and test techniques are such that real, cost-sensitive consumer-type systems could readily be manufactured today.

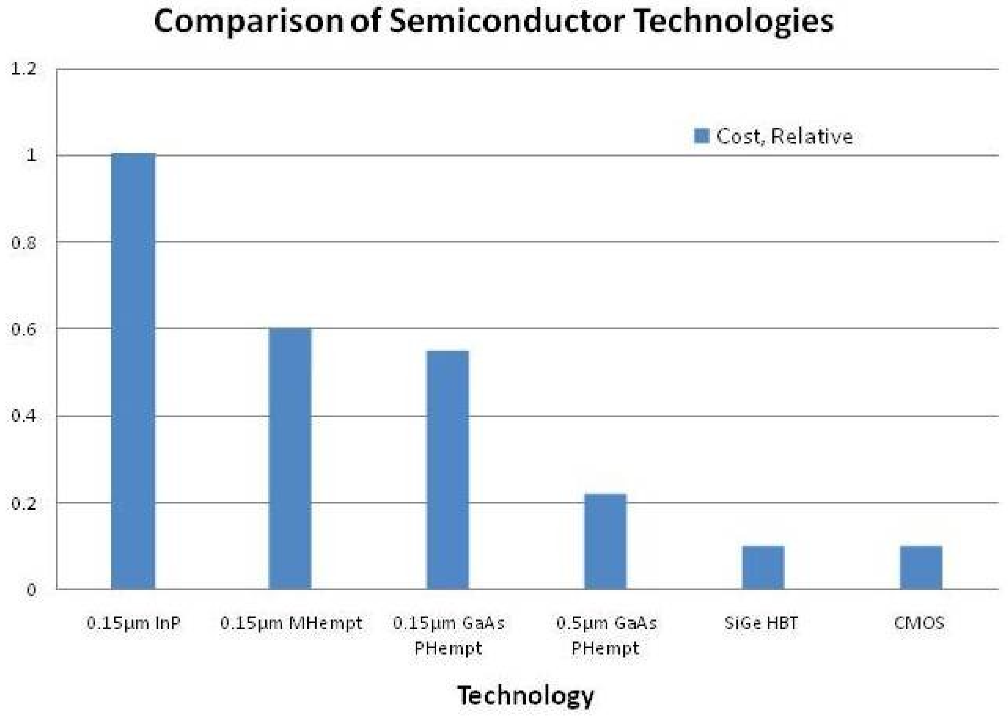


Figure 1.3: Semiconductor Cost versus Technology. [32].

Overview of System Requirements and Challenges

The background section of this document will examine the requirements at the physical (PHY) and media access control (MAC) layers in a wireless network that can provide sufficient QoS for consumer multimedia applications. Since the primarily early adopter appears to be the in-home high definition streaming video application, low-cost and excellence of performance, though conflicting goals, are both requirements. It turns out that for uncompressed video streaming, a small interference in reception of even one channel of HDMI (which has three channels of video), for example, causes a huge glitch in the display of the content. Therefore, initial deployment of these systems must be very robust in its operation. With this in mind, a system that is capable of adapting to various environments but with minimal complexity of both hardware and installation is necessary. This implies a dynamically adaptable or other alternate solution. For example, it might be necessary to adjust QoS requirements according to a continuously changing channel. This can easily be envisioned in the case of the so-called super bowl party environment where several people are in a room and may be mobile.

A further impairment is the challenge of human bodies causing blockage of a direct link. This phenomenon is pronounced at 60 GHz, as compared to much lower frequencies such as 5 GHz, and has only recently been addressed in the literature. For example, direct blockage of a 60 GHz signal can attenuate the signal by as much as 30 dB [49]. Compounding this situation even further is that the bodies can be moving, stopping and moving again, and so on resulting in shadowing and other interference phenomena [40]. Since the allowable RF power is very low, ways of providing alternate paths are needed. Many proposed antenna solutions such as beam-forming or steerable antennas may—without additional MAC/PHY optimization— prove inadequate for such use case scenarios and may be prohibitively expensive to implement.

The hidden terminal problem [74], which is common to all wireless networks, is aggravated in 60 GHz wireless networks. Particularly, devices can be hidden to each other not only because of distance separation, but

Material	Loss (dB/cm)
Acrylic Glass	1.03
Concrete	6.67
Glass	6.05
Marble	10.56
Plasterboard	1.0
Stone	5.73
Tile	7.81
Wood	4.22

Table 1.1: Loss characteristics of various common building materials at 60 GHz [29].

also because of directional misalignment. For example, devices can be hidden to each other when they are within the communication range but not transmitting or receiving in a certain direction. The underlying cause of this is the directional nature of the antennae required at these carrier frequencies. Asymmetry between the transmitter and receiver antenna directivity can also cause these types of problems [25].

An interesting aspect of the 60 GHz band is its proximity to an oxygen absorption peak, which contributes about 15 dB/km of attenuation in addition to free space losses. Atmospheric losses are lower at higher elevations because oxygen absorption is the dominant contributor at 60 GHz. Rain and other forms of precipitation cause further losses. These are not first order effects for WPAN/WLAN applications, especially when the application is indoors.

The attenuation and other properties of 60 GHz propagation result in an inherent degree of built-in security. Interception of a signal without the user’s knowledge would be very difficult if not impossible. This is primarily due to the extremely low signal level that would be available outside of a very localized area – defined by the beam width of transmitting antenna or antenna array. Further, equipment needed to monitor or interfere with radios operating in this band is not readily available and is expensive. You probably won’t see this type of equipment at the local pawnshop [15].

The attenuation and highly-directional beam characteristics inherent to the 60 GHz band provide isolation from nearby transmitters which can be a distinct advantage for frequency reuse and makes this spectrum potentially very attractive for short to medium range indoor or outdoor broadband communications. This leads to an interesting insight. The 60 GHz wireless world can be envisioned as a three dimensional space: time, frequency, and location. Exploitation of this new paradigm should provide an excellent basis for multimedia QoS networking [17].

Qualitative and Quantitative QoS Requirements

Perceived quality of service (PQoS) is the subjective QoS that a viewer experiences. PQoS can be considered to be the definitive qualitative metric for video streaming and other high definition video applications [48]. One very commonly used metric used to evaluate PQoS is the Mean Opinion Score (MOS) test. For this evaluation, a number of viewers observe the demonstration video and rate the perceived quality on a scale from one to five, with five being the highest rating. The MOS is the average of the viewers ratings. It is apparent that this method of defining the PQoS is time consuming, expensive, non-repeatable —unless a very carefully controlled evaluation environment is used— and in general, a rather inefficient means to exact the required feedback.

Network-level QoS, or simply QoS, is a based on numerical data that is derived from simulations or measurements. The most widely used and simplest to implement is the peak signal-to-noise (PSNR) method. The primary shortcoming of this evaluation method is that the problems encountered in a wireless environment, specifically packet corruption or loss, are not typically accounted for. Mitigation of these very issues are key to a high level PQoS. The correlation between the PSNR and the MOS methods are very good and can be improved further by implementing linear regression techniques [22]. Though proposed values vary, typical PSNR values for good to excellent quality images is approximately in the 30 to 50 dB range. PSNR values in the 20 to 30 dB range are considered good, below 20 dB most references are in agreement that images are typically in the poor category [5], [65], [53]. Other common metric estimators used for high speed wireless data links include network capacity in terms of end-to-end throughput, BER or PER versus SNR, and other similar parameters readily simulated or measured

[59], [54], [40]. Regardless of the strategy used for evaluation, the bottom line is that from an end- user perspective, the QoS concept must be aligned to the degree of satisfaction that is related to the PQoS [43].

The most quantitatively important metric of QoS for high definition streaming video applications is the ability of the network to guarantee the required service bandwidth. This is somewhat simplified compared to more dynamic types of networks since the bit-rate traffic is constant and predictable. MAC functionality can be less complex and more efficient [57]. However, for wireless networks, a service bandwidth guarantee may be infeasible to be achieved due to the impact of time varying fading channels. This implies that a statistical-based QoS guarantee may be appropriate for these networks [70].

Proposed PHY, MAC and Cross-Layer Solutions

Overview of Layer Structure

Communication networks, whether wireless or wired demand some type of protocol in order to facilitate efficient transfer of information. An illustrative analogy can be formulated using interactive speech, that being person-to-person, or inter-group discussion. Using this analogy, a communication protocol dictates such items as whose turn it is to talk, at what speed the participants are talking at, perhaps even what language is to be used. This analogy can be extended further by specifying what modulation technique is to be use (voice) and what medium is to be employed (air), although for speech, these are preselected parameters.

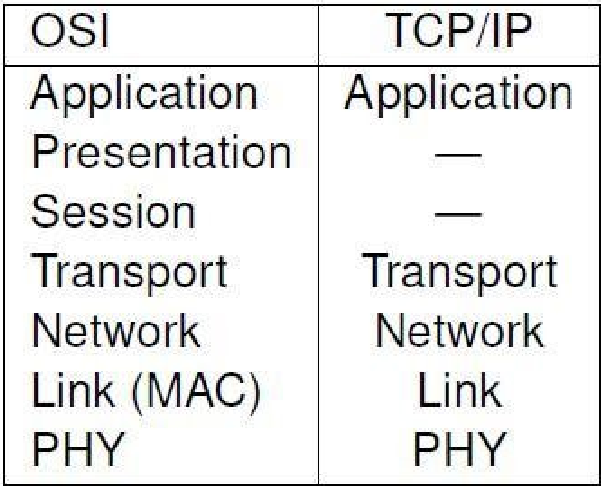
Returning to our analogy, the lowest layer in the structure, the physical PHY) layer, can be considered as specifying what the modulation scheme to be used is (voice) and what the transmission media is to be (air). The PHY layer is the hardware and media that operates on raw bits or groups of symbols. In actual practice, the PHY layer adds information to the data sent down from the MAC and forms a PHY frame. This frame usually includes a header containing the PHY address, type of modulation used and so on. The PHY also can add some error protection such as FEC. A group of bits at the tail of the PHY frame indicates that the frame has ended [36]. Similarly, issues such as whose turn it is to communicate, speed of communication and so on fall into a sub-layer of the Data Link Layer, specifically the media access control (MAC) layer. The MAC layer provides the protocols needed for communication between two or more devices (DEVs) including channel access, MAC addressing, and most of the high-level coding and error correction [36].

Cross-layer refers to issues that can be tied to two or more layers. Returning once more to our vocal communication analogy, an example of cross-layer utilization might be the volume of speech (PHY layer) together with the speed (MAC layer). At low volumes, it is much easier to discern slower, distinctive speech (e.g. a whisper) than rapid, staccato rhetoric.

In the case of modern electronic communication networks, the Open Systems Interconnection (OSI) seven-layer model is arguably the de-facto standard [8]. More recently, a specialized architecture was developed specifically to service the internet. This protocol is known as the TCP/IP, or alternately, the Internet Protocol model [44]. Regardless of which model is referenced, the lower two layers, which are substantially in common in both models, are among the layers of interest for the network portion of a communication system and key elements of these two are present in any communication network [46]. For the case of multi-gigabit wireless millimeter-wave networks, the time variant nature of the channel suggests that the PHY layer might be a prime candidate for optimization. Since the MAC, being the adjacent higher layer, directly interfaces with the PHY layer, and can readily and expediently support adaptation and feedback mechanisms, I chose to focus on the MAC-PHY cross-layer problem for this study. Other studies have shown that these two layers significantly influence end-to-end network performance [26].

PHY Layer Solutions

The PHY layer is the hardware and media that operates on raw bits or symbols or predefined groups of bits or symbols. This layer defines the type of modulation used, the frequency of the RF carrier, the power level of the signal and other fundamental low-level tasks. However, there are numerous modulation types and hardware technologies available to implement the PHY, each with its unique characteristics.



OSI	TCP/IP
Application	Application
Presentation	—
Session	—
Transport	Transport
Network	Network
Link (MAC)	Link
PHY	PHY

Table 1.2: OSI and TCP/IP Layer Structure.

Digital modulation schemes can be divided into two broad categories: single carrier (SC) schemes, and multiple carrier or (MC) schemes. Examples of SC schemes include on-off-keying (OOK), amplitude-shift keying (ASK) and so on. The primary MC modulation scheme being considered in recent times is orthogonal frequency domain multiplexing (OFDM).

Selection of a SC modulation scheme requires analysis of the compromises between bandwidth efficiency, complexity and the required signal to noise ratio (SNR) for a given BER or PER. For reasonably-priced consumer and commercial applications, particularly for LOS or near LOS (NLOS) deployment, easily implementable solutions may be sufficient [19], [51]. For example, a PHY layer based on direct-conversion ASK is used to demonstrate a ultra-low complexity, low cost 60 GHz, multi-gigabit system [16]. Moderately-high directivity antennas are used to provide adequate PHY layer robustness to obtain required QoS as measured by the BER at for LOS or near LOS scenarios. More recently, OOK and other similar schemes have been demonstrated in CMOS technologies that integrate all conversion functions at the lowest reported energy per bit — very important for mobile or even dongle-based applications [39].

Differential QPSK (DQPSK) has the advantage compared to ASK/OOK of slightly improved BER performance and is only moderately more complex to implement. A DQPSK based system was proposed and implemented for LOS HDTV video transmission in [41]. In order to facilitate QoS requirements of video streaming, an efficient random/packet error recovery and symbol-timing recovery with an effective interpolation method was implemented. Specifically, for random error correction Bose and Ray-Caudhuri (BCH) code that can correct up to five random errors together with a partially-overlapped block (POB) code to address burst errors and packet loss was implemented. It was found that the combination of random/ packet error recovery and symbol-timing recovery results in very high PQoS.

Minimum shift keying (MSK) may also to be a good candidate for SC modes as it provides good balance between implementation

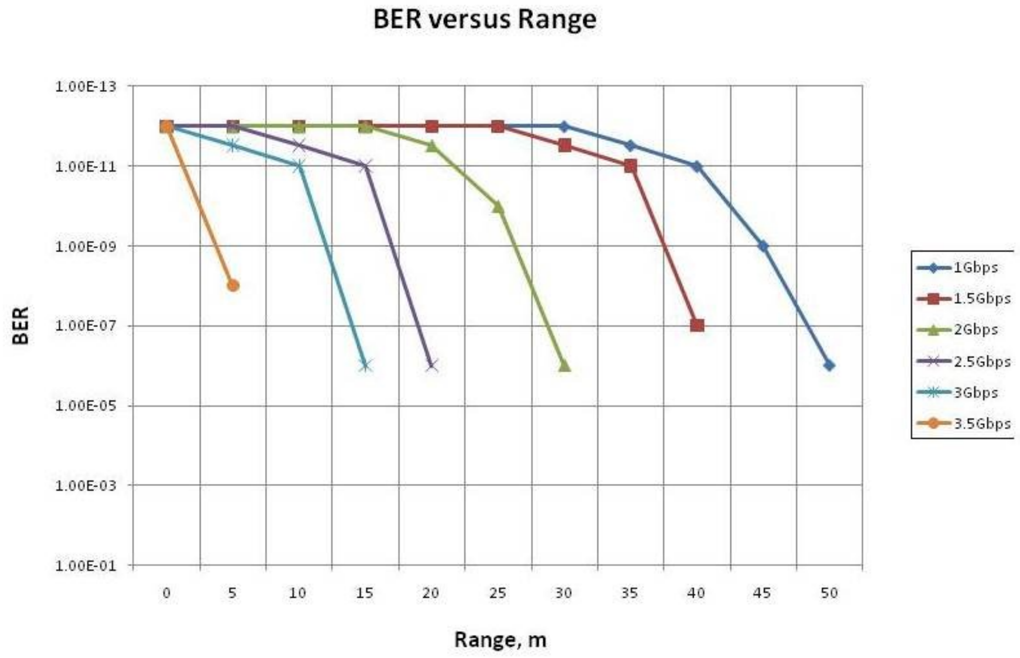


Figure 1.4: BER versus Range. Plot is of demonstration, low-complexity ASK direct conversion 60 GHz transceiver [16].

complexity and bandwidth efficiency [74]. MSK encodes each bit as a half-sinusoid which helps minimize non-linear distortion issues. Basic frequency shift keying (FSK) is shown in [71] to be able to provide a very low cost, robust network implementation. Devices utilizing MSK, FSK, BPSK [73] or other similar SC PHY modes may prove to be excellent candidates for low cost, compact, power efficient implementations.

The downside to the SC modulation schemes discussed thus far are that they all are capable of only transmitting a theoretical data rate of 1 bit/second/Hz. To increase bandwidth utilization, high order schemes that utilize phase in conjunction with amplitude information can be implemented. Modulation schemes that use one amplitude but varying phase differences include quadrature phase shift keying (QPSK) or equivalently, 4-PSK, 8-PSK, 16-PSK and so on [77].

Quadrature amplitude modulation (QAM) schemes use both amplitude and phase information to convey information. Two carrier signals that are shifted by pi/4 radians (quadrature) are modulated and then summed. For most applications the constellations are square and so the number of points must be a power of 2. This feature simplifies the modulation and demodulation of the signal but leads to a sub-optimal constellation in terms of maximizing point to point separation. Examples of QAM include 2, 4, 8... up to (and beyond) 256-QAM. Note that 2 -QAM is the same as BPSK, 4-QAM is the same as QPSK. 8-QAM, while distinctive, has a SNR requirement (for a given BER) of only about 0.5 dB better than 16-QAM while only able to supply about 3/4 of the data rate. Therefore, 16 QAM and above are normally encountered [50], [64], [58].

Employing these higher order modulation schemes comes at a cost. As the order of modulation increases, the distance between adjacent points on the constellation decreases. Noise, fading, multi-path effects and other degradation modes of the signal can cause the demodulated signal to be moved relative to the correct location. This may lead to errors in interpreting the signal information. To overcome this problem, an increase of SNR with increasing modulation order for a given BER is required. More complex modulation/demodulation implementation is needed. More RF power, lower phase noise and noise figure, along with higher linearity in the signal path may be needed to meet the higher SNR requirement [42].

One possible solution to the trade offs involved for high order modulation but at reduced complexity are the single-carrier frequency domain equalization (SC-FDE) schemes [13]. This work reports that zero forcing equalization can be employed for robust links up to about 4m in range. For longer range, more sensitive requirements, minimum mean square error (MMSE) equalization is required.

For applications requiring high throughput, OFDM may be a good option at a cost of a more complex architecture. OFDM uses multiple orthogonal sub-carriers at some fraction of the composite data rate to provide efficient modulation. These sub-carriers are modulated using one of the SC schemes such as QPSK or 16- QAM. Further, OFDM is reported to have benefits over SC modes for non line of sight (NLOS) applications [23]. There is some questions to the validity of these benefits in the 60 GHz band due to the attenuation factors previously discussed. The frequency selective fading characteristics of the 60 GHz channel are such that the ultimate performance will be degraded. Non-linear distortion, a byproduct of any real world power amplifier and carrier frequency offset (CFO) are huge disadvantages for OFDM [47], [60]. Regardless, optional OFDM PHY modes are included in the IEEE 802.15.3c standard and are the basis for the WirelessHD [27] specification. Other variants of OFDM include OFDMA [75] and OFDM-CDM [72].

In order to complete transmission through the channel, antennas are required for wireless networking. It has been discussed that high directivity antennas are need for efficient high data rates while more omni-directional antennas may be needed to establish a network. Many antenna schemes of various complexities have been proposed. These include simple, fixed gain antennas such as horns or patch types [18], moderately complex and adaptable designs such sectorized arrays [55] up to and including full electronically steerable multi-element arrays [27]. A scheme that has recently been studied extensively for WiFI and other uses at RF and low microwave carrier frequencies is the multiple-out (MIMO) system. There has been some recent work in this area specific to 60 GHz systems. For example, in [61] a scheme that uses MIMO in conjunction with a switched beam approach is proposed.

For a realistic, useful system, some sort of mechanism to alleviate potential blockage situations, being either fixed or a moving body, will be required implying an antenna system that has methods of steering around such blockage. This requirement essentially eliminates fixed types unless they are mechanically steered— probably not an option for a low cost, consumer-type application. A sectorized-style of antenna might be useful in certain situations where only limited steering requirements are needed

[55]. One example might be for use in a repeater. Indoor repeaters are being considered in 802.11TGad for room-to-room accessibility using 60 GHz. These might, for example, be placed on the ceiling in or near doorway or other opening. Since there would be only one way in and one way out for unimpeded transmission, a few elements might be sufficient.

Fully electronically steerable patch array antennas have been proposed and demonstrated specifically for use for 60 GHz multimedia applications [24]. These antennas function by selectively varying the phase difference between the antenna elements. Antenna gain/directivity can also be adjusted by selecting varying numbers of elements. The major downside to this scheme is that the antennas are necessarily large and expensive. Even more problematic is the very complex control and feedback circuitry required to manipulate such an antenna system. A hybrid smart antenna scheme that might provide most of benefits of a fully steerable array but with fewer elements is proposed and tested in [21].

MIMO uses the multiplicity of antennas to increase gain by transmitting and then recombining the signals in as way that maximizes the signal content. These signals include direct LOS as well as those bounced off walls, floors and other physical structures. At microwave frequencies, carrier signal power is a very expensive commodity. With each split of a signal, the power decreases by one-half, or 3 dB. Therefore, with just a few splits needed for say an 8 element MIMO, the power will be down by a factor of eight, or 9 dB. Further, since the channel environment at 60 GHz has been shown to be lossy and time variant, the benefit of multiple elements is questionable since only LOS and possibly some single-bounce signals will contribute significantly to the signal. On the other hand, delay spread from bounced signals will lead to inter-signal interference (ISI) unless proper equalization techniques are used.

A variation of the MIMO approach that uses multiple antennas for spatial multiplexing is a possible alternate approach [49]. Since the wavelength at 60 GHz is very small, multiple antennas, for example positioned on the outer cover surface of a laptop computer, would transmit different parallel data streams. An alternate idea might be to transmit the same data in parallel streams. The reverse operation would take place on the receive side. The advantages this architecture offers include higher composite data rate and increased robustness.

A dynamic, multi-beam antenna scheme can also be realized. This is different than MIMO in that only a predetermined selection of elements is used. Further, this is different than a steerable antenna in that again, only predetermined elements or combinations of elements are used at any given time. One possible realization would use a time division scheme of such a rate as to be transparent to the user. Ideally, the total time for one cycle of element selection would have to be less than the time needed to transmit one frame. Realistically, several frames duration might be needed to reach convergence and other options might additionally be needed in order to maximize PQoS. Once an optimal set of elements is found, the sequence could either stop, or occasionally refresh to check for a better condition. If a new problem in the channel occurs, the sequence would begin again immediately.

A number of PHY-based solutions have therefore been proposed specific to multi-gigabit data rates and high frequency carriers such as that for the 60 GHz band. Several of these studies have some comparison between perhaps two different schemes. For example [47] contrasts the throughput of SC-FDE versus OFDM taking into account the non-linear effects of a representative power amplifier in the transmitter front end. However, to the author’s knowledge, none of the literature has provided an exhaustive survey of PHY solutions specific to the demanding, but yet cost sensitive uncompressed HD video streaming applicable for home/consumer applications. Further, this work proposes a PHY layer classification system based on the type of modulation, the relative complexity of the system, and the theoretical comparative data rates in bits per Hz of bandwidth. The proposed classification scheme for implementation of the PHY layer is depicted in Figure 1.5.

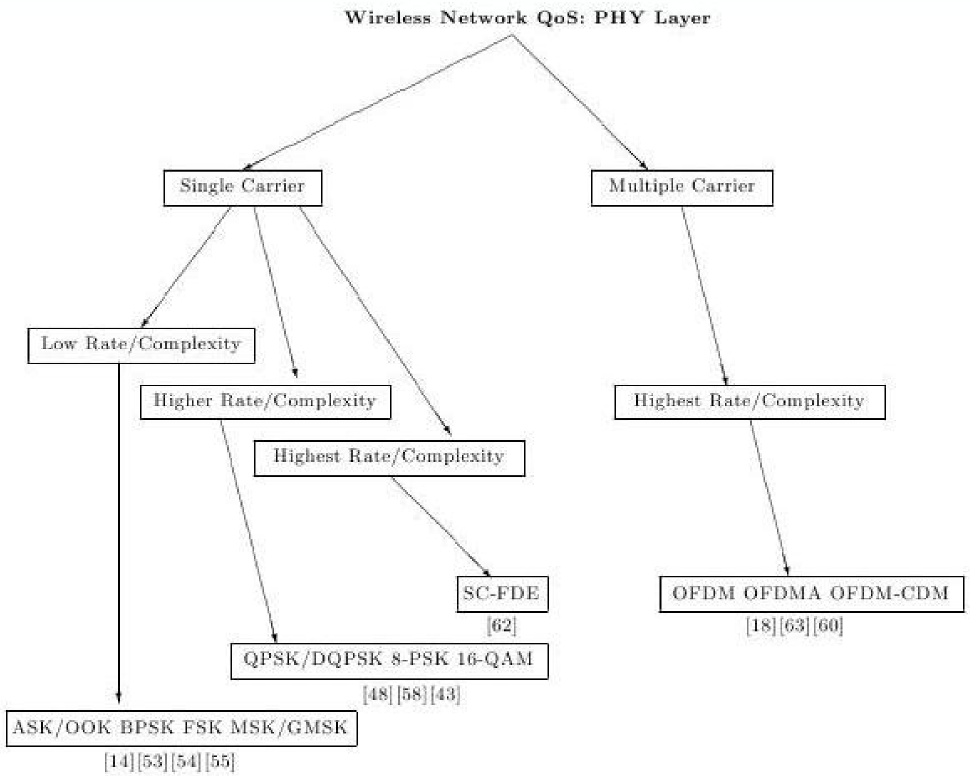


Figure 1.5: PHY Layer Classification of Proposed Solutions.

MAC Layer Solutions

The MAC layer provides the mechanisms that controls channel access and acts as the interface between the PHY and the Link layers. Specifically, channel access protocols that facilitate a fair and balanced distribution of network resources are implemented in the MAC. Packets containing the data, identification frames, forward error correction (FEC) or other correction features, beacons and so on are formed by the MAC. Device and system level security features may be supported in the MAC. Once the packets are completed, the MAC transfers them to the PHY layer where the data is sent via a physical media such as air and then transferred back up to the MAC. In summary, the MAC is responsible for establishing and maintaining a reliable link between two or more devices in a specified network.

Numerous MAC protocols have been developed to handle traffic in wireless networks. These protocols can be channel-based or packet-based. TDMA, CDMA and FDMA are examples of channel-based protocols. Packet-based protocols can be subdivided into three categories: collision recovery (ALOHA, Slotted ALOHA), collision avoidance (CSMA/CA, CSMA/CD) and collision free (polling, token ring). Currently popular protocols that are in use or being considered of emerging standards [28] for high-speed wireless networks include CSMA/CA, TDMA and Polling.

So-called hybrid MAC approaches have also been proposed. For example, in IEEE802.15.3c a hybrid MAC scheme based on TDMA and CSMA/CA is specified [79]. Contention-based CSMA/CA is used for setup and control of channel access while contention-free TDMA is used for high-speed data transmission. This hybrid scheme is reported to reduce data transmission collisions and maximize data throughput. A basic classification scheme showing candidate MAC protocols including a hybrid approach is shown in Figure 1.6.

It has been previously been indicated that higher PHY layer efficiency can be obtained with directional antennas. Several papers have proposed schemes to increase the efficiency at MAC layer for WPANs when directional antennas are used. One such scheme, proposed in [9], is a rate-adaptation based scheme to coordinate both directional and omni-directional antenna transmissions in WPANs. Further, the work proposes a directional transmission scheduling (DTS) algorithm, which is reported to enhance spatial reuse. This algorithm allows the MAC layer to control the modulation and coding schemes (MCS) at the PHY layer.

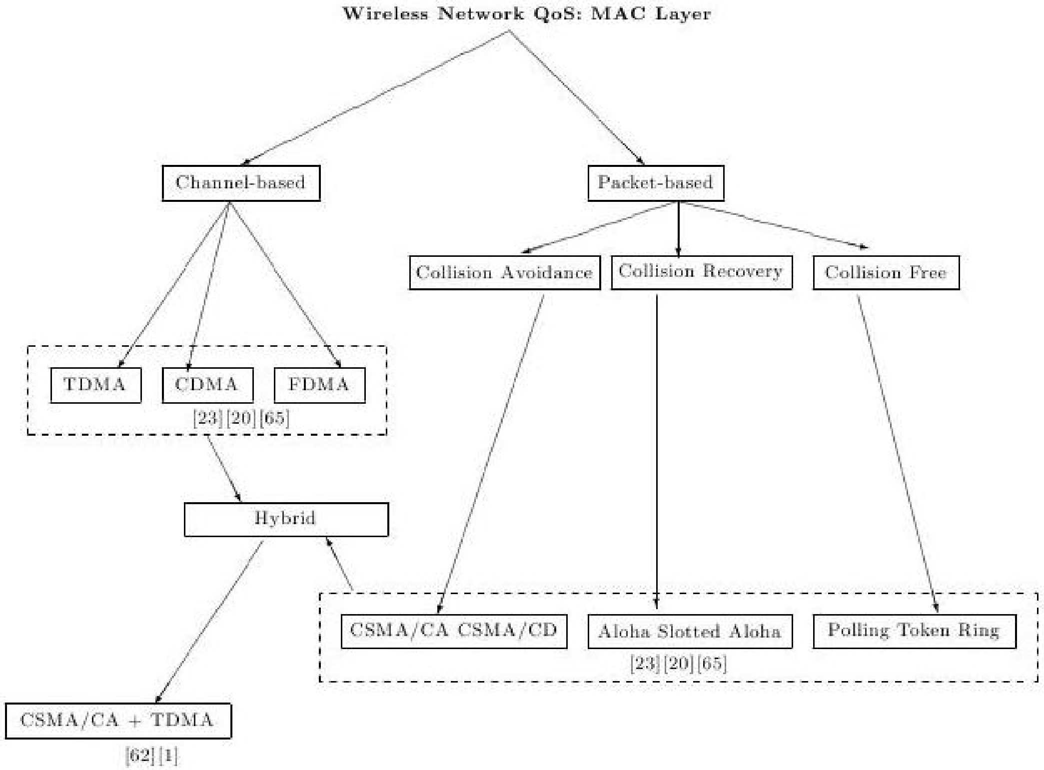


Figure 1.6: MAC Layer Classification of Proposed Solutions.

Cross-layer Solutions

Cross-layer design and optimization techniques can be used to enhance the QoS of wireless networks through a strategy of linking adjustment of specified parameters between two or more protocol layers . These techniques might be implemented by design and be static in nature or could be optimized periodically or quasi-real time and be dynamic — or a combination of the two methods [78]. Although any combination of the protocol layers can be jointly optimized, the interaction between the PHY and MAC layers is one of the most important due to the inherent time variability of the channel [8]. Therefore, this study focuses on the PHY-MAC cross-layer solution for QoS requirements through design and optimization techniques.

In general, a higher signal to noise ratio (SNR) is required to support a higher data rate modulation-coding scheme (MCS), therefore relatively more power is required at the receiver to correctly recover the received signals [67]. In actual system implementations, near omni-directional antennas can be used for discovery and network setup using a lower data rate MCS to compensate for the low antenna gain . During the actual data transmission period, a MCS having sufficient data rate capacity is switched in and directional antennas are used. For example, in IEEE 802.15.3c, the so-called common mode is a pi/4 QPSK code at a rate of 25.8 MHz. This low rate is used to establish a connection from a device (DEV) to a new or established network. This interface may involve directional or omni-directional antennas and is left up to the implementer. Once the link is established, the DEV switches to one of many available

PHY modes that can provide gigabit-plus data rates [1]. Therefore, both low and high data rate MCS are necessary for this scheme [79].

Another option along these lines is to use variable data rates and MCS options as proposed in [14]. In this model, the MCS rates would be selected primarily to allow interface between devices of different classes [2]. For example, a lower class device might have one higher rate MCS that would allow it to communicate with a higher class device – which would have a lower rate MCS in order to communicate with low class devices, and so on. The motivation behind this work was to allow compliance with developing standards while targeting an application requiring less than two Gb/s, namely the so called sync-and-go use case for downloading movies, games and other medium to high definition content from a kiosk to a portable device.

For the case of transmitting uncompressed video, retransmission of back packets is not typically feasible. However, in virtually all video images the neighboring pixels have very similar or even same values as their adjacent or neighboring pixels. This spatial redundancy can be exploited by partitioning adjacent video pixels into different video packets. Since channel errors are typically uncorrelated, successfully received video packets can be leveraged in concealing an erroneous video packet from the same or nearby pixel region. Therefore, if one or more packets is lost or corrupted, packets containing adjacent pixel information can be used to recover the lost data. A similar alternative recovery method is to use an average of all neighboring pixels to recreate the missing pixel [65]. Further, certain pixels can be construed to be of higher importance. For example, the pixels near the center of a monitor are subject to higher scrutiny from a viewer than those at the monitor edge. A scheme that is based on unequally error correction (UEP), relative to the perceptual importance of the pixel region, is proposed in [63]. This scheme is reported to help in providing error concealment for corrupted pixels only and may increase the MAC/PHY efficiency in terms of effective the peak signal to noise ration (PSNR). Two unique schemes that are somewhat more complex are proposed in [67]. In the display random pixels (DRP) scheme, pixels received in error are replaced by randomly generated pixels. The Reed-Solomon code swap (RRS) scheme is more complex in that in addition to using error-free RS codes from uncorrupted adjacent packets to reconstruct erroneous data, cross-layer feedback from the PHY to the MAC layer is used.

More advanced cross-layer design using adjustable MCS and corresponding data rates and spatial redundancy techniques in conjunction with adaptable antenna schemes can be implemented [65]. This work proposes a combination of three interwoven cross-layer schemes to provide sufficient QoS even in NLOS scenarios. First, a pixel partitioning scheme is used for correction of lost or corrupted pixels. This is a similar concept as previously described in this section. Next, a multi-beam transmission mechanism using a refined version of the adaptive multi-beam antenna concept is presented. The work describes possible allocation plans for distributing the data on multiple elements. Specifically, for the case of two elements, three such plans are identified. First, assuming that one element is sufficient to transfer data at required QoS, the second element would be redundant and would provide robustness to the system. Second, if the two beams are found to have similar channel conditions, the data would simply be split evenly between the two. Third, if conditions were such that one element was much better, but the second was adequate to provide sufficient assistance to the first, that in the combination of the two, adequate QoS would be achieved. In this case, the data would be be unequally allocated between the two elements. Finally, a format adaptation scheme is proposed to be used in conjunction with the two previously described schemes. This scheme adaptively adjusts video resolution in conjunction with adjusting the MCS and data rate for a reduced channel quality condition. The adjustment parameters are designed such that minimal if any loss of PQoS will be observed. Further, the adjustments would only be required for short-term channel variations. Once the channel is back in a static state, the antennas will find the best path(s), the MCS and data rates will maximize throughput and the format adaptation scheme will not be active. Of interest perhaps is how these mechanisms might actually be implemented in a quasi-real-time environment targeted towards consumers’ electronics.

In order to provide a means of evaluating the potentially complex and extensive cross-layer solutions, I propose a task-orientated classification system as depicted in Figure 1.7. This system was selected because there are two basic requirements for the uncompressed streaming multimedia application discussed here. First: establishing the network through channel access protocols. Once the network is established, the idea is to maximize throughput while maintaining an established minimum QoS at the network level. This task can be described as the data transmission component of the wireless networking model. The figure indicates that the most beneficial area for application of cross-layer techniques is at the data transmission task.

A brief description of the need for very high-speed wireless networks for cost-sensitive applications is presented. The 60 GHz unlicensed band is proposed as a very viable solution primarily because of the enormous bandwidth availability. Recent advances in key technologies however will allow creative designers to mitigate, and possibly even leverage, the channel characteristics at 60 GHz.

An overview of the layer structure is presented and discussed. Details of the MAC and PHY layers and the significance of MAC/PHY cross-layer design and optimization is presented. Next, specifics of proposed implementations for both the MAC and the PHY layers, along with high-level classification schemes are presented. Finally, present art in the area of MAC/PHY cross-layer is presented along with what I suggest might be an insightful MAC/PHY cross-layer classification scheme. The proposed classification attempts to visually show what areas are prime candidates for natural implementation of adaptive cross-layer solutions.

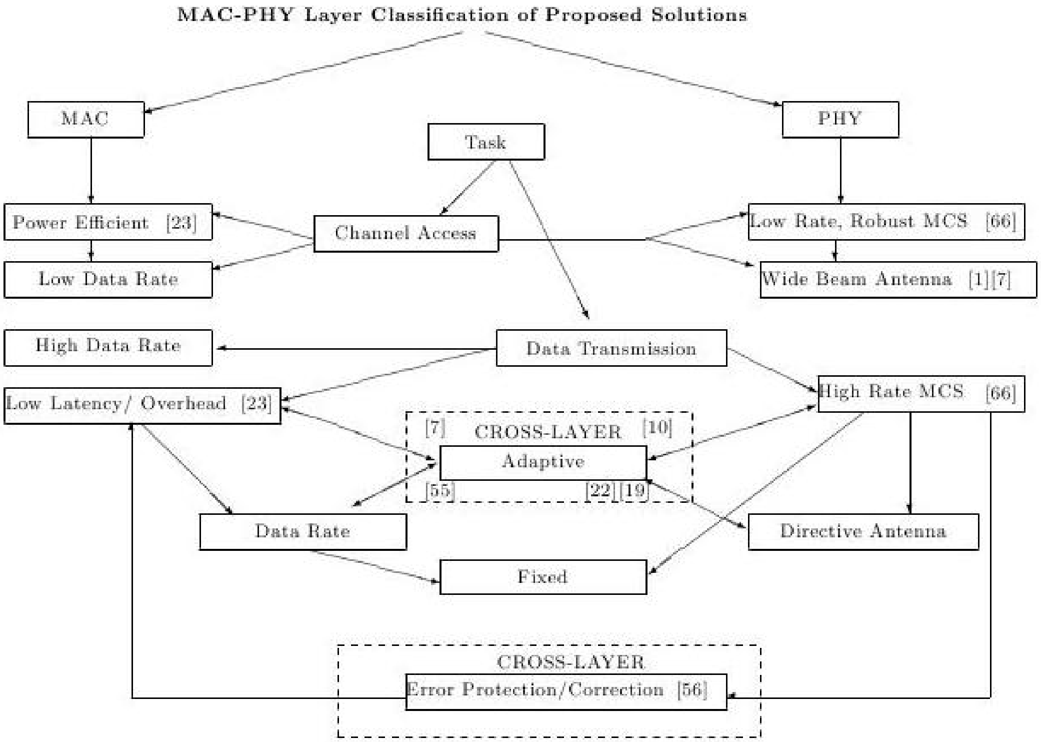


Figure 1.7: MAC-PHY Layer Classification of Proposed Solutions.

Thesis Outline

This thesis is arranged as follows: Chapter 1 discusses the background and motivation behind this research. The chapter provides an in-depth overview of the requirements, challenges and potential benefits of the utilizing the available 60 GHz radio channel. Chapter 2 is a review of literature specific to PHY-MAC adaptive cross-layer design and modeling in addition to a review of the more generalized literature discussed throughout Chapter 1. Chapter 3 provides details of the requirements, strategy, design and implementation of a functional, adaptive cross-layer algorithm. Chapter 4 begins with a brief description of the implemented scenarios and the video reference sequence used for the simulation This section goes on to discuss the simulation parameters and then displays and thoroughly analyzes each of the simulations. The chapter concludes with a discussion of the results. Chapter 5 summarizes this research and suggests topics for future research.

Chapter 2

LITERATURE REVIEW

Discussion

The literature presented in Chapter 1 of this thesis indicates that a good amount of work has been done in the areas of the MAC and PHY layers specific to uncompressed multimedia streaming at gigabit-plus rates. Most of the works are directly related to a standard or other organization and are often tied to a group attempting to leverage a specific approach to the wireless network problem. I have shown that there are a few comparative analysis for PHY-layer design options. For example, in [47] a comparison of SC-FDE and OFDM is presented. In the area of the MAC layer, most comparative results are high-level, text book-type summaries of the various MAC protocols currently being studied for use in such wireless networks [28].

A number of papers in the area of MAC-specific design for optimized performances for this application are available. The majority of these are focused on frame design at the MAC level. A rate-adaptation scheme is propose in [9]. However, it turns out that the work proposes a high level and low level rate with corresponding directive and omni-directive antennas. The low rate/omni case would be used for discovery and network setup while the high/rate would be used for data transmission. This is the same concept that was proposed for use in the IEEE 802.15.3c standard [1] and provides no real-time optimization of system throughput. Rate adaptation is discussed in [33] and includes a description of "adaptive modulation coding". However, this work focuses existing and emerging mobile networks that operate using cellular technologies and delivers content from 10’s of Kb/s to about 14 Mb/s. Common techniques such as compression and retransmission of any lost or erroneous frames is possible. Further, the work reports that the so-called adaptive rate is set before hand, depending on the level of QoS expected for a specific service.

In the area of MAC/PHY cross-layer, much literature has been devoted to this subject but almost all for lower rate, less demanding applications. Only recently has cross-layer design and optimization been looked at for the applications described in this document. One work that appears to have a great deal of potential is found in [65]. This work addresses key areas for low-cost, realistic systems that might be able to provide adequate QoS for the average consumer. However, though the paper states that they did some simulated evaluations, only a very few results in the text are given.

A relevant paper that was just recently published [53] does propose a somewhat similar approach –to what this thesis proposes–for an adaptive PHY-MAC design for uncompressed video streaming. The work outlines an algorithm that uses QPSK and 16-QAM over a dynamically changing environment, similar to what this thesis addresses. There exists however several major differences than what is proposed in this thesis. First, the work proposes the use of OFDM for the modulation scheme, QPSK and 16-QAM being the core modulation schemes for implementation of OFDM. Next, the work does not suggest or show an actual method of how this will be implemented in a real system. Further, the paper proposes a combination of unequal error protection (UEEP) in conjunction with equal error correction (EEP). I agree with their findings in this area. That is, for very low-level BER rates, UEEP seems to provide better PSNR values, although literature at large is mixed on this issue. My conclusion however was that UEEP was not worth the effort in terms of implementation as only very modestly sized frames could even be processed using the remote (Citrix) version of Matlab. This version is available through the ASU Applications site for current students. The remote version is required due to necessity of the Communications and Fixed Point Toolboxes for the calculations performed in the various algorithms and functions that are not available on the down-loadable versions. This implies that hardware requirements required to facilitate such complex data manipulations will be costly if achievable at all in consumer-level products. Finally, the work does not specify what RF band they are supposedly employing, and if this is the 60 GHz band, associated issues are certainly not addressed.

Summary and Suggested Research Topics

Shortcomings of previous works specifically in the area of MAC/PHY cross-layer solutions for relevant application, as described in this document, suggest several possible topics for a Thesis. The area of adaptive MAC/PHY cross-layer design, specifically for 60 GHz, multi-gigabit wireless networks appears to be a topic that is ripe for further research. Work in this area should include performance enhancements as well as the trade-offs between static and adaptive techniques. Additionally, further work to develop the cross-layer solutions that are suggested by Fig. 1.7 in this paper could lead to one or more possible algorithms to facilitate these solutions. A series of simulations showing relative QoS results for various combinations of the solutions would be completed. These could potentially consist of both static and dynamic realizations. The simulations should provide the necessary data to support the proposed MAC/PHY cross-layer solution or lead to a modified or alternate proposal as the data dictates.

My Thesis Advisor, Dr. Martin Reisslein and I discussed the above topic set, and seeing that there appears to be a gap in published literature on this topic, concluded that this would be a good topic for my thesis. Empirically, from previous personal experiments and experience and from available literature, an adaptive implementation that uses the PHY and MAC layers of a high rate, sensitive wireless links should benefit from a low-complexity adaptive cross-layer design methodology. How much benefit and at what cost, what the trade-offs are and how readily could this be implemented into consumer-grade hardware are a few of the questions that will be addressed.

Chapter 3

CROSS-LAYER ALGORITHM DESIGN AND IMPLEMENTATION

Networking Requirements and Constraints

The basic requirement for any wireless network is establishing a link from the transmitter to the receiver with a sufficient amount of power in the data stream to be correctly recovered. Signal to noise (SNR) ratio is the fundamental measure of this requirement. Bit error rate (BER), a function of SNR, is a key metric for any communication system. For an implementable, consumer-orientated system transmitting multi-gigabit data streams using the 60 GHz band, a limited set of options is available to correct or adjust for varying channel conditions that could jeopardize the minimum SNR necessary for the desired level of QoS.

As discussed previously, the most readily available system parameters for this application include the modulation scheme, the implementation of any coding and the use of some type of directional antenna that can overcome – or at a minimum reduce to an acceptable level– any severe channel blockage and subsequent fading. Since the BER, as well as occupied bandwidth for a given data rate, is related to the type of modulation used, this parameter for a fixed bandwidth can easily be envisioned to provide a degree of scalability for a changing channel condition. Initially, 16-QAM, 8-PSK, QPSK and BPSK of various rates were candidates for inclusion in the adaptive modulation portions of the adaptive cross-layer algorithm. A study was subsequently undertaken to down-select which modulation schemes and which full and/or partial rates should be included. The key requirement for this set of parameters was that the resulting schemes and rates would provide a reasonably smooth upward – and downward– transition in terms of BER and data rate. Schemes and rates that overlapped or provided a minimal benefit in terms of BER versus throughput were eliminated.

An addition requirement was the ability of the scheme and rate to allow for transmission of high definition (HD) video. This document targets the rates from 1280x720px30 frames/s (0.976 Gb/s) through HDMI (1.2) at 4.455 Gb/s. Note that these are raw, uncoded data rates. Therefore, only schemes and associated data rates that would meet these requirements were selected. Further, schemes such as 64-QAM, OFDM and others were not chosen for reasons outlined in the background section. One may notice that the proposed 16-QAM data rate is 5.0 Gb/s while HDMI (V1.2) requires 4.455 Gb/s plus any coding overhead. In fact 16- QAM is capable of 6.912 Gb/s when fully utilizing the available 2160 MHz channel as defined in 802.15.3c [1]. However, it turns out that with packet-level data and coding plus (optional) RS coding overhead that 16-QAM cannot quite meet this specification– and remain under the 2160 MHz bandwidth requirement. However, this mode is retained for reference purposes and to represent the mode that would be selected – except for the need for pixel-level coding – for the case of a wide open, very low loss channel.

The selected rates for all modulation were purposely selected to scale conveniently by a factor of 2x for the case of increasing data rates – and of course by 1/2 in the downward direction. This is a realistic approach and could be used in a consumer-grade video transfer system.

Adaptive Cross-Layer Design Strategy

The base code was targeted to provide a means of adjusting, through an adaptive process, 1) the link margin to meet a set minimum and then 2) to maximize the data rate in order to provide the highest possible QoS for the proposed HD wireless uncompressed video use case. This use case is similar as that defined in IEEE 802.15.3c, ECMA,

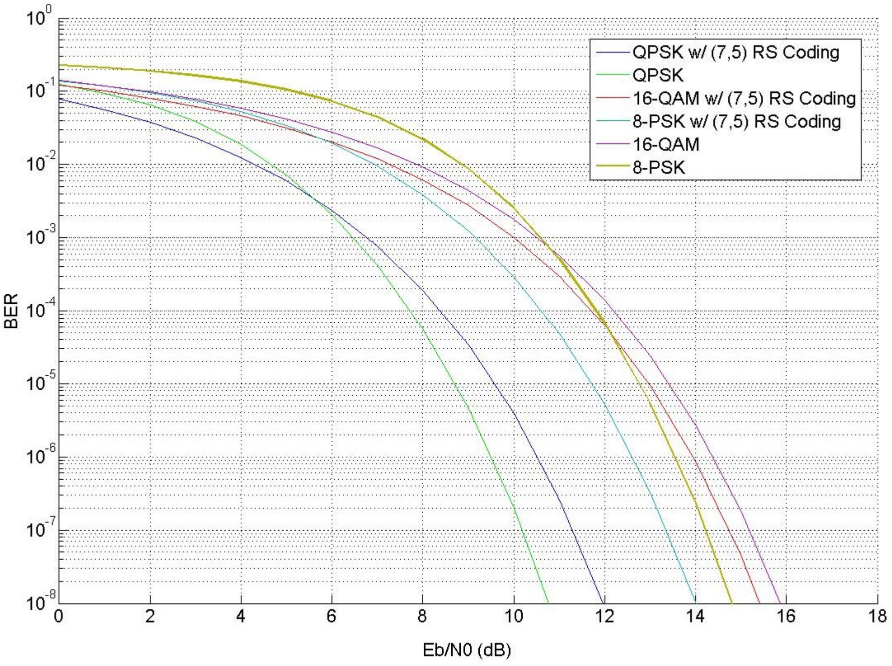


Figure 3.1: BER vs. Eb/No for Selected Modulation Schemes.

and other giga-bit standards utilizing the 60 GHz band. Number 1) and 2) are implemented using an adaptive modulation and coding (MCS) scheme. By falling back to lower rates, more robust modulations schemes can be used to provide higher PSNR under temporarily adverse channel conditions. As the channel conditions improve, the MCS rates would adaptively adjust upwards until full-rate is again achieved. This is augmented by the option of using a scanning antenna implementation.

It should be noted that the vast majority of code was written by scratch by the author. Much of this code relied heavily on Matlab help examples. The only two functions that were not written from scratch were the PSNR calculation function (for bitmap images) and the yuv to rgb transformation routine for images- which I have acknowledged per the authors’ instructions. It should also be noted that this work is not a demonstration of Matlab expertise. Matlab is simply used as a tool to demonstrate the proposed adaptive scheme.

The primary outputs of the code are 1) link margin (LM) versus excess path loss (EPL), PSNR vs. LM, EPL, number of iterative steps and bit rate. EPL is essentially the attenuation caused by by the movement of humans around in the the transmit to receive beam. Other factors, such as furniture and so on would be minimized to some degree with favorable placement of the transmitter. Residual fixed losses would be calibrated out during a learning phase at power up.

Model Implementation and Associated Parameters

A simplified, high-level flow chart representation of the full-adaptive algorithm is shown in Figure 3.2. The code consists of two primary loops and several secondary loops as well as three functions. The first primary loop is entered if the new excess path loss (EPL) is such that the link margin, as calculated with the parameters carried over from the previous frame, is less than the minimum link margin. When this is the case, the algorithm will attempt to maximize the link margin by decreasing the data rate by selection of modulation schemes. If no higher order and rate modulation scheme will meet this criteria, the algorithm defaults to 1/2 rate QPSK. If the link remains lower than minimum link margin, the adaptive antenna option and the Reed-Solomon coding option are enabled. If the link is lower even for this very robust combination the data is processed and warning message is displayed. This represents the best effort to provide PQoS and depending on that requirement and other variables may meet this objective. Details of the link margin calculations and associated available data rates for BPSK, 1/2 and full rate QPSK, 8-PSK and 16-QAM are included in the Appendix.

If the first loop can successfully meet the minimum link margin requirement, then the algorithm attempts to increase the data rate. This occurs only if the first loop does not resort to the last case, that is, 1/2 rate QPSK, adaptive antenna and coding. The increase in data rate is accomplished by comparing the present link margin with the minimum link margin. The next modulation and rate is selected from this comparison and then the new link margin is calculated. The comparison factors are selected and arranged such that a minimum number of steps is required to maximize the data rate.

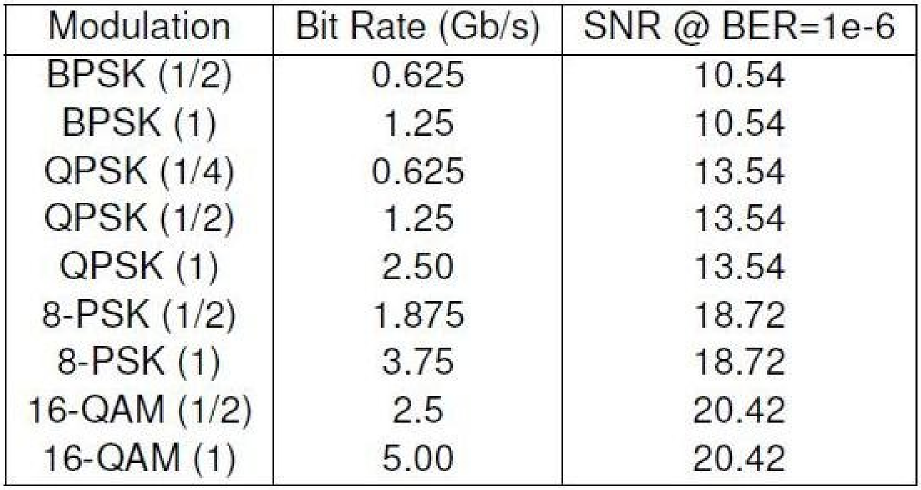
Once the data rate is at a maximum, the PSNR calculations take place. Recall that an alarm function that is at or above the minimum link margin level is featured in the adaptive and quasi-adaptive algorithms. The alarm is now used to decide whether to encode the data or not. If the link margin is above the alarm level, no encoding is enabled. A function is called that adds the appropriate number of errors to the data and re-assembles the data but does not attempt to correct the errors. If the link margin falls below the alarm level, coding is enabled. A similar function as above is called but in this case the data is decoded and all correctable errors are handled. Depending on the number of errors set by the user, there may or may not be residual errors after completing this step. For the simulations presented here, the maximum number of correctable errors per line per frame is 80. I selected 88 errors, which is 10 percent above the maximum correctable. The reasoning behind selecting a higher value is to to ensure the possibility of obtaining some errors even when the data is coded. Of course the probability of errors is modified to reflect the selected number of errors. Details of the probability of error calculations are included in the Appendix.

An additional processing step in calculating the PSNR is required for any data rates that are below the maximum, that is , 16-QAM at 5.0 Gb/s. A means of providing a back off of the actual amount of streamed data proportional to the back-off of the transmitted data rate is needed. This is implemented by eliminating a number of frames and then comparing the actual data with the closest previous frame – for a certain percentage of the total frames [69]. Depending on the back-off rate, the probability of having to compare the frame with a previous frame changes. For example, for 1/2 rate QPSK, the probability is three out of four (75 percent) that the data frame will be compared with a previous reference frame. Other possible ways to achieve this back off of transmitted data are certainly possible. For example the number of pixels per frame could be adjusted or the coding rate could change and so on. The simplest method is to reduce the number of frames. This strategy would be implementable for the very high data rates covered here, others may not be so easily implementable due to the sheer speed and quantity of data that would have to be processed.

Several studies have concluded that for many types of video PQoS is less sensitive to moderate frame rate back-off than to a decrease in frame resolution [38, 11]. For example [38] concludes that a 50 percent rate back-off from full rate – 25 frames per second – produces MOS scores around 4.25 compared to 4.4 for full rate. An additional 50 percent decrease, that is 1/4 rate, caused a modest decrease in MOS to about

3.75, but still quite acceptable. The MOS begins to drop quite quickly below 1/4 rate, for example for 1/8 rate the MOS is below 2.25. These findings further support a methodology that adaptively scales the frame rate as needed to maintain the highest PQoS.

An adaptive coding plan was also considered and implemented in the adaptive algorithm. In actual implementation, the coding rate could vary in proportion to the probability of frame corruption [35]. In the demonstrative algorithm, I simply either implement the Reed-Solomon code or do not implement the code to simulate an adaptive process. Error correction codes are often used along with a sufficiently strong rate frame-level code such as CRC-8 that would provide packet error or loss detection with minimal overhead [62]. For multi-gigabit uncompressed video applications, error detection will not suffice since the possibility for



Modulation	Bit Rate (Gb/s)	SNR @ BER=1e-6
BPSK (1/2)	0.625	10.54
BPSK (1)	1.25	10.54
QPSK (1/4)	0.625	13.54
QPSK (1/2)	1.25	13.54
QPSK (1)	2.50	13.54
8-PSK (1/2)	1.875	18.72
8-PSK (1)	3.75	18.72
16-QAM (1/2)	2.5	20.42
16-QAM (1)	5.00	20.42

Table 3.1: Initial Candidate Modulation Schemes. Criteria included ease of implementation, sufficient bit rate for "high definition" video and efficient scalability in terms of both bit rate and BER.

retransmission of data is either very low or zero. Therefore, an error correction code such as Reed-Solomon, Hamming or other similar types are used. The frame-level coding is required to guarantee that the frames, including information on modulation scheme, data rate, error correction status, antenna steering/beam forming status, frequency domain equalizer codes and other data is successfully received. I use RS(31/21) with a net coding gain at a BER of 5e-5 of 2.75 dB. Pixel-level adaptive code is meant to guarantee a minimum QoS despite statistically severe channel conditions. Plainly, using up valuable bandwidth, if not absolutely required, is contradictory to efficient system implementation. That is, if the link margin indicates that the maximum possible data rate with no back off due to optional coding is needed, then this could be considered to be optimum assuming no degradation due to other interwoven factors [12]. Finally, there simply may not be sufficient available bandwidth for maximum data rate transmission with along with the necessary overhead due to a sufficiently robust coding scheme. The included 16-QAM with packet overhead plus RS coding algorithm that exceeds the proposed bandwidth limits of 2160 MHz demonstrates this.

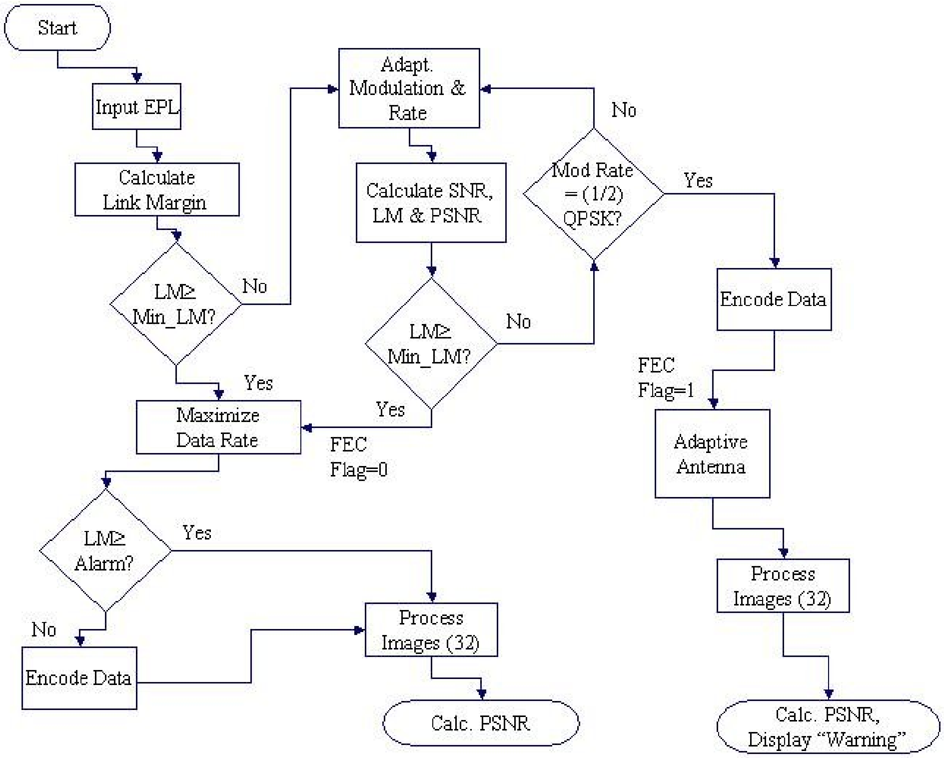


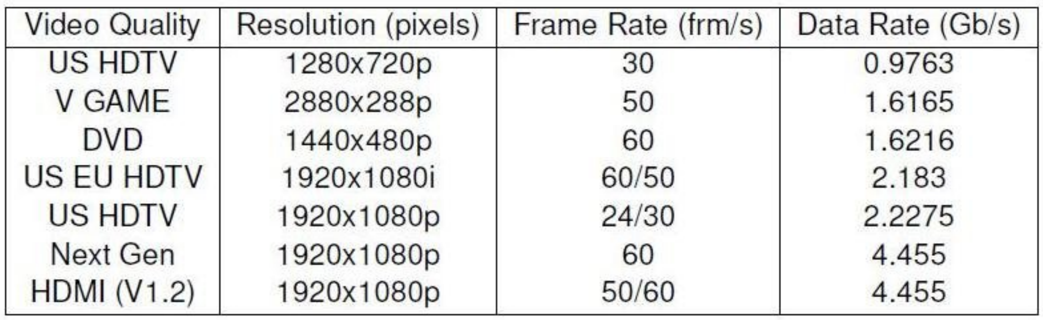
Figure 3.2: Flow chart representation of full-adaptive algorithm.

Modulation	Gb/s	SNR@BER=1e-6	SNR@BER=1e-5	SNR@BER=5e-5
QPSK (1/2)	1.25	13.54	12.60	11.80
QPSK (1)	2.50	13.54	12.60	11.80
8-PSK (1)	3.75	18.72	17.75	16.90
16-QAM (1)	5.00	20.42	19.46	18.60

Table 3.2: Final Modulation Scheme Selection.

Typical industry standard rates for FECs are 2/3, 3/4, 7/8 and other short sequence codes. I experimented with several different rates. Again, the idea is to maintain a minimum QoS which in addition to the relative number of errors per frame requires an certain number of frames/pixels in order to a portray "high definition" video experience. Since Matlab only allows n values such as $n = 2^m - 1;m = 3; 4; 5:::;$ the best short code is RS

5/7 bit-level coding for the optional code since it appears to offer the best trade-off of FEC gain versus added overhead. However, due to the restriction in the n value as mentioned, and the fact that we must fix m=8, for Matlab implementation the optional coding of the 351x288 pixel image stream was actually RS (511, 351). This ratio is close to 7/5. In an actual system, these limitations would be removed.



Video Quality	Resolution (pixels)	Frame Rate (frm/s)	Data Rate (Gb/s)
US HDTV	1280x720p	30	0.9763
V GAME	2880x288p	50	1.6165
DVD	1440x480p	60	1.6216
US EU HDTV	1920x1080i	60/50	2.183
US HDTV	1920x1080p	24/30	2.2275
Next Gen	1920x1080p	60	4.455
HDMI (V1.2)	1920x1080p	50/60	4.455

Table 3.3: Data rate requirements for various high definition video resolutions.

Chapter 4

SCENARIOS, SIMULATIONS AND RESULTS

Channel Model Scenarios and Reference Sequence

In order to evaluate the proposed adaptive algorithms, I have developed three "scenarios" simulating various channel conditions. The primary scenario is the so-called realistic model. This is based on measured and simulated data for 60 GHz channels with 1 or more humans in motion in or near the transmit to receiver path . The maximum fade for this model is 28.5 dB and is characterized by a Rayleigh distribution, [52]. The second scenario is the ramp - using the same data as used in the realistic scenario, but the data points simply ramp up to a maximum and then back down to a minimum. Finally, I propose the random scenario - again the same data, but organized in a random order.

A variety of different images and sequences were used to evaluate the algorithms. Early on, the test images were composed of murals of overlapping images cropped from a single, large high definition image. The reason for using these images was because the Matlab code was specifically written to handle bitmap images. I could not find any video clips that were in bitmap format. However, I eventually did find a Matlab routine that could perform a yuv to rgb transformation. With this code plus and an addition post transformation frame -by-frame modification step, I was able to obtain bitmap-formatted video clips of the standard test sequences "ElephantsDream" and "BigBuckBunny". 32 frames from each test sequence are used to evaluate the proposed algorithm. This represents one second of real-time video. Frames were selected from what I considered to be among the most interesting visual portions of the full video clips sequences.

A series of simulations of the full-adaptive algorithm, various subsets of the full-adaptive algorithm and a non-adaptive algorithm were planned and performed. The full-adaptive algorithm included the modulation schemes and data rates as summarized in Table 4.1. The full-adaptive algorithm also included a Reed-Solomon coding option and the scanning antenna option. These options are implemented by an alarm flag which is set above the minimum link margin. For this demonstration, the alarm value is fixed at 3.0 dB while the minimum link margin is set at 2.25 dB, For example, if the environment is found to be fairly static, the alarm may be set as per the example, i.e. 3.0 dB. Now say the environment is found to be very dynamic. The system may increase the alarm level thereby smoothing out the variation in the image quality. A comparison of PSNR for the full-adaptive case (simulation 7) with the alarm function and with the alarm function disabled is shown in Figure 4.3. Regardless, the coding and scanning options are designed to be implemented as a final step in attempting to obtain an acceptable PQoS. A summary of simulations and adaptive techniques are shown in Table 4.1.

Figure 4.1: Example frames from the sequence "ElephantsDream". [3].

Figure 4.2: Example frames from the sequence "BigBuckBunny". [3].

Simulation Parametric Study

18 simulation set-ups were identified and are listed in Table 4.1. The first nine use the "ElephantsDream" (ED) video sequence. Simulations one through three consisted of a 16-QAM and fixed coding, non-adaptive implementation. This was repeated for the realistic, ramp and random channel model scenarios. This set of simulations represent the implementation that most single carrier proponents would suggest – namely a high level modulations scheme supported by strong coding

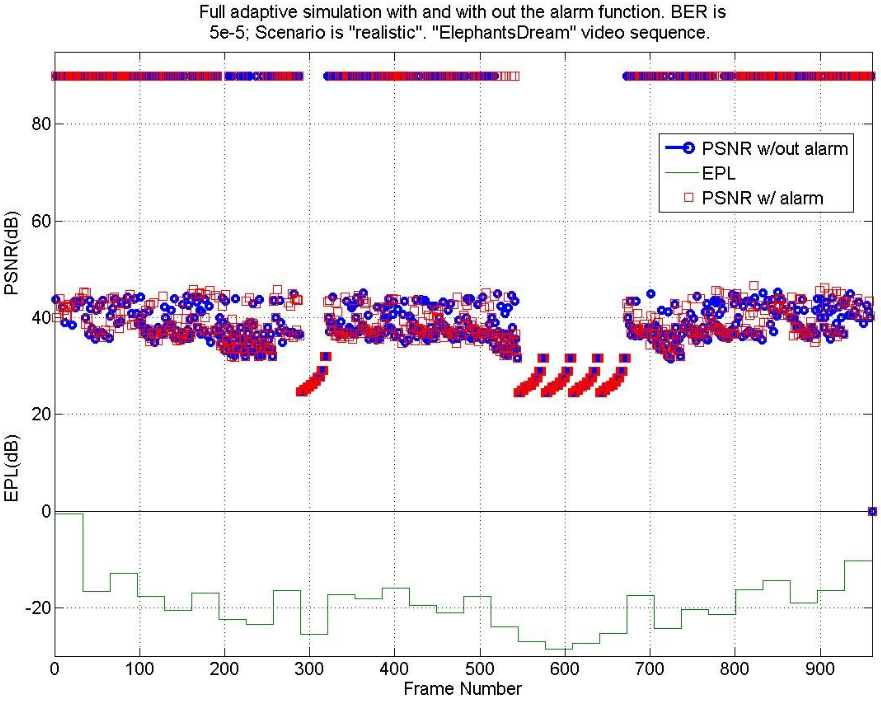


Figure 4.3: PSNR for the full- adaptive simulation with and with out the alarm function.

The fourth through sixth simulations implemented what could be referred to as a hybrid or quasi-adaptive approach. 16-QAM was again used, but this time with no optional coding. 1/2 rate QPSK with optional coding and adaptive antenna implementation was the adaptive component for this simulation. Note that this simulation is not that much different than that for the full adaptive case. The idea behind this experiment is to evaluate the gain (if any) in PSNR for the case of multiple intermediate steps between the extremes.

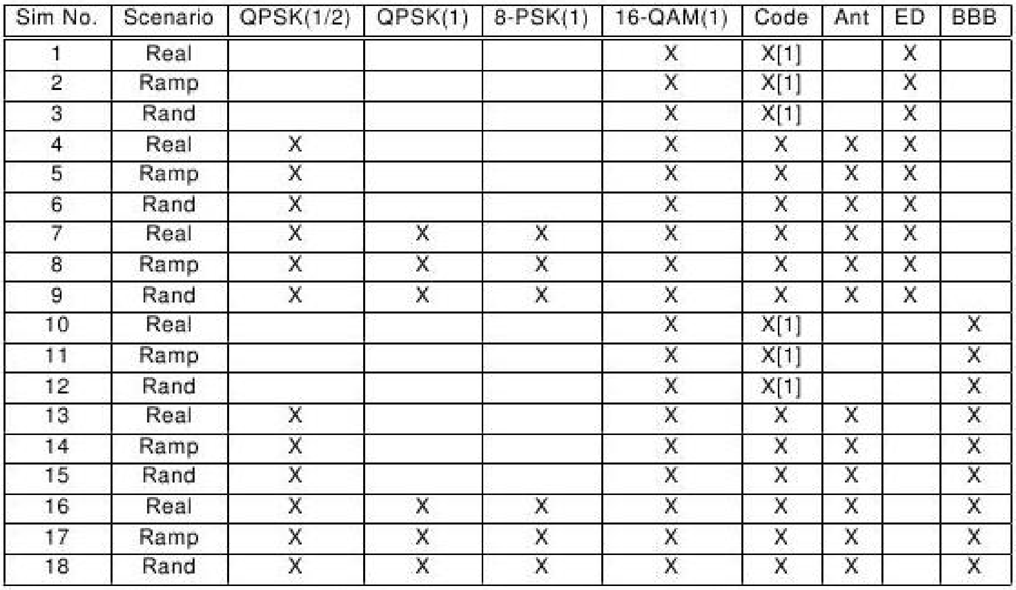
The seventh through ninth simulations implemented the full-adaptive algorithm, again using the realistic, ramp and random scenarios respectively. This set of simulations is meant to represent the baseline standard for the proposed adaptive cross-layer scheme.

This set of nine simulation set-sups are subsequently repeated using the “BigBuckBunny" video sequence. Refer to Table 4.1 for simulation details.

Additional common parameters for this set of simulations include a BER of 5e-5. This may seem rather high, but in order to obtain a meaningful number of errors in a reasonable simulation time, I found this to be a good compromise. However, a comparison of simulations versus BER might be instructive. A limited subset of the simulations defined in Table 4.1 will be simulated for other BER rates later on in this section. As described elsewhere, the reference videos are 32 frames of the "ElephantsDream" sequence for simulations 1 through 9 and the "BigBuckBunny" sequence for simulations 10 through 18. The 32 frame sequences were repeated for a total of 960 frames.

Assumptions

A key to any scientific process is to minimize, or at the very least, identify and support any assumptions. For these simulations, two key assumptions had to be made. First, the channel model loss characteristics in dynamic family room environment had to be obtained. As described elsewhere in this thesis, measured data for 60 GHz transmission exists. However, most of the data is targeted for other applications such as in office environment – with doors, cubical walls and so on – or in home, but typically for a wireless LAN type of scenario. I could not find any data that fit my application specifically, that is for a one way, end-to-end use case. I ended up using the results found in [52] to create a set of data point using a Rayleigh distribution and meeting the statistics of S6 – two persons walking back and forth between the transmitter and receiver antennae at 1.0 m/s – of that work. I further compared the loss data to that found for an in-home, but again multi-user case, found in [68]. I also referred to the data found in [34] that that reports that model using a human 80 cm from the receiving antenna resulted in 10 to 30 dB of signal attenuation.



Sim No.	Scenario	QPSK(1/2)	QPSK(1)	8-PSK(1)	16-QAM(1)	Code	Ant	ED	BBB
1	Real				X	X[1]		X	
2	Ramp				X	X[1]		X	
3	Rand				X	X[1]		X	
4	Real	X			X	X	X	X	
5	Ramp	X			X	X	X	X	
6	Rand	X			X	X	X	X	
7	Real	X	X	X	X	X	X	X	
8	Ramp	X	X	X	X	X	X	X	
9	Rand	X	X	X	X	X	X	X	
10	Real				X	X[1]			X
11	Ramp				X	X[1]			X
12	Rand				X	X[1]			X
13	Real	X			X	X	X		X
14	Ramp	X			X	X	X		X
15	Rand	X			X	X	X		X
16	Real	X	X	X	X	X	X		X
17	Ramp	X	X	X	X	X	X		X
18	Rand	X	X	X	X	X	X		X

Table 4.1: Details of simulations. [1] denotes that all data is encoded for the case of 16-QAM full rate. Real, Ramp and Rand indicates the realistic, ramp and random scenarios respectively. Code means Reed-Solomon pixel-level coding. Ant is the adaptive antenna implementation. ED denotes the "ElephantsDream" sequence while BBB indicates the "BigBuckBunny" sequence. All simulations referred to in this table use a BER of 5e-5.

The Random Waypoint model is used in [68] to formulate an WPAN model at 60 GHz. However, the only useful data shows results for two different wireless terminals (out of several evidently modeled) and these happen to be very poor performers with about 40 dB of loss. Note that this model is for the so-called Super Bowl party scenario and includes the models representing eight people moving about the room. This feature of this work is excellent and very in-line with the scenario described in this thesis. The other major problem with the work is that it is addressing a multi-user network use case with the wireless terminals scattered about the room, but with access point(s) strategically located. Other wireless terminals appear to have much better performance than the two that specified identified in the loss figure. This can be seen in the connectivity consistency plots show in the work.

For the scenario described in this thesis, the transmitter would be fixed and placed in a somewhat-to-very favorable position in the room. The receiver would also be fixed. Initially, the receiver might be a separate unit(s) from the monitor/television. For example, the antenna/RF front end might be in appearance and size similar to a video game antenna and could be attached using double sided tape and so on to the top of the monitor. The rest of the receiver would be in a separate box and reside wherever might be convenient. Both units could be powered via USB or other means. Over a longer term, the receiver may well be integrated

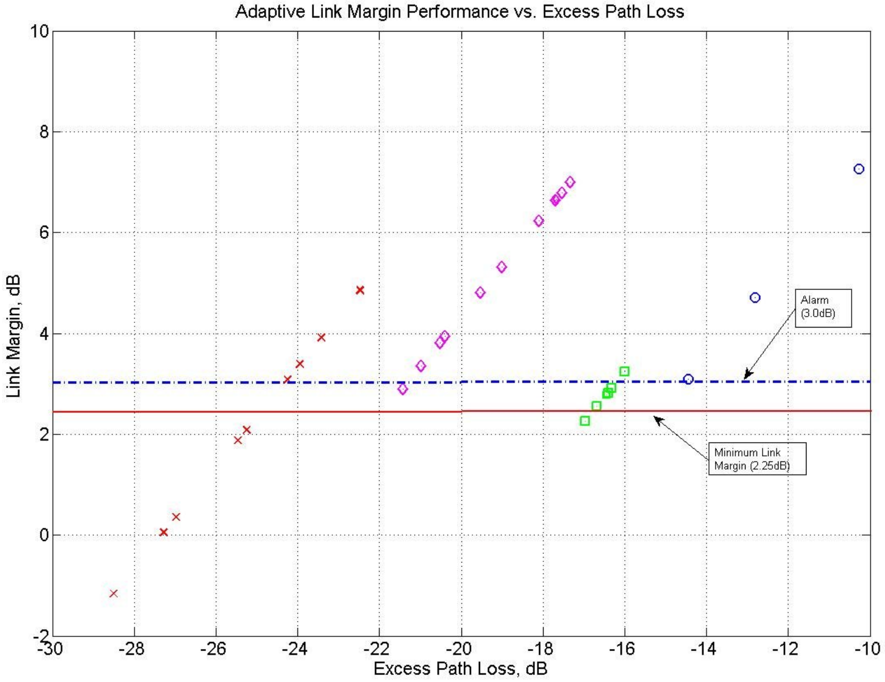
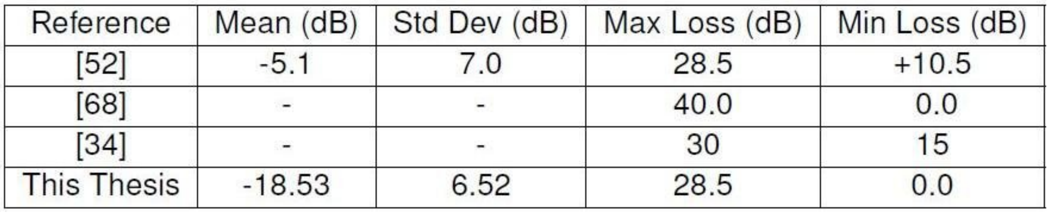


Figure 4.4: Link margin versus excess path loss for adaptive case. This portrays a typical example of the core algorithm. In this figure, the red ’x’ denotes that the algorithm selected 1/2 rate QPSK as the modulation scheme. Similarly, the magenta diamond represents full rate QPSK, the green square is 8-PSK and the blue circle denotes 16-QAM.

directly into the monitor/television. One other note on the data is that I removed data points –other than the two lowest points at each end – of between zero and -10 dB. The justification is that for EPL levels in this range, any of the simulation techniques will generate few if any errors. Therefore these EPL points were eliminated and the number of points in the region of interest were increased. This resulted in the mean value being much lower than what the references propose. In conclusion, I relied heavily on [52] and support this by the other references. Table 4.2

summarizes the channel loss statistics that is available in literature along with the data that is used in the simulations in this thesis.



Reference	Mean (dB)	Std Dev (dB)	Max Loss (dB)	Min Loss (dB)
[52]	-5.1	7.0	28.5	+10.5
[68]	-	-	40.0	0.0
[34]	-	-	30	15
This Thesis	-18.53	6.52	28.5	0.0

Table 4.2: Comparison of statistical channel model loss due to human body interference and movement data.

The other assumption is in the area of the system gain that can be obtained through the use of a relatively simple "steerable" antenna scheme. For this information, I relied heavily on the very limited published data and extracted a conservative model based on this information. The best data I found was also in [34]. The work shows that a steerable beam antenna can produce up to 14 dB of "excess gain" for regions of deep fade for the case of a single person. It can be extrapolated that two people standing together at the worst case position between the two antennas would likely double the loss - that is, a net decrease in excess gain– and so on. However, for the case of three or more persons in room a saturation effect has been observed [52]. I use a maximum "excess gain" of 7 dB for my proposed adaptive antenna scheme that I feel is quite conservative. The selection of this low value also influenced by the desire to implement a very simple scheme as discussed elsewhere in this thesis. Simplification may result in some degradation of performance versus the fully steerable design that is the key reference. However, [21] proposes a hybrid smart antenna solution that is reported to have nearly the same performance as that of a fully electronically steerable array, but with substantially reduced complexity. So again, I think the 7 dB number is a reasonable assumption for the maximum antenna added gain.

It might appear that these are fairly substantive assumptions. However, for the case of the channel loss, this simply scales the results up or down - for all simulation cases. The assumption involving the antenna "gain" is more complicated. This factor comes into effect only for the very severe channel loss conditions and would have an impact particularly if the channel loss scenario had many points of severe loss. The scenarios used in these simulations have only a very few severe loss data points corresponding to cases where one or more humans is positioned directly between the transmitting and receiving antennas. Further, for the quasi-adaptive and full-adaptive simulations, the impact would be identical as both cases use the same adaptive antenna algorithm. Finally, the code is written so that the for the first frame of any scenario step requiring the adaptive antenna scheme, no gain is allocated for that frame. This simulates the temporal requirement to implement any such scheme, regardless of how fast or efficient. Note that the alarm function that is implemented in the code is designed to minimize this delay however.

Simulation Results

Simulation results are displayed in figures 14 through 30. PSNR and EPL, both in dB, are displayed versus the frame number of the video clip. Note that the associated ELP is plotted on each of the graphs for convenient reference to channel scenario. The mean, median and standard deviation statistics are also displayed graphically. A tabulated data summary is included in Table 8.

In order to get some prospective about the PQoS versus the PSNR level, two example images are displayed in Figure 14. The left image is at a PSNR of about 40 dB while the image on right is for a PSNR value of 21.9 dB. A 40 dB or greater PNSR is considered to be a very high quality image. While a PSNR value of 21.9 dB is within the "acceptable" – although not "good" – range for wireless video transmission, numerous pixel errors can readily be seen. More than a few frames of this nature during the duration of feature length movie would probably result in unacceptable PQoS for many viewers.

The first observation from the simulation data is that the statistics for the full adaptive, as well as the non adaptive models are somewhat dependent on the channel scenario. For the 16-QAM with coding model, the mean of the PSNR varied by about 1.93 dB while the standard deviation varied by 1.89 dB. While certainly not insignificant given the challenges of this application, this grouping is tighter than what I anticipated. I expect that the reason for this is that even for the case of the random scenario, the randomly generated data stream has few EPL excursions of near maximum magnitude. The EPL data for the realistic and random scenarios are actually rather similar in nature and so the small variation between these simulations is reasonable.

For the full-adaptive model, the mean of the PSNR varied by 0.98 dB and the standard deviation only by 0.38 dB. This low standard deviation confirms that the system is well controlled and that the adaptive process is working well to stabilize the throughput even under very adverse channel conditions. Result indicate however that even the full-adaptive model has some trouble maintaining acceptable PSNR levels under loss conditions of greater than about 26 dB.

Figure 4.5: Example frames after processing. The frame on the left is for a PSNR of about 40 dB while the frame on the right is for a PSNR of 21.9 dB.

Another observation that I really did not expect was the number of over 40 dB points. Recall that the majority of references indicate that

PSNR values over 40 dB indicate excellent image quality. This characteristic is observed to some degree in all simulations for all the algorithms. The proportion of 40 dB plus data is much more prevalent for the full-adaptive simulations as will be discussed shortly.

I will now proceed to analyze and comment on each of simulation. Figures 4.7 - 4.24 are simulated results using the "ElephantsDream" reference sequence. Figure 4.7 is the simulation for the non-adaptive 16-QAM with fixed coding case. A closer look at this figure clearly shows the lack of any attempt at adapting to varying EPL. PSNR values are reasonably well behaved for EPL levels of greater than about -18 dB. Below this level, the PSNR is seen to be proportional to the EPL. Note also that most of the data points are either clustered around the mean or they reside below the median value. The PSNR is over 40 dB dB for 219 out of 960 frames, or about 22.8 percent of the frames. A higher number of greater than 40 dB PSNR points is better. Values of PSNR between 30 and 40 dB is 269 or 28 percent – a higher number also better for this metric. The number of points below 30 dB is 482, which is 50.2 percent. A lower number is better for this metric.

The ramp scenario in conjunction with 16-QAM and fixed coding is shown in Figure 4.8. The PSNR data trend follows the ramp effect of the EPL data particularly for EPL data levels of about again -18 dB and below. Above this level, the PSNR begins to become rather random in nature. For this case, the PSNR is over 40 dB for 197 frames, or about 20.5 percent. 249 – 25.9 percent – PSNR values are in the 30 to 40 dB range. The number of PSNR points below 30 dB is 515 or about 53.6 percent.

Figure 4.9 is the simulation for 16-QAM using the random scenario. This data compares vary closely to that of Figure 4.7, the case for 16-QAM using the realistic data. The distribution of data along the Frame Number axis is different due to the nature of the data. The statistics for this case compared to the realistic case supports this observation. For this simulation, the PSNR is over 40 dB for 216 frames, or 22.5 percent – very close to this metric for the realistic case. PSNR values for the 30 to 40 dB range was 264 (27.5 percent). 481 (50.1 percent) of the PSNR data points were less than 30 dB for this test case. Note that the latter 2 sets of data also align well with those from the "realistic" scenario.

Figure 4.10 is the simulated data for the hybrid, quasi adaptive case of 16 QAM with 1/2 rate QPSK, the adaptive antenna and the optional Reed-Solomon (511,351) coding. This figure is for the realistic scenario. The first observation is the adaptive tendency for PSNR data points corresponding to EPL levels below about -25 dB. For the 32 frame interval at these low levels the PSNR level moves upward but stops its climb just below the median PSNR level. Another observation is the main bulk of the data points is tightly clustered about the median with a smaller number of points distributed between the median and mean. Finally, it appears that a large number of PNSR data points exceed the 40 dB level. Indeed, the PSNR is above 40 dB for 299 frames, or about 31.1 percent while the number of PSNR data points between 30 and 40 dB is 521, which is about 54.3 percent. The number of points under the minimal 30 dB level are 141 (14.7 percent).

Figure 4.11 displays the results for the hybrid model for the ramp scenario using the ramp scenario. Similar adaptive tendencies can again be clearly observed although for this case, the adaptive attempts are all bunched up at the lowest data points of the EPL ramp. For this case, 265 PSNR data points (17.6 percent) were greater than 40 dB while 555 (57.8 percent) were between 30 and 40 dB. 141 (3.1 percent) fell below the minimal 30 dB level.

The hybrid approach using the random scenario is displayed in Figure 4.12. Again, a strong similarity to that using the realistic scenario is observed. The statistics are 297 (30.9 percent) above the 40 dB benchmark and 523 (54.4 percent) between 30 and 40 dB. Once again, 141 (3.1 percent) were observed to be less than 30 dB.

Figure 4.13 depicts the simulated data for the full-adaptive algorithm for the realistic scenario. The plotted data initially does not appear to be substantially different than that of Figure 4.10. Statistics indicate a however that the mean and median PSNR values have shifted upward by 7.2 dB. The standard deviation however has also increased by

2.4 dB. Despite the similar trends, this algorithm clearly is different than the quasi-adaptive case. The number of 90 dB frames is 297 for this case, or 30.9 percent. This explains the increase in the standard deviation compared to the quasi-adaptive case. 496 frames, or 51.6 percent, are less than 40 dB for this algorithm/scenario combination.

The full-adaptive simulation using the ramp scenario is shown in Figure 4.14. This data in appearance is similar to that for the realistic scenario but, as with the 16-QAM case, redistribution along the Frame Number access. Statistics show the mean PSNR has decreased by 0.5 dB while the standard deviation has also increased but by only 0.17 dB. Statistically, this is not a very large difference in performance from the case realistic case. The number of PSNR points over 90 dB is 290 frames or 30.2 percent. The number less than 40 dB is 511, about 53.2 percent.

Figure 4.15 shows the full-adaptive simulation for the random scenario. Similar to results for the 16-QAM case, the simulated data seems to mimic that for the real scenario but fundamentally shifted corresponding to the EPL input. Statistics show that, relative to the full-adaptive real scenario, the mean PSNR has increased by nearly 1 dB while the standard deviation of the PSNR has increase by only 0.4. Further, the number of PSNR points over 90 dB has increased to 307 which is 31.9 percent. PSNR points under 40 dB are found to be 489 or 51 percent.

Results for simulations 4.16–4.24 for the "BigBuckBunny" sequence reveal very similar results as for simulations 4.7–4.15. This supports the robust nature of this algorithm since the "BigBuckBunny" sequence can be construed as an action video versus the "ElephantsDream" sequence in which action is very minimal from frame to frame. For sake of a compact presentation, explicit simulation-by simulation analysis are therefore not made for these frames. Please refer to Table 4.2 and Figures 4.25 and 4.26 for a summary of the statical results for all simulations.

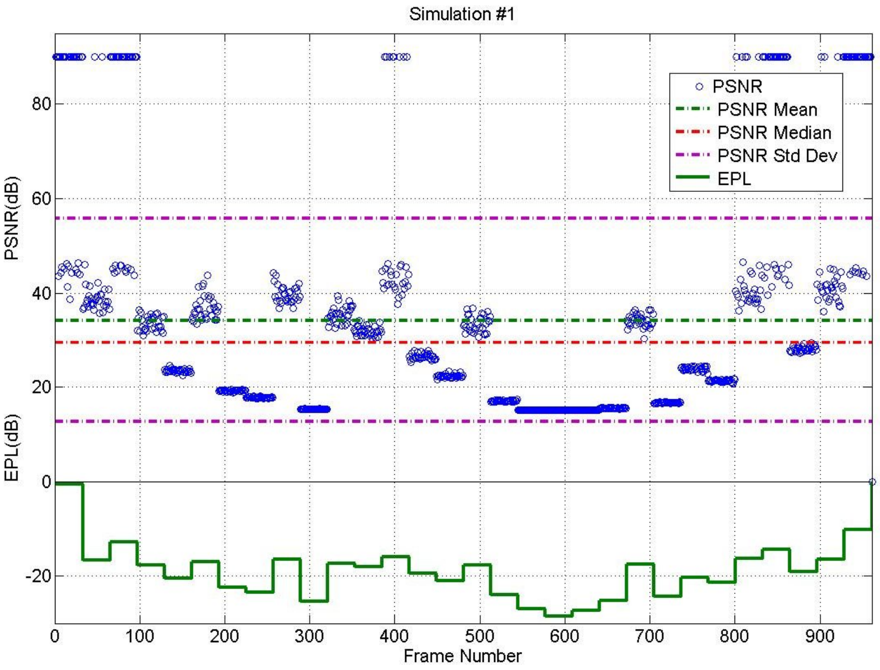


Figure 4.6: PSNR vs. frame number for the real scenario, 16-QAM with full-time RS(7,5) coding. Video is the "ElephantsDream" (ED) sequence. Excess path loss (EPL) is also shown for reference.

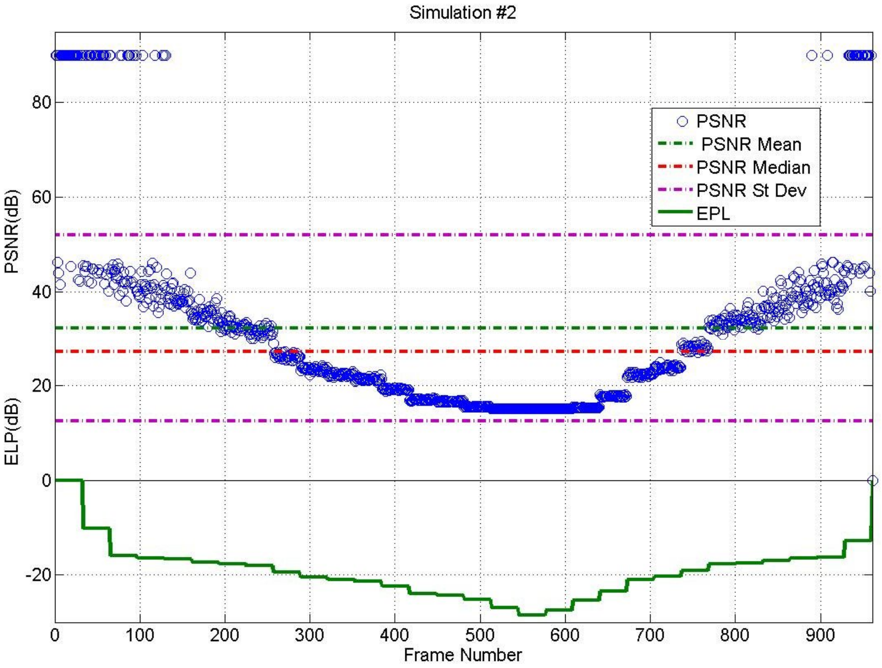


Figure 4.7: PSNR vs. frame number for the ramp scenario, 16-QAM with full time RS coding. ED sequence.

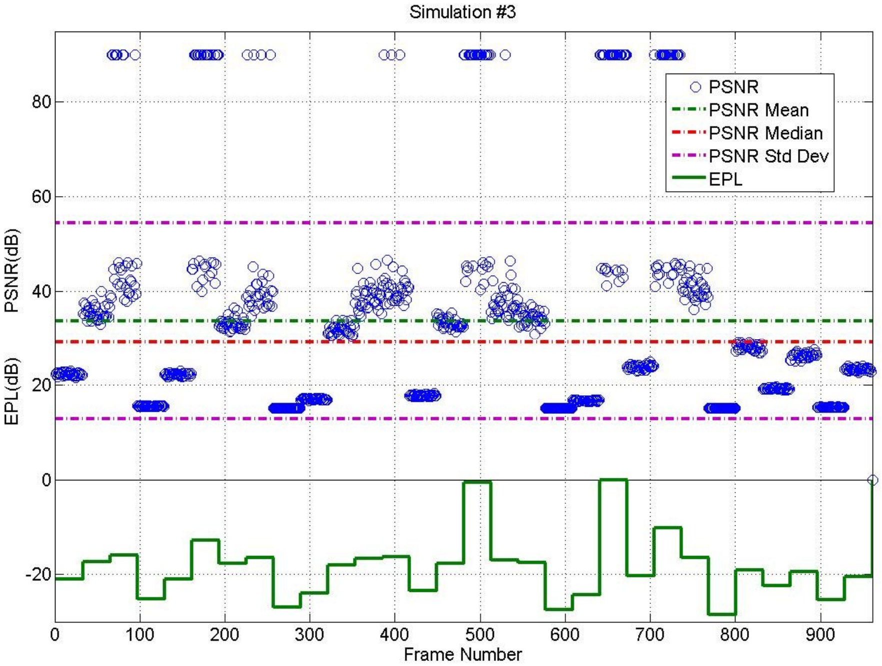


Figure 4.8: PSNR vs. fame number for the random scenario, 16-QAM with RS coding. ED sequence.

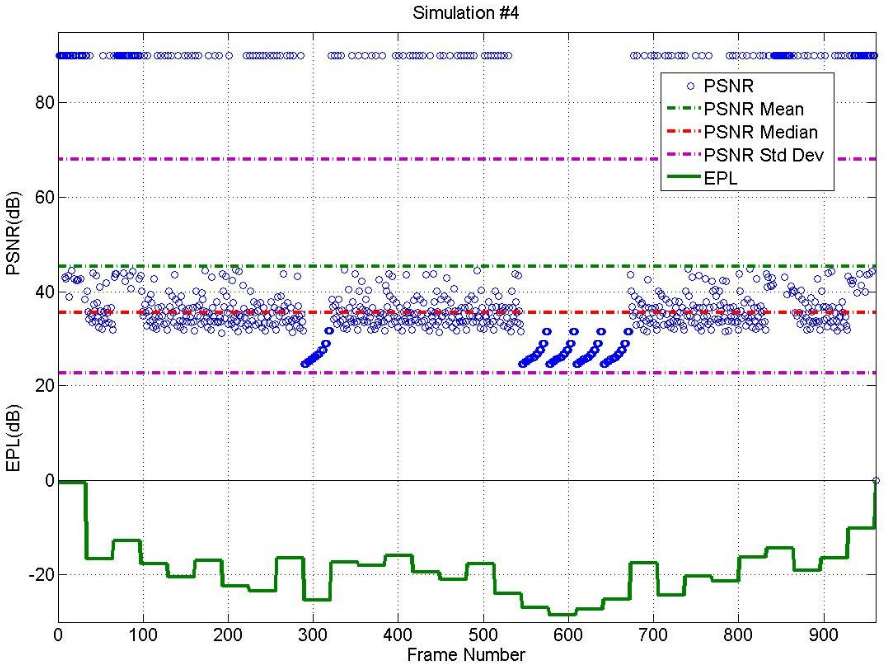


Figure 4.9: PSNR vs. frame number for the real scenario, 1/2 rate QPSK with optional RS coding plus 16-QAM. ED sequence.

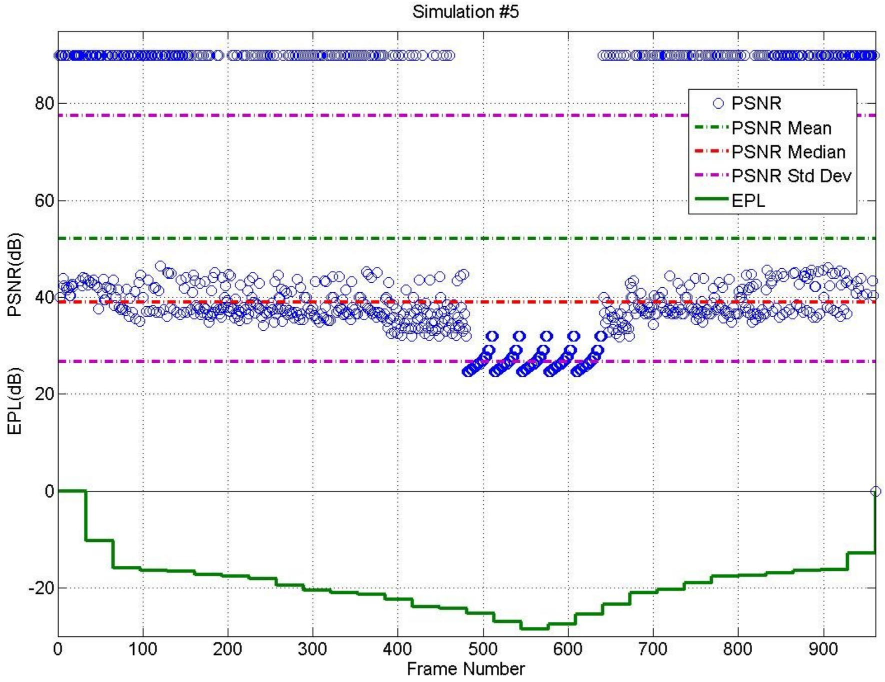


Figure 4.10: PSNR vs. frame number for the ramp scenario, 1/2 rate QPSK with optional RS coding plus 16-QAM. ED sequence.

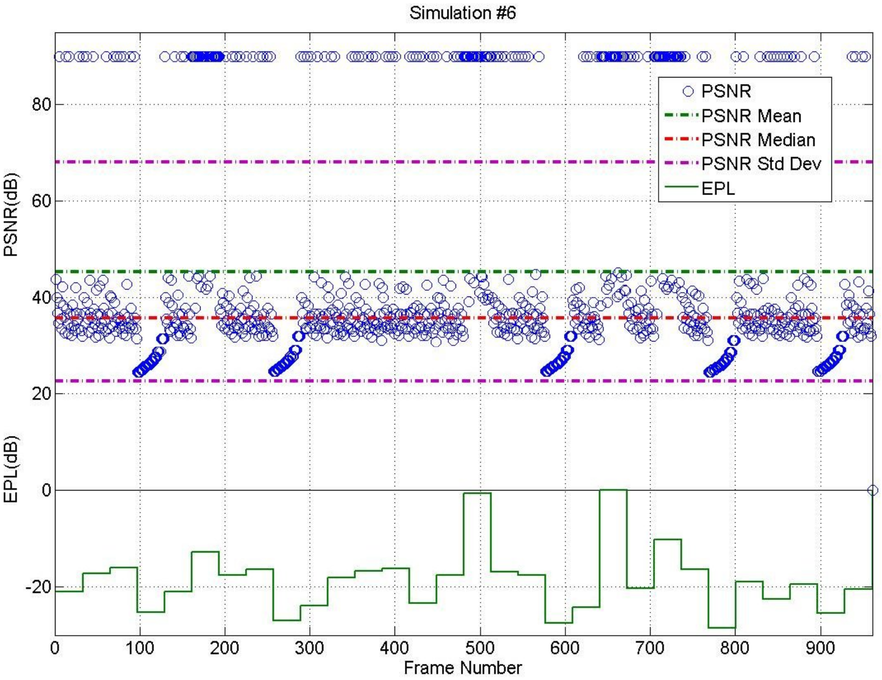


Figure 4.11: PSNR vs. frame number for the random scenario, 1/2 rate QPSK with optional RS coding plus 16-QAM. ED sequence.

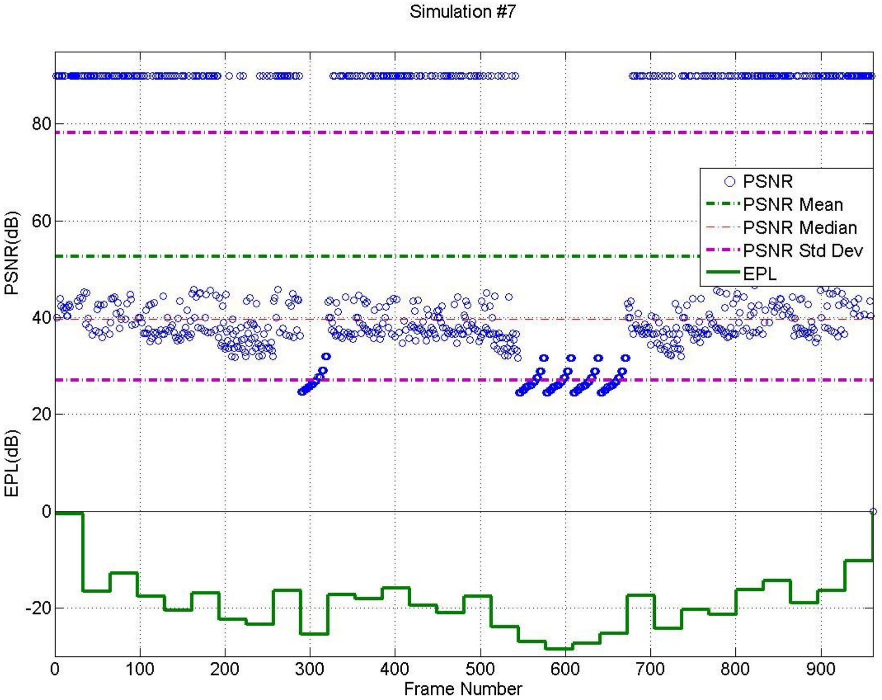


Figure 4.12: PSNR vs. frame number for the real scenario, full-adaptive algorithm. ED sequence.

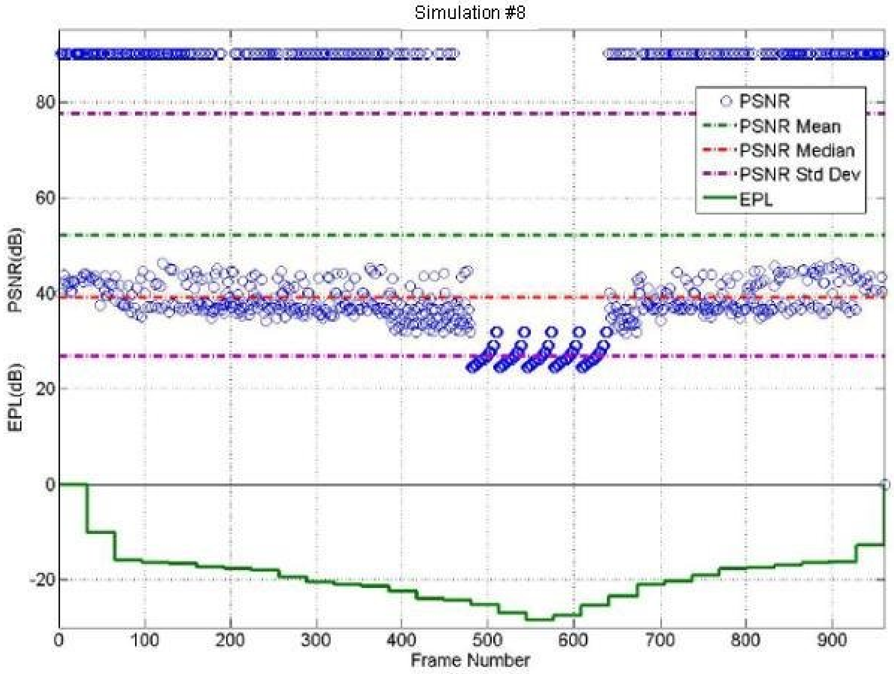


Figure 4.13: PSNR vs. frame number for the ramp scenario, full-adaptive algorithm. ED sequence.

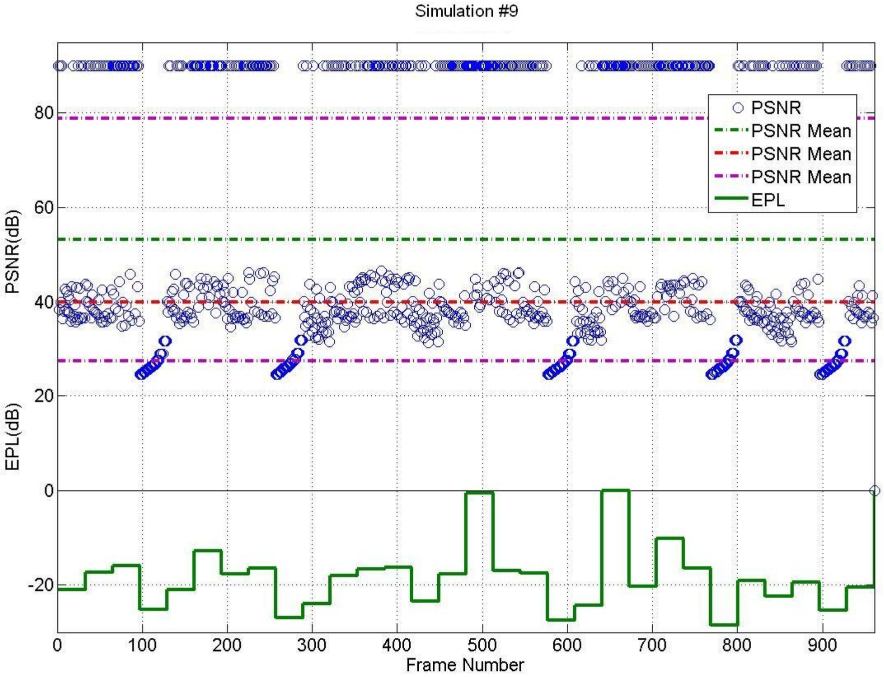


Figure 4.14: PSNR vs. frame number for the random scenario, full-adaptive algorithm. ED sequence.

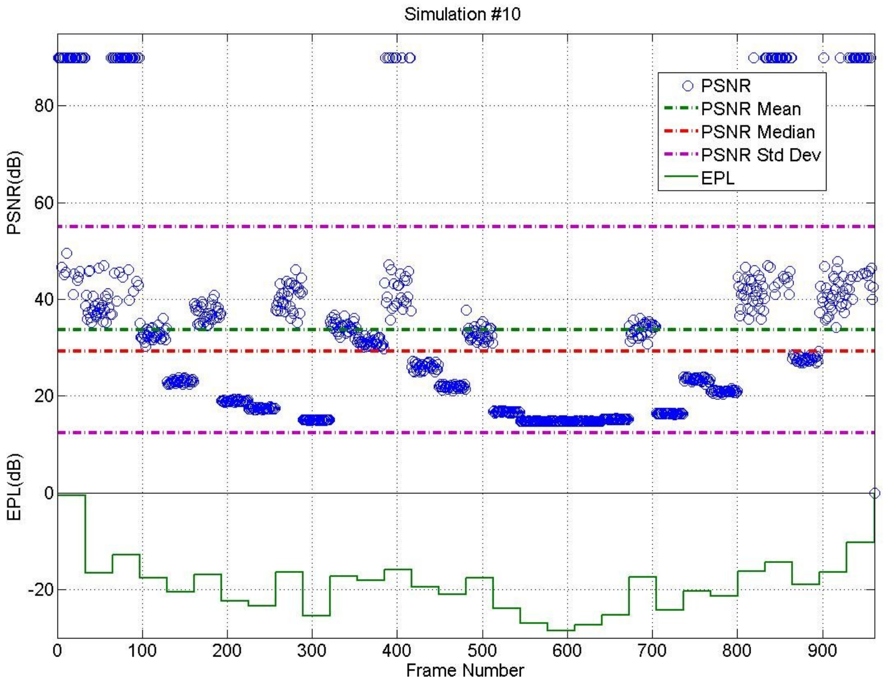


Figure 4.15: PSNR vs. frame number for the real scenario, 16-QAM with full-time RS(7,5) coding. Video is the "BigBuckBunny" (BBB) sequence.

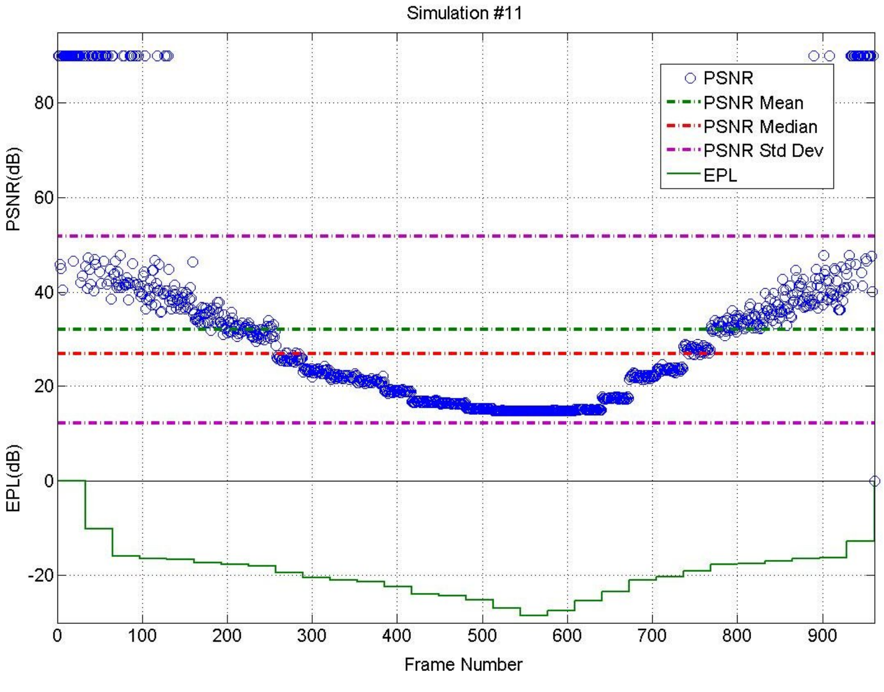


Figure 4.16: PSNR vs. frame number for the ramp scenario, 16-QAM with full time RS coding. BBB sequence.

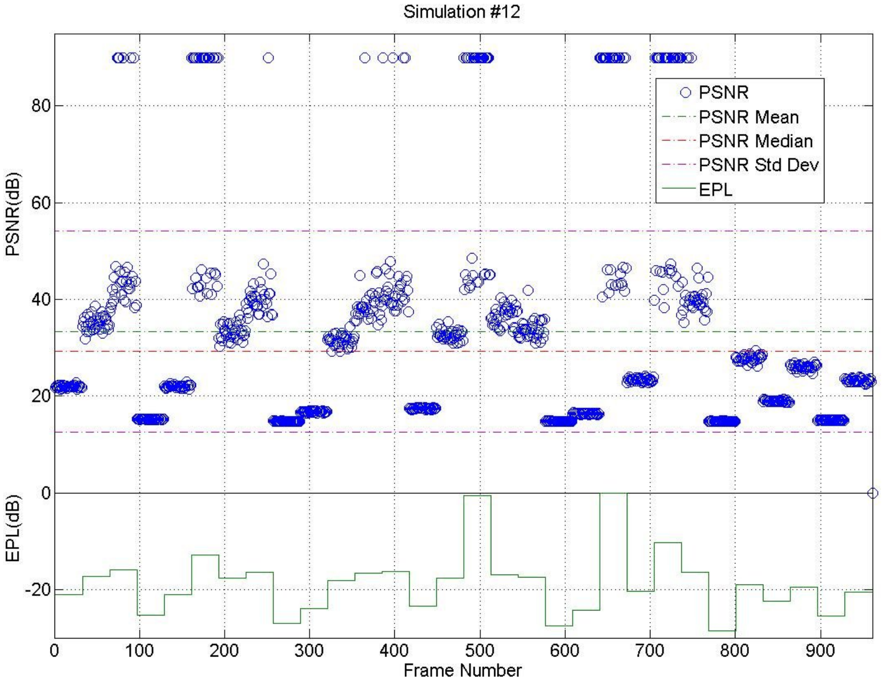


Figure 4.17: PSNR vs. fame number for the random scenario, 16-QAM with RS coding. BBB sequence.

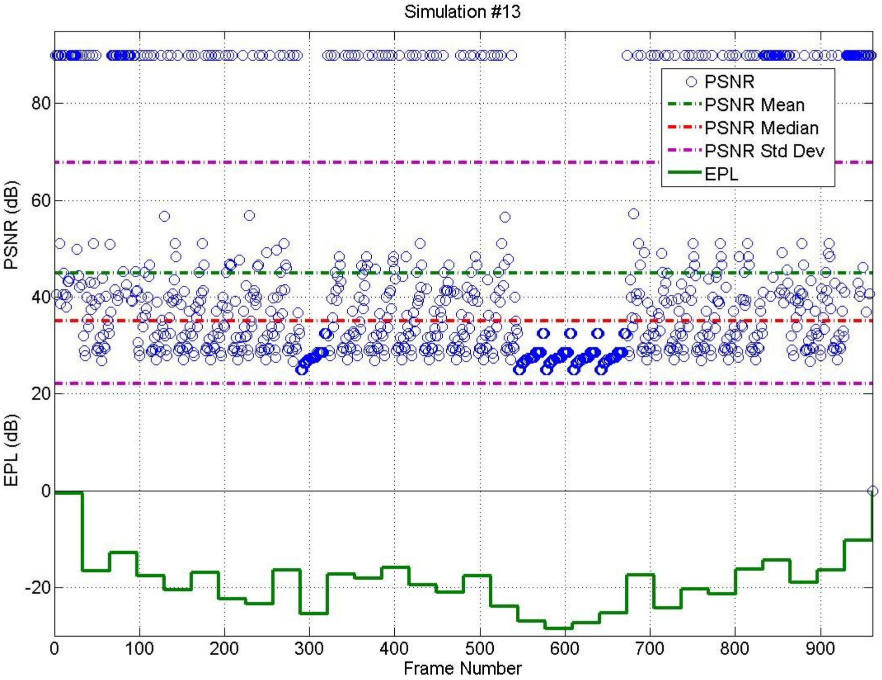


Figure 4.18: PSNR vs. frame number for the real scenario, 1/2 rate QPSK with optional RS coding plus 16-QAM. BBB sequence.

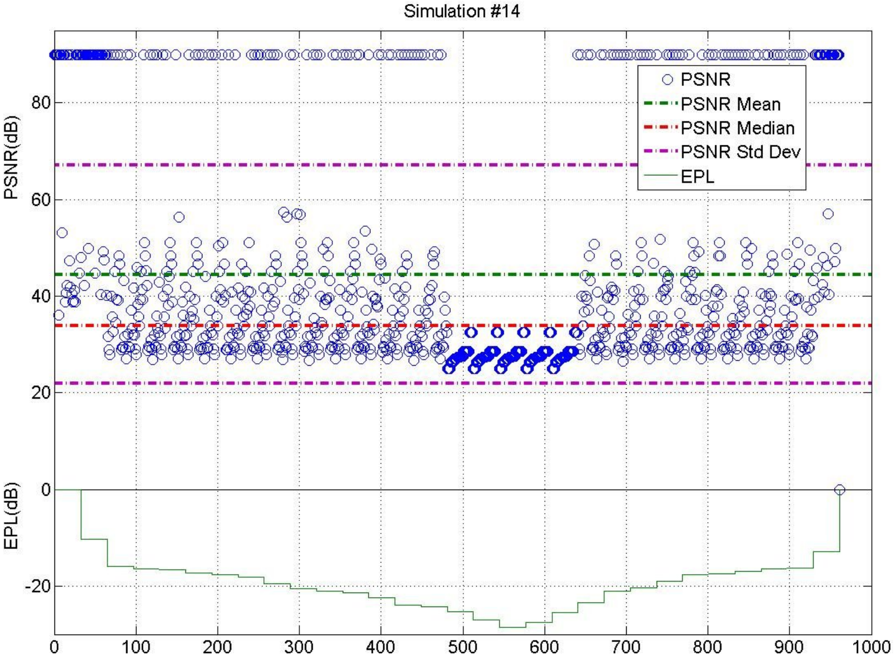


Figure 4.19: PSNR vs. frame number for the ramp scenario, 1/2 rate QPSK with optional RS coding plus 16-QAM. BBB sequence.

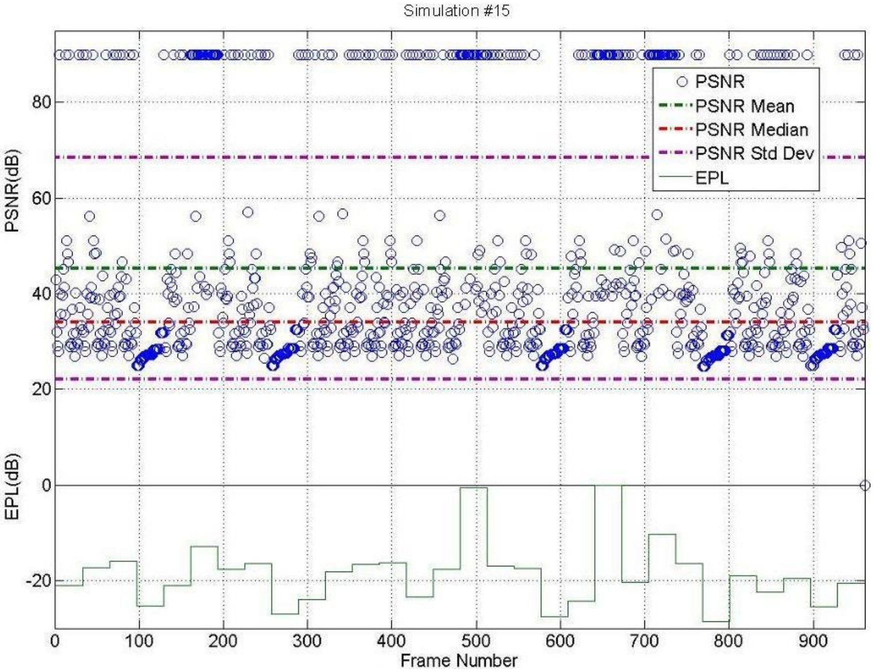


Figure 4.20: PSNR vs. frame number for the random scenario, 1/2 rate QPSK with optional RS coding plus 16-QAM. BBB sequence

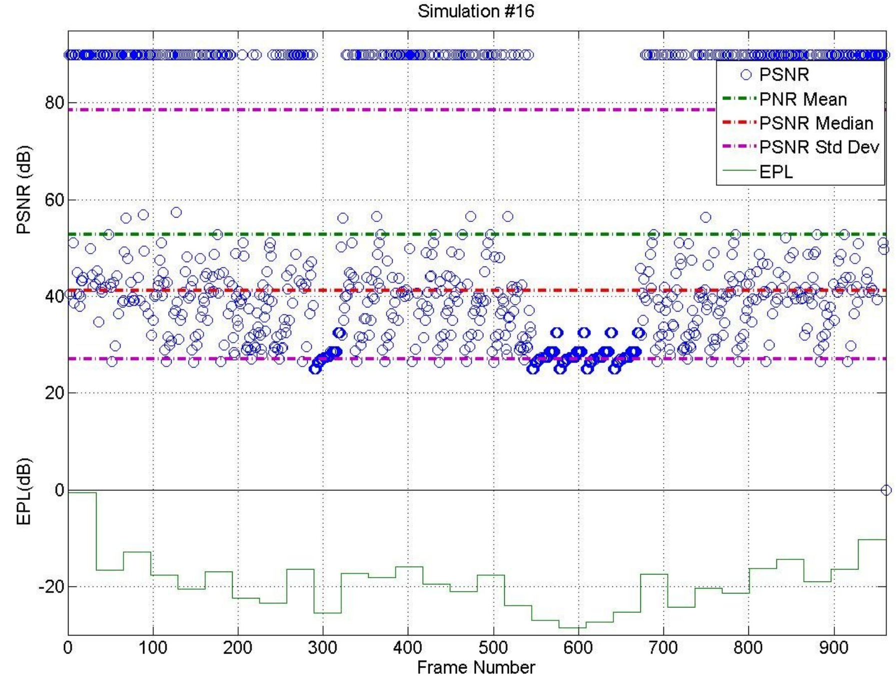


Figure 4.21: PSNR vs. frame number for the real scenario, full-adaptive algorithm. BBB sequence.

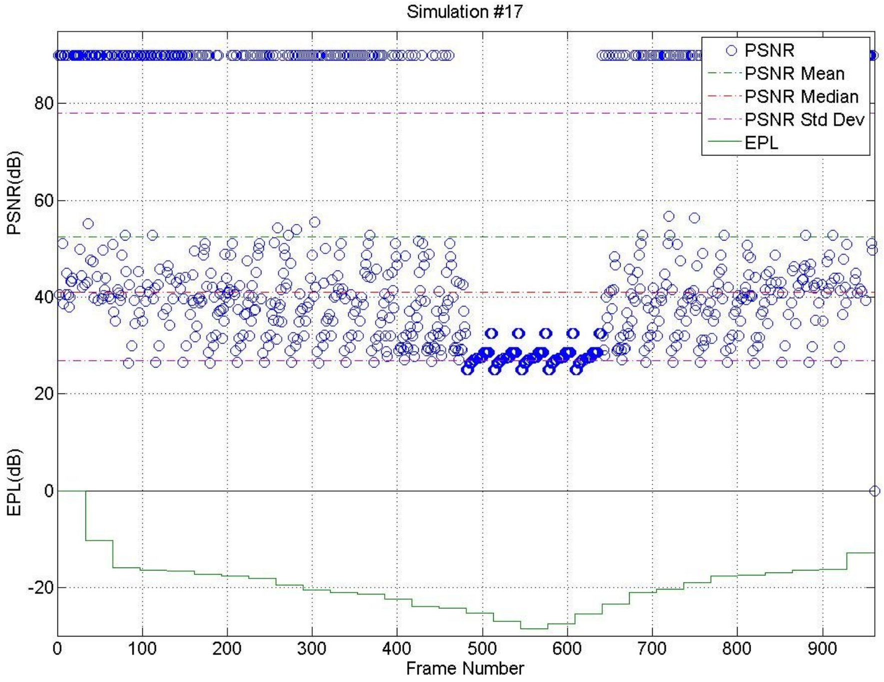


Figure 4.22: PSNR vs. frame number for the ramp scenario, full-adaptive algorithm. BBB sequence.

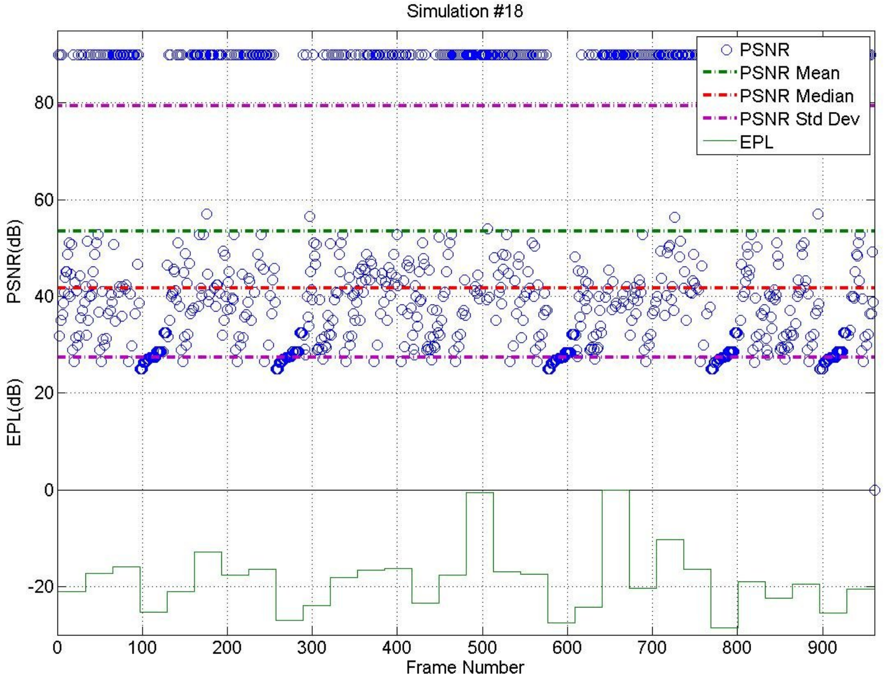
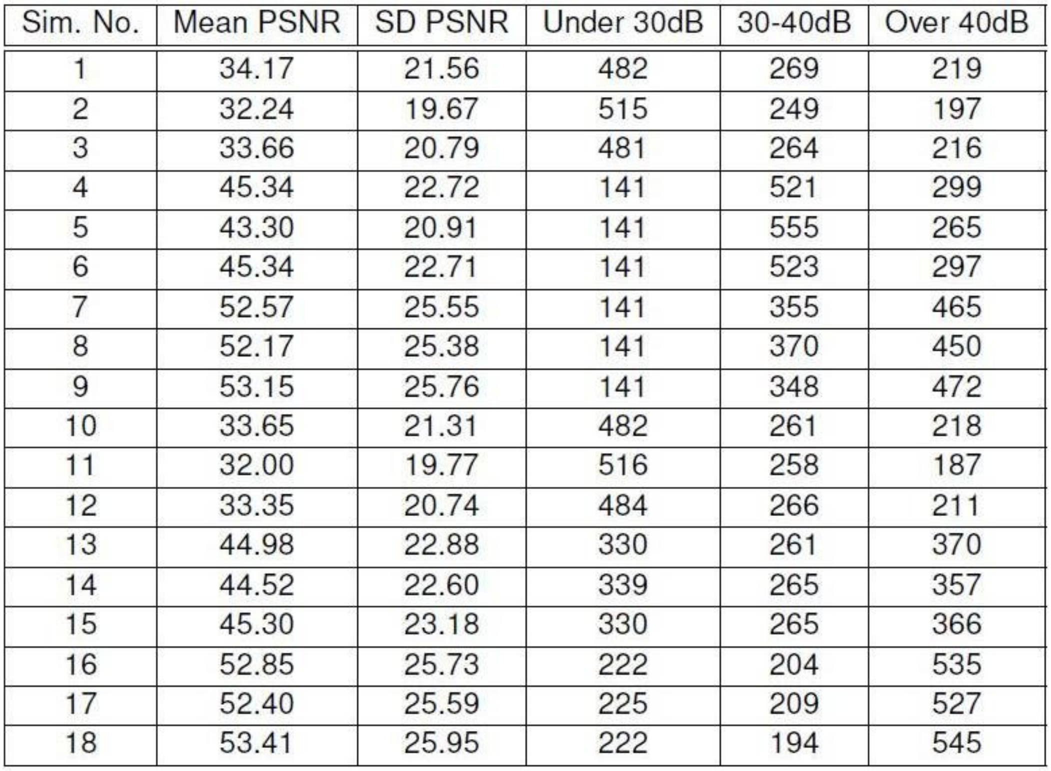


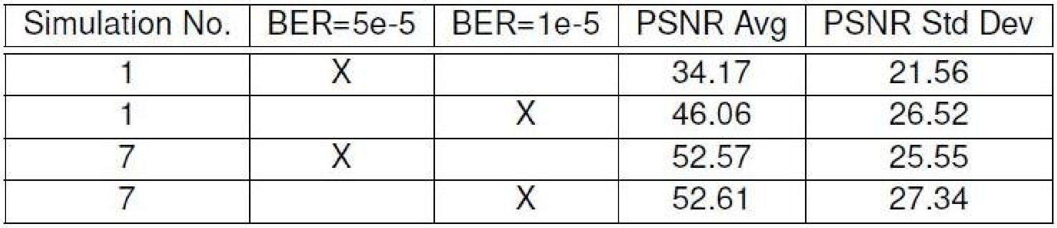
Figure 4.23: PSNR vs. frame number for the random scenario, full-adaptive algorithm. BBB sequence.

In the assumptions section of this thesis , I proposed examining the effect of varying the BER for a limited subset of the 18 simulations. Further, discussion with my advisor and general literature approaches suggest that a reasonable number for BER is 1e-5. Therefore, simulations 1 and 7 were selected to be simulated using BERs of 1e-5 in addition to the previously simulated BER of 5e-5. Table 4.3 shows the results of this set of simulations. Note that there is a substantial increase in average PSNR for simulation 1 (16-QAM w/ full-time coding) while a modest increase in average PSNR for the adaptive algorithm. This is an expected result because as the channel conditions approach the limit of zero EPL and perfect conditions, the full-rate algorithm –with or without coding– will prove to be the best case since no reduction of frame rate is required.



Sim. No.	Mean PSNR	SD PSNR	Under 30dB	30-40dB	Over 40dB
1	34.17	21.56	482	269	219
2	32.24	19.67	515	249	197
3	33.66	20.79	481	264	216
4	45.34	22.72	141	521	299
5	43.30	20.91	141	555	265
6	45.34	22.71	141	523	297
7	52.57	25.55	141	355	465
8	52.17	25.38	141	370	450
9	53.15	25.76	141	348	472
10	33.65	21.31	482	261	218
11	32.00	19.77	516	258	187
12	33.35	20.74	484	266	211
13	44.98	22.88	330	261	370
14	44.52	22.60	339	265	357
15	45.30	23.18	330	265	366
16	52.85	25.73	222	204	535
17	52.40	25.59	225	209	527
18	53.41	25.95	222	194	545

Table 4.3: Tabulated results for simulations 1 through 18. Refer to Table 6 for details of the various simulations.



Simulation No.	BER=5e-5	BER=1e-5	PSNR Avg	PSNR Std Dev
1	X		34.17	21.56
1		X	46.06	26.52
7	X		52.57	25.55
7		X	52.61	27.34

Table 4.4: Tabulated results for simulations 1 and 7 for BER rates of 5e-5 and 1e-5.

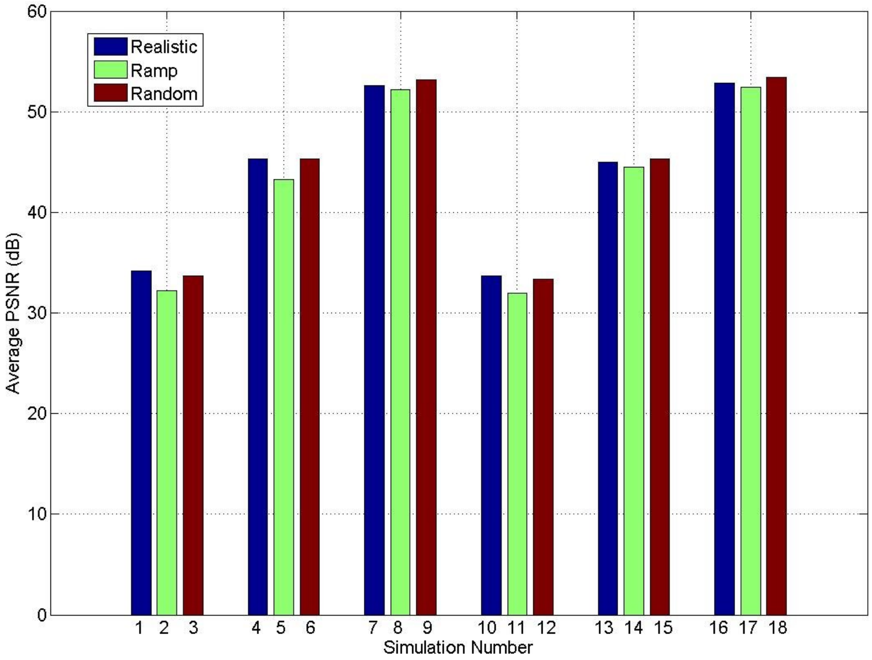


Figure 4.24: Average PSNR for all simulations.

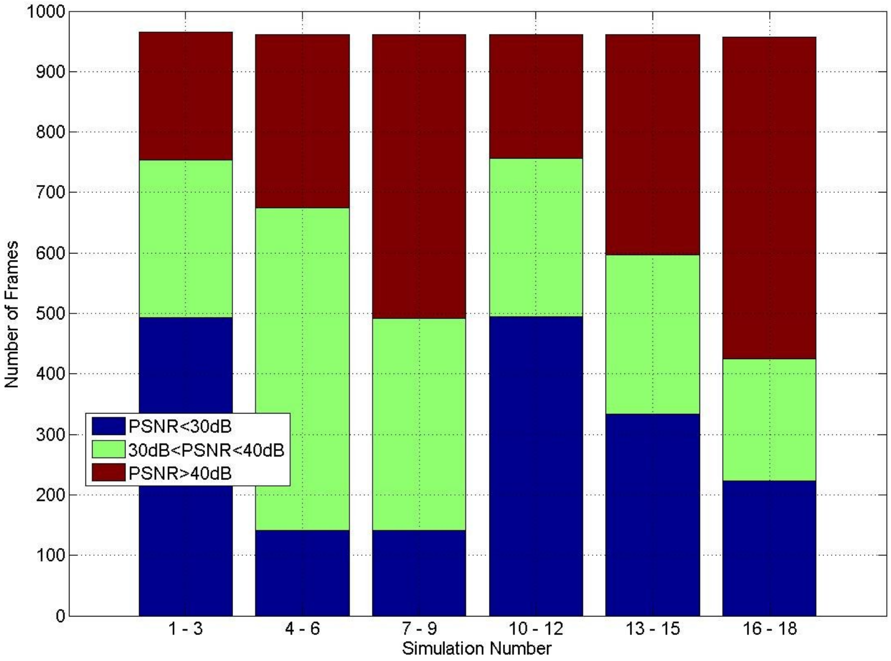


Figure 4.25: Number of frames versus averaged PSNR category. Each bar represents the average of the 3 simulations noted. The total number of frames for each simulation set is 960.

Chapter 5

CONCLUSIONS AND RECOMMENDATION FOR FUTURE WORK

In this thesis, a brief but thorough background into the newly emerging problem space for multi-gigabit wireless applications is established. It is shown that the nearly universal license-free 60 GHz band is a primary candidate for applications requiring the bandwidth to distribute content at these rates. Problems as well as benefits of establishing consumer-orientated networks is examined. Recent improvements in low cost silicon CMOS and HBT processes appear to enable viable solutions for the low cost, high performance systems today.

Although many potential use cases have been proposed, the use case that most likely will drive initial deployment of this technology appears to be the home video market. Therefore, this thesis will focus on this application and issues associated with the application. Note that this is probably the most demanding of the proposed applications. PQoS expectations will be essentially the same as for a wired network.

Numerous proposals within and outside of the standards and organization bodies are discussed. It is found that little if any concrete literature exists that discusses realistic mid-level consumer system implementation that will provide required PQoS levels for at least most of "typical" installations. This thesis examines what has been proposed at the PHY, MAC and PHY-MAC cross-layer for this application. It is found that specifics for actual implementation of an adaptive cross-layer approach are somewhat limited , again specifically targeting this use case.

Previous, relevant literature has focused typically on a limited subset of the proposed adaptive implementation. In this thesis, additional options and combinations, without an undue pre-selection process, has been examined. Exceptions include very high order modulation schemes such as any over 16-QAM and any variants of OFDM. Though OFDM in particular seems to be very popular currently for any application, many effective arguments have been made recently that show that OFDM is probably not, at least currently, the best choice for system realization. This work focuses on proven, single carrier modulation schemes using – again proven– coding schemes, namely Reed-Solomon or other block code at the frame-level and Reed-Solomon at the symbol-level. To date, for bursty type errors , Reed-Solomon coding scheme is still optimal.

A PHY-MAC adaptive cross layer approach specific towards multi-gigabit video applications utilizing the 60 GHz millimeter-wave spectrum is derived and its performance evaluated for several different scenarios. The relatively low complexity of the proposed approach aligns with the findings of the introductory sections. For a realistic, mid-range, consumer level product, a practical implementation is required to meet contradictory requirements of low to moderate cost but very good to excellent PQoS.

Further, set-up by the consumer must require a minimal amount of effort and therefore the system must be able to adapt to some degree to various initial set-ups. Finally, the consumer expects PQoS on the level of wired service for wireless implementations. Some occasional, very short-term glitch might be tolerated in order to enjoy the benefits of wireless, but overall, the experience must not be degraded substantially, if at all, from the wired version. We can readily conclude that any such proposed system must be very robust for widespread consumer acceptance.

The proposed solution effectively combines a number of techniques, several of which have been proposed or even implemented in one form or another at much lower data rate, frequencies, and expected quality levels. These three parameters are key to the delivery of an algorithm that can support the readily implementable solution. For the data rates, carrier frequencies and expected PQoS for the applications targeted here, scaling existing solutions up to the required levels may not provide an approach that is near optimal primarily in terms of cost and performance. New, modified or combinations of new, modified and existing adaptive approaches appears to be a workable solution.

A computer model using Matlab is used to model the proposed algorithm. Actual high definition video clips of two reference sequences are used to evaluate the algorithm. PSNR as function of excess path loss (EPL) is the metric used to evaluate the proposed algorithm as well as several progressively less adaptive subsets of the program. Each of these uses 3 proposed channel model scenarios – namely realistic, ramp and random – that provide a statistically accurate model of a family room environment with multiple humans either fixed and/or in random motion. Finally, a number of simulations over varying bit error rates are performed for comparison purposes.

Simulations 1-3 and 10-12 utilize 16-QAM with all data protected with Reed-Solomon coding. This scheme can be considered the traditional approach for high data rate transmission and is very commonly used for point-to-point applications. Though this approach works very well for clean, clear, relatively static channel conditions, the lack of a means to adapt when conditions are not optimal is shown to result in worse PSNR values. This occurs at EPL levels of around 18 dB which has been shown to be on the low side if a human is anywhere in the vicinity of the transmit to receive signal path.

The algorithm used in simulations 4-6 and 13-15 makes use of some adaptive technique, namely an optional 1/2 rate QPSK modulation state, optional coding and an adaptive antenna scheme. The purpose of this experiment is to evaluate a partially adaptive solution to ascertain how much benefit versus the traditional – and ultimately for the fully adaptive– implementation is realized. It is shown that a 11-12 dB improvement in average PSNR over the traditional method is obtained with this algorithm.

Standard deviations values are about the same for the partially adaptive solution. This value is somewhat misleading since the partially adaptive solution results in about a 30 percent increase in the amount of over (excellent) 40 dB PSNR frames.

A fully adaptive algorithm is used in simulations 8-10 and 16-18. The algorithm uses 1/2 rate QPSK, QPSK, 8-PSK and 16-QAM along with optional coding and the proposed adaptive antenna scheme. Conceptually, the algorithm is designed to provide the best possible PQoS for any likely channel conditions as modeled by the EPL scenarios. The algorithm provides an adaptive, scalable solution that might allow a user experience that is transparent to problems generated by humans moving about or standing at strategically poor locations in a home environment. This model somewhat surprisingly provides substantially better performance even compared to the partially adaptive algorithm. Improvement values for mean PSNR are 7 - 8 dB for the fully adaptive versus the partially adaptive algorithm.

A graphical presentation summarizing the average PSNR values for the 18 simulations is shown in Figure 33. The full-adaptive cases (simulations 7–9 and 16–18) are improved compared to both the hybrid and the 16-QAM case by roughly 8 dB and almost 20 dB respectively. For all cases, there is little difference between the three scenarios. However, the full adaptive algorithm appears to have slightly better performance for this important metric as well.

Figure 34 shows the categorized PSNR values for each trio of simulations. It was shown in Figure 33 that for all algorithms, performance was quite similar for the three scenarios. The plot shows that for progressively adaptive solutions, the number of PSNR values over 40 dB increases dramatically. The number of 30 to 40 dB PSNR values as well as the number of the below 30 dB values is not quite so straight forward. For the first video sequence, the number of below 30 dB cases for the hybrid and full-adaptive algorithms, while improved over the fixed case, is the same for both. This might be attributed to the adaptive performance of the two algorithms in conjunction with the rather slow progression of "motion" from frame to frame in the sequence.

Comparison of simulations 10–18 to those of simulations 1–9 is interesting. Note that simulations 10–18 are for the second video sequence, namely "BigBuckBunny". The 32 selected frames include 12 frames in which the apple is falling and represents relatively high frame-to-frame difference when compared to slowly changing "ElephantsDream" sequence. The intermediate (30–40 dB) values are very similar for simulations 10–18. However, the over 40 dB values increase in percentage while the under 30 dB values decrease at the same rate. The other important point to be noted is that the number of below 30 dB values is almost double to that for the comparable simulations using the "ElephantsDream" sequence. The nature of the video sequence suggests that the frame-to-frame variation while under severe EPL conditions, would lead to an increase in low PSNR values for cases where rate back-off is needed. One final note is that for the full adaptive case, the below 30 dB PSNR values does show about a 50 percent improvement over the hybrid case. This shows that even under poor channel conditions, and high frame-to-frame variance, the adaptive algorithm appears to be providing performance improvement.

The fully adaptive implementation has been conclusively shown to be superior to non-adaptive techniques and sufficiently superior to even quasi-adaptive algorithms. The case then becomes that if this level of improvement over alternative methodologies is sufficient to justify the implementation of such a scheme versus possible realistic alternatives, then this algorithm should certainly be considered as a primary candidate for implementation in any detailed specification for multi-gigabit application(s) per this discussion.

Future Work

Recommendations for future work include further investigation into implementable adaptive antenna solutions and cross-layer optimization specifically for this technique. MAC layer design including means of efficiently monitoring and interfacing with the PHY-level antenna hardware might be examined as well. This work may also include new or improved algorithms to enable simple but effective antenna adaptive in the dynamic wireless environment and may include beam steering or scanning and might include variable gain/directivity as well. Further simulations to extract better data for the steerable antenna array, for various scenarios involving multiple humans moving about in an indoor environment should be included as part of this work.

A step up towards simulation of complete, end-to-end system including actual data modulation and demodulation, and so on certainly would be an interesting topic for research. While this commonly done for lower frequency networks such as WiFi and cellular, this is new territory for multi-gigabit, millimeter wave carrier implementations. I envision a hybrid approach to accomplish such a model. The PHY-MAC core might be very similar to that suggested in this thesis. The outer model might use for example Simulink, SystemVue or other system level tool. Actual data would be transmitted over a lossy channel, adaptive measures would be automatically implemented as needed, and the data would ultimately be received and the video frame displayed and analyzed.

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APPENDIX A

LIST OF ACRONYMS

BER — Bit Error Rate

CDMA — Code Division Multiple Access

DEV — Device

DQPSK — Differential Quadrature Phase Shift Keying

DVI — Digital Video Interface

Eb/No — Energy per Bit divided by Noise Power Spectral Density

EPL — Excess Path Loss

FDE — Frequency Domain Equalizer

FDMA — Frequency Division Multiple Access

FEC — Forward Error Correction (code)

GMSK — Gaussian Minimum Shift Keying

HDMI — High Definition Multimedia Interface

MCS — Modulation and Coding Scheme

MIMO — Multiple Input Multiple Output

MMSE — Minimum Mean Square Error

MOS — Mean Opinion Score

MSK — Minimum Shift Keying

OFDM — Orthogonal Frequency Division Multiplexing

PQoS — Perceived Quality of Service

PSNR — Peak Signal to Noise Ratio

QAM — Quadrature Amplitude Modulation

QoS — Quality of Service

QPSK — Quadrature Phase Shift Keying

RS — Reed-Solomon (code)

SNR — Signal to Noise Ratio

TDMA — Time Division Multiple Access

WLAN — Wireless Local Area Network

WPAN — Wireless Personal Area Network

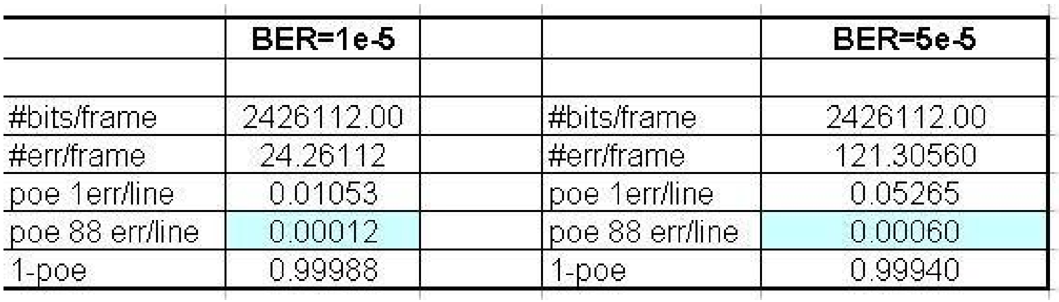
APPENDIX B

LINK BUDGET CALCULATIONS

BER=5e-5	SNR	BER
BPSK	8.79	5.0E-05
QPSK	11.80	5.0E-05
8-PSK	16.90	5.1E-05
16-QAM	18.63	5.0E-05

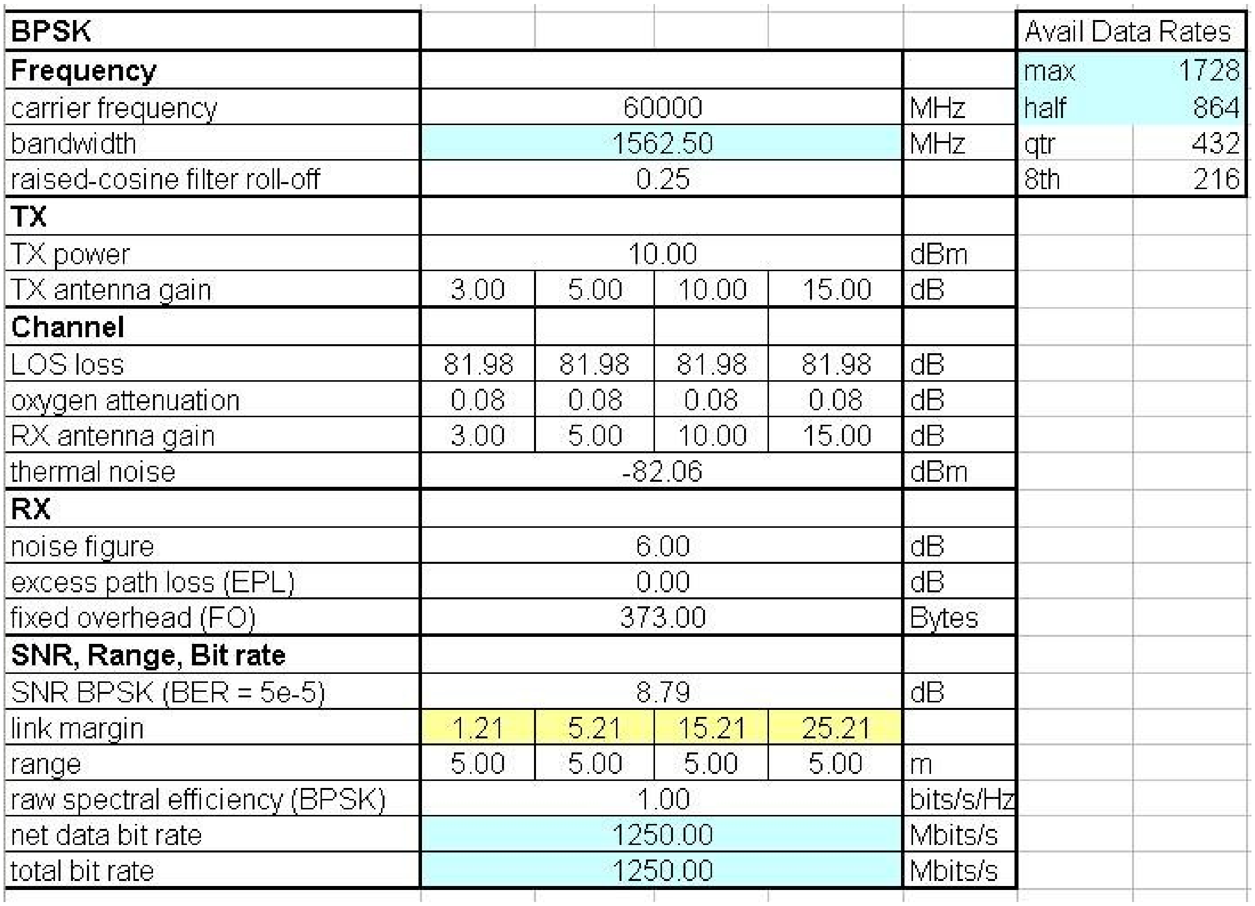
BER=1e-5	SNR	BER
BPSK	9.57	1.0E-05
WPSK	12.56	1.1E-05
8-PSK	17.70	1.1E-05
16-QAM	19.45	1.0E-05

Figure B.1: BER versus SNR for candidate modulation schemes.



	BER=1e-5			BER=5e-5
#bits/frame	2426112.00		#bits/frame	2426112.00
#err/frame	24.26112		#err/frame	121.30560
poe 1err/line	0.01053		poe 1err/line	0.05265
poe 88 err/line	0.00012		poe 88 err/line	0.00060
1-poe	0.99988		1-poe	0.99940

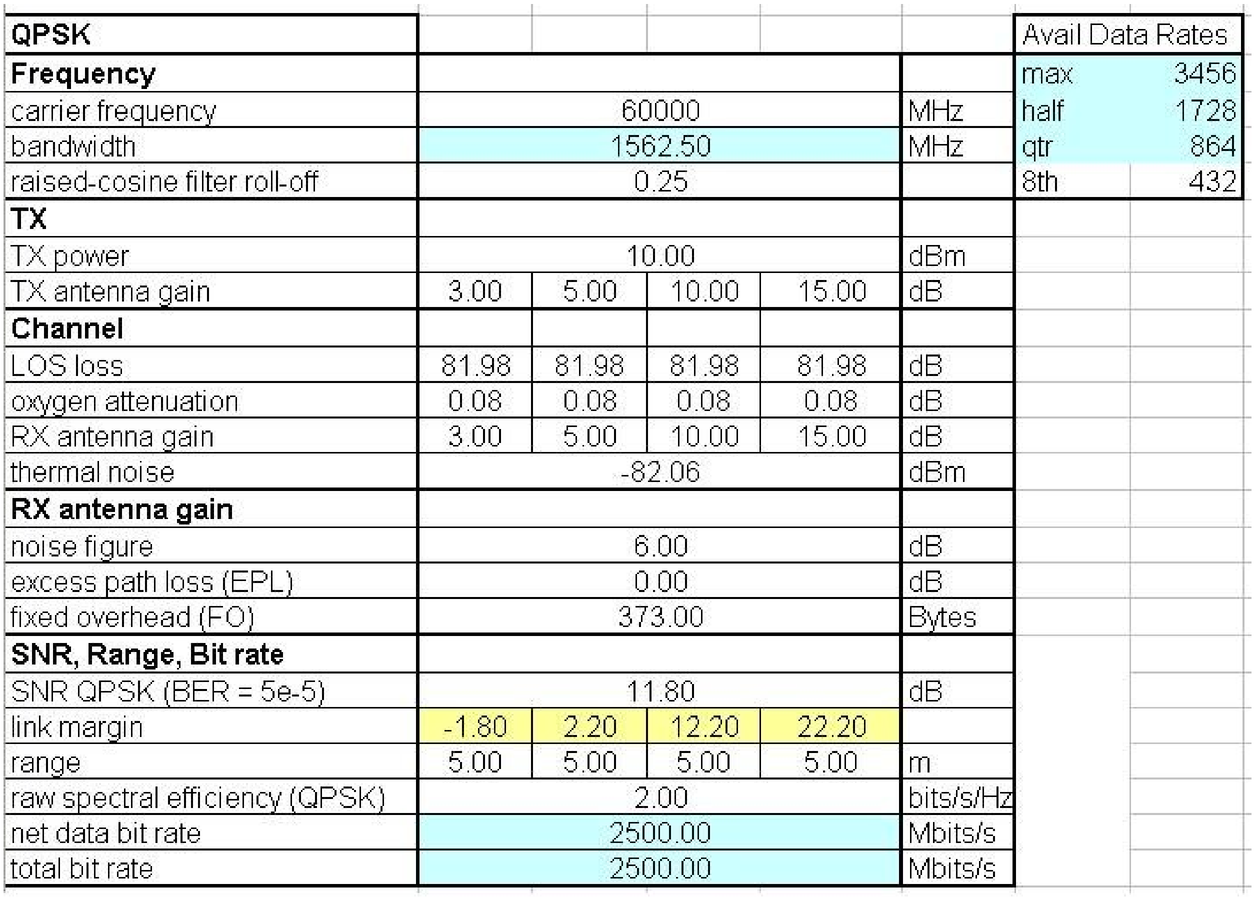
Figure B.2: Probability of error calculations.



BPSK					
Frequency					
carrier frequency	60000				MHz
bandwidth	1562.50				MHz
raised-cosine filter roll-off	0.25				
TX					
TX power	10.00				dBm
TX antenna gain	3.00	5.00	10.00	15.00	dB
Channel					
LOS loss	81.98	81.98	81.98	81.98	dB
oxygen attenuation	0.08	0.08	0.08	0.08	dB
RX antenna gain	3.00	5.00	10.00	15.00	dB
thermal noise	-82.06				dBm
RX					
noise figure	6.00				dB
excess path loss (EPL)	0.00				dB
fixed overhead (FO)	373.00				Bytes
SNR, Range, Bit rate					
SNR BPSK (BER = 5e-5)	8.79				dB
link margin	1.21	5.21	15.21	25.21	
range	5.00	5.00	5.00	5.00	m
raw spectral efficiency (BPSK)	1.00				bits/s/Hz
net data bit rate	1250.00				Mbits/s
total bit rate	1250.00				Mbits/s

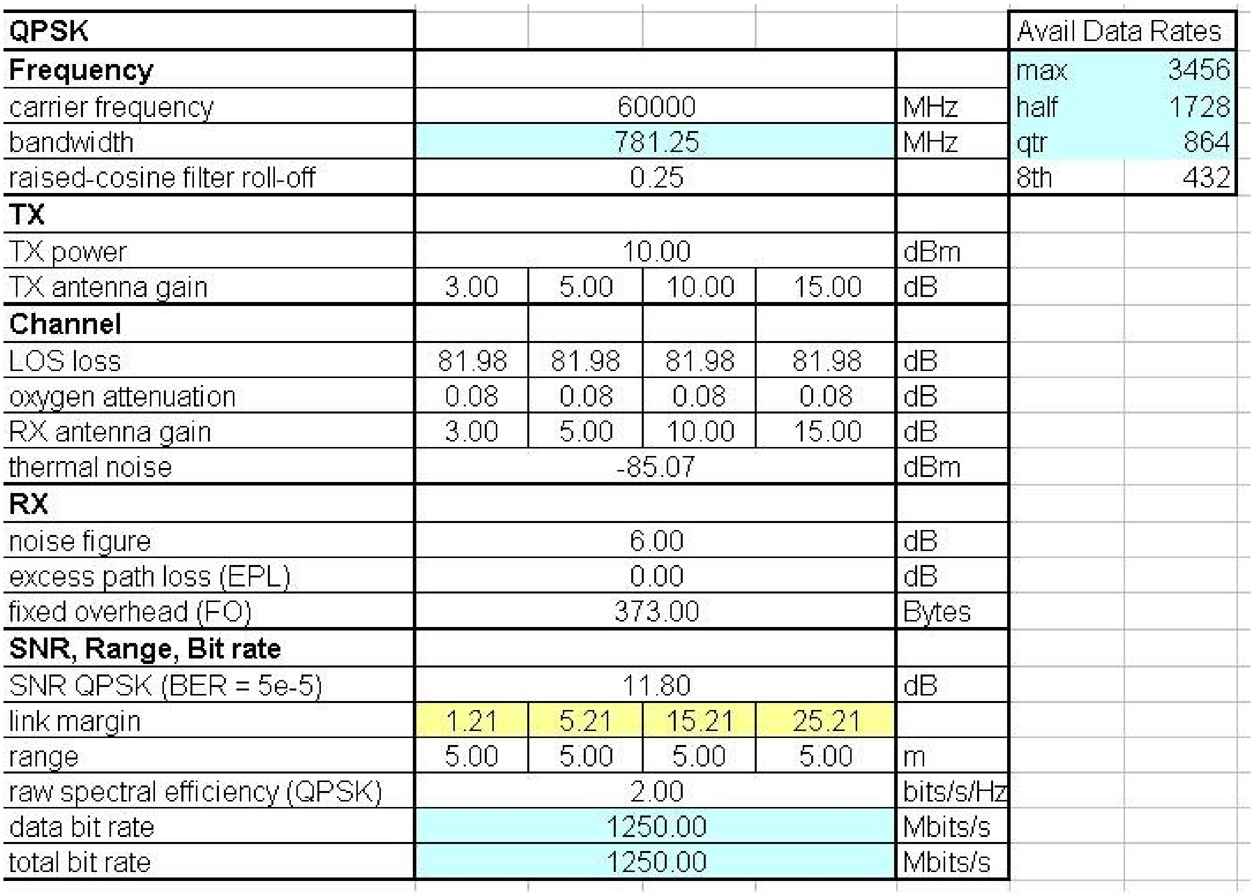
Avail Data Rates	
max	1728
half	864
qtr	432
8th	216

Figure B.3: Spreadsheet link budget analysis for BPSK. This MCS was not used ultimately, but is included for completeness.



QPSK						Avail Data Rates	
Frequency						max	3456
carrier frequency	60000				MHz	half	1728
bandwidth	1562.50				MHz	qtr	864
raised-cosine filter roll-off	0.25					8th	432
TX							
TX power	10.00				dBm		
TX antenna gain	3.00	5.00	10.00	15.00	dB		
Channel							
LOS loss	81.98	81.98	81.98	81.98	dB		
oxygen attenuation	0.08	0.08	0.08	0.08	dB		
RX antenna gain	3.00	5.00	10.00	15.00	dB		
thermal noise	-82.06				dBm		
RX antenna gain							
noise figure	6.00				dB		
excess path loss (EPL)	0.00				dB		
fixed overhead (FO)	373.00				Bytes		
SNR, Range, Bit rate							
SNR QPSK (BER = 5e-5)	11.80				dB		
link margin	-1.80	2.20	12.20	22.20			
range	5.00	5.00	5.00	5.00	m		
raw spectral efficiency (QPSK)	2.00				bits/s/Hz		
net data bit rate	2500.00				Mbits/s		
total bit rate	2500.00				Mbits/s		

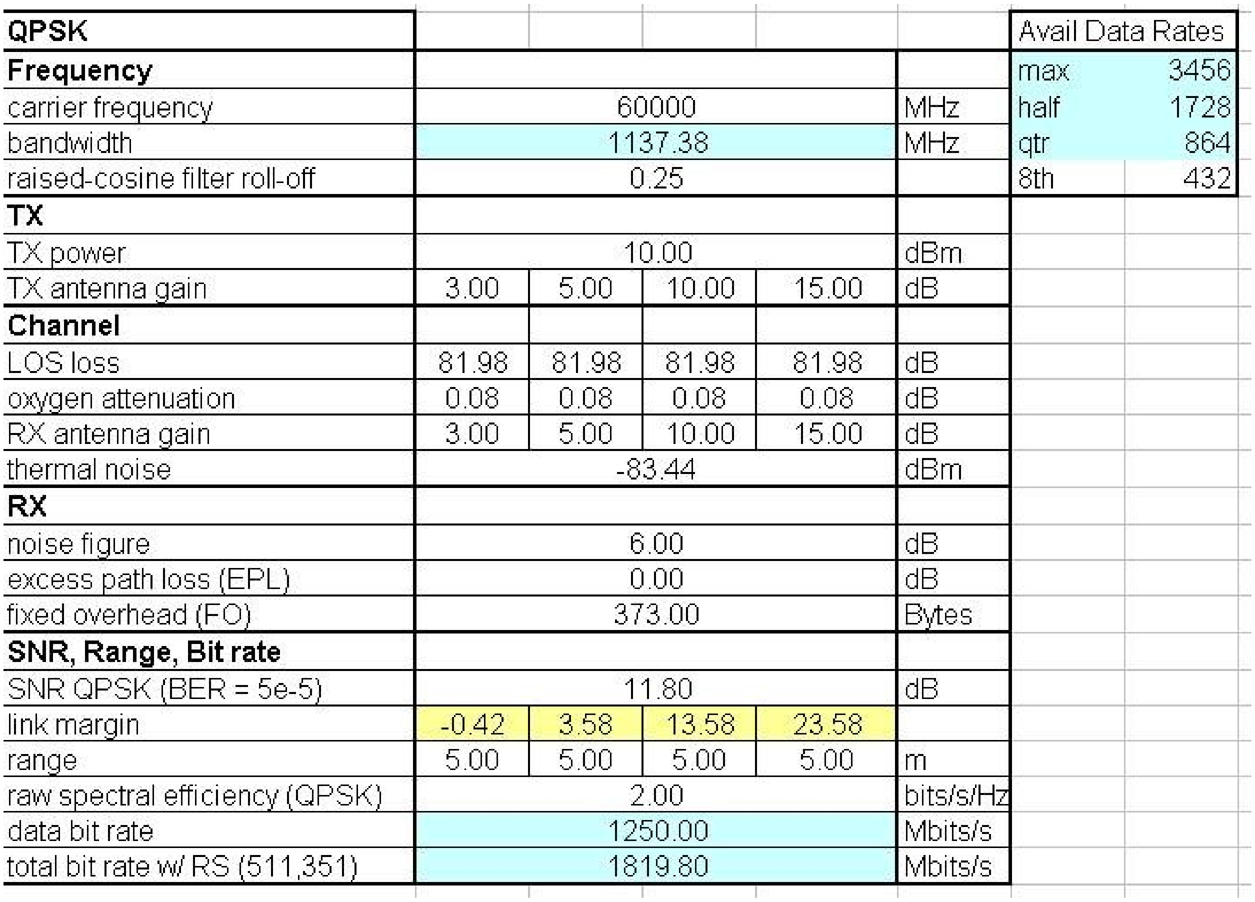
Figure B.4: Spreadsheet link budget analysis for QPSK.



QPSK					
Frequency					
carrier frequency	60000				MHz
bandwidth	781.25				MHz
raised-cosine filter roll-off	0.25				
TX					
TX power	10.00				dBm
TX antenna gain	3.00	5.00	10.00	15.00	dB
Channel					
LOS loss	81.98	81.98	81.98	81.98	dB
oxygen attenuation	0.08	0.08	0.08	0.08	dB
RX antenna gain	3.00	5.00	10.00	15.00	dB
thermal noise	-85.07				dBm
RX					
noise figure	6.00				dB
excess path loss (EPL)	0.00				dB
fixed overhead (FO)	373.00				Bytes
SNR, Range, Bit rate					
SNR QPSK (BER = 5e-5)	11.80				dB
link margin	1.21	5.21	15.21	25.21	
range	5.00	5.00	5.00	5.00	m
raw spectral efficiency (QPSK)	2.00				bits/s/Hz
data bit rate	1250.00				Mbits/s
total bit rate	1250.00				Mbits/s

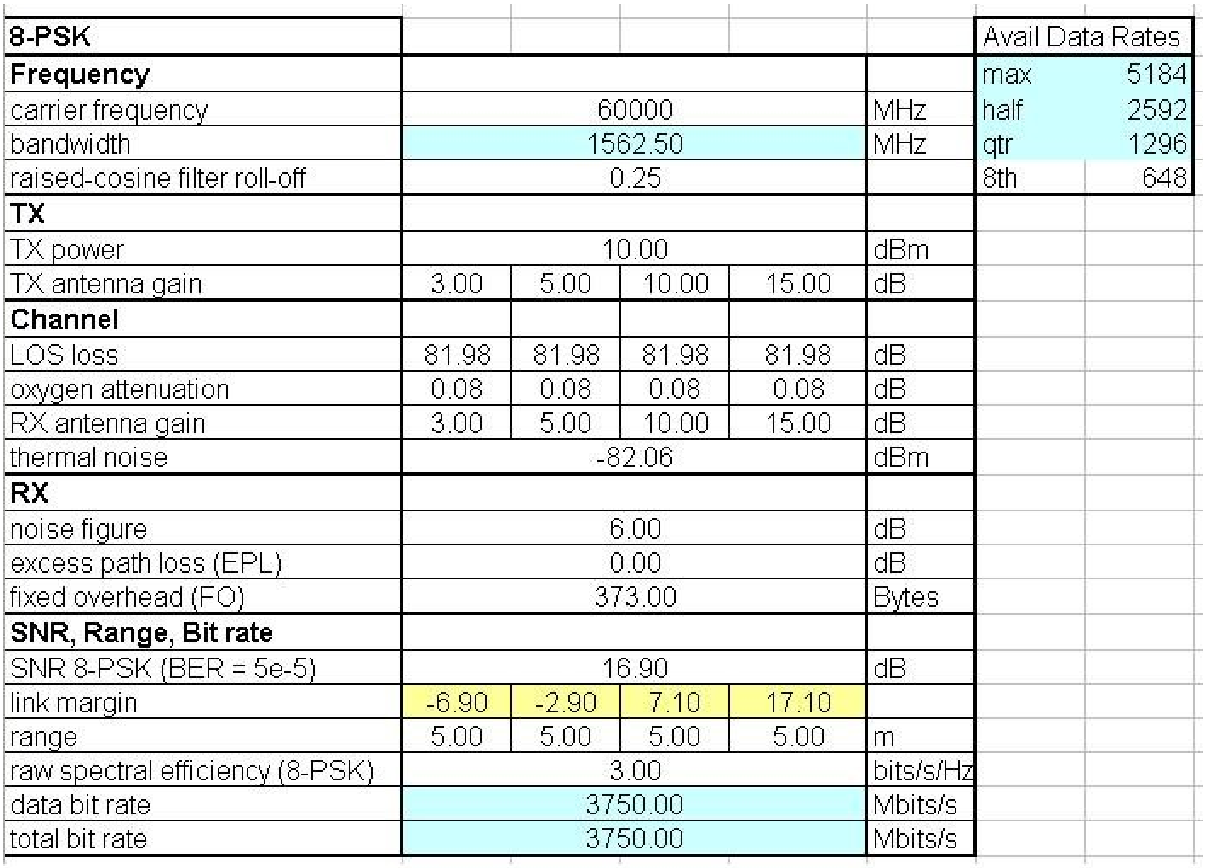
Avail Data Rates	
max	3456
half	1728
qtr	864
8th	432

Figure B.5: Spreadsheet link budget analysis for half-rate QPSK.



QPSK						Avail Data Rates	
Frequency						max	3456
carrier frequency	60000				MHz	half	1728
bandwidth	1137.38				MHz	qtr	864
raised-cosine filter roll-off	0.25					8th	432
TX							
TX power	10.00				dBm		
TX antenna gain	3.00	5.00	10.00	15.00	dB		
Channel							
LOS loss	81.98	81.98	81.98	81.98	dB		
oxygen attenuation	0.08	0.08	0.08	0.08	dB		
RX antenna gain	3.00	5.00	10.00	15.00	dB		
thermal noise	-83.44				dBm		
RX							
noise figure	6.00				dB		
excess path loss (EPL)	0.00				dB		
fixed overhead (FO)	373.00				Bytes		
SNR, Range, Bit rate							
SNR QPSK (BER = 5e-5)	11.80				dB		
link margin	-0.42	3.58	13.58	23.58			
range	5.00	5.00	5.00	5.00	m		
raw spectral efficiency (QPSK)	2.00				bits/s/Hz		
data bit rate	1250.00				Mbits/s		
total bit rate w/ RS (511,351)	1819.80				Mbits/s		

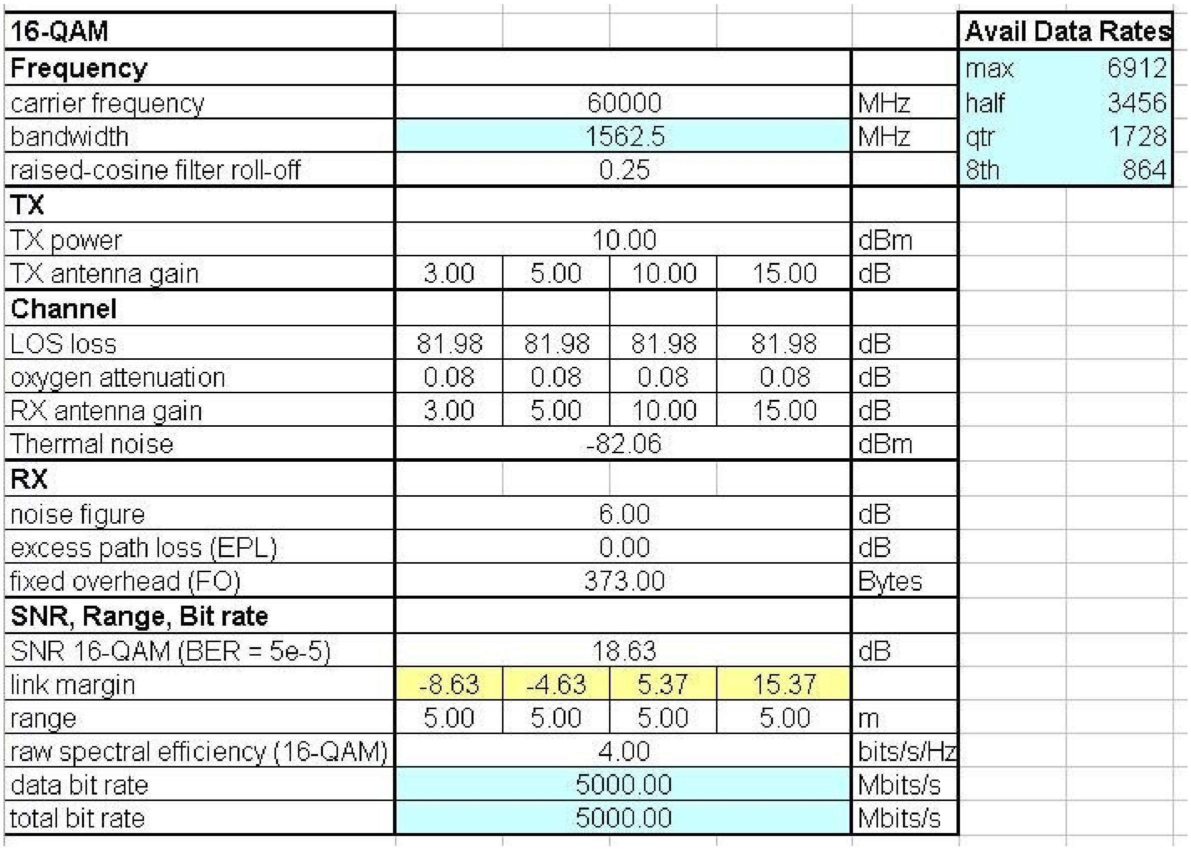
Figure B.6: Spreadsheet link budget analysis for half-rate QPSK with RS(511,351) coding.



8-PSK					
Frequency					
carrier frequency	60000				MHz
bandwidth	1562.50				MHz
raised-cosine filter roll-off	0.25				
TX					
TX power	10.00				dBm
TX antenna gain	3.00	5.00	10.00	15.00	dB
Channel					
LOS loss	81.98	81.98	81.98	81.98	dB
oxygen attenuation	0.08	0.08	0.08	0.08	dB
RX antenna gain	3.00	5.00	10.00	15.00	dB
thermal noise	-82.06				dBm
RX					
noise figure	6.00				dB
excess path loss (EPL)	0.00				dB
fixed overhead (FO)	373.00				Bytes
SNR, Range, Bit rate					
SNR 8-PSK (BER = 5e-5)	16.90				dB
link margin	-6.90	-2.90	7.10	17.10	
range	5.00	5.00	5.00	5.00	m
raw spectral efficiency (8-PSK)	3.00				bits/s/Hz
data bit rate	3750.00				Mbits/s
total bit rate	3750.00				Mbits/s

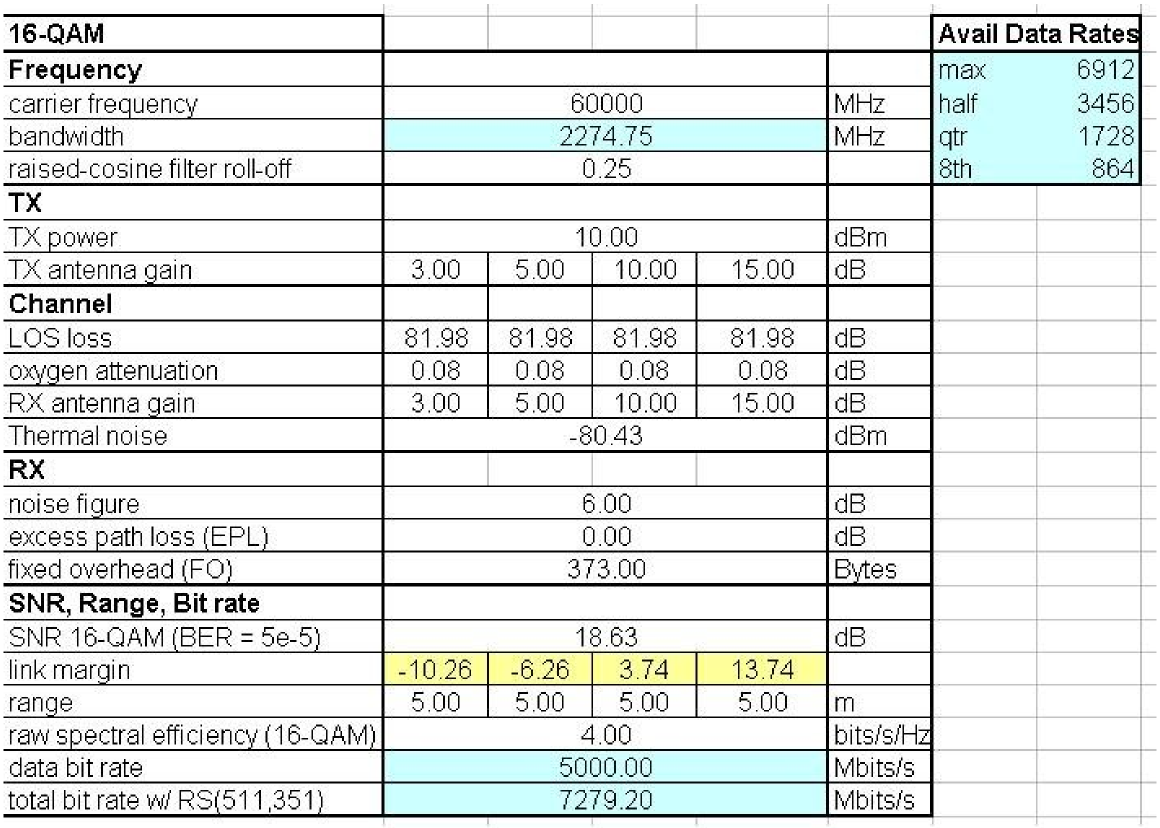
Avail Data Rates	
max	5184
half	2592
qtr	1296
8th	648

Figure B.7: Spreadsheet link budget analysis for 8-PSK.



16-QAM						**Avail Data Rates**	
Frequency						max	6912
carrier frequency	60000				MHz	half	3456
bandwidth	1562.5				MHz	qtr	1728
raised-cosine filter roll-off	0.25					8th	864
TX							
TX power	10.00				dBm		
TX antenna gain	3.00	5.00	10.00	15.00	dB		
Channel							
LOS loss	81.98	81.98	81.98	81.98	dB		
oxygen attenuation	0.08	0.08	0.08	0.08	dB		
RX antenna gain	3.00	5.00	10.00	15.00	dB		
Thermal noise	-82.06				dBm		
RX							
noise figure	6.00				dB		
excess path loss (EPL)	0.00				dB		
fixed overhead (FO)	373.00				Bytes		
SNR, Range, Bit rate							
SNR 16-QAM (BER = 5e-5)	18.63				dB		
link margin	-8.63	-4.63	5.37	15.37			
range	5.00	5.00	5.00	5.00	m		
raw spectral efficiency (16-QAM)	4.00				bits/s/Hz		
data bit rate	5000.00				Mbits/s		
total bit rate	5000.00				Mbits/s		

Figure B.8: Spreadsheet link budget analysis for 16-QAM.



16-QAM					
Frequency					
carrier frequency	60000				MHz
bandwidth	2274.75				MHz
raised-cosine filter roll-off	0.25				
TX					
TX power	10.00				dBm
TX antenna gain	3.00	5.00	10.00	15.00	dB
Channel					
LOS loss	81.98	81.98	81.98	81.98	dB
oxygen attenuation	0.08	0.08	0.08	0.08	dB
RX antenna gain	3.00	5.00	10.00	15.00	dB
Thermal noise	-80.43				dBm
RX					
noise figure	6.00				dB
excess path loss (EPL)	0.00				dB
fixed overhead (FO)	373.00				Bytes
SNR, Range, Bit rate					
SNR 16-QAM (BER = 5e-5)	18.63				dB
link margin	-10.26	-6.26	3.74	13.74	
range	5.00	5.00	5.00	5.00	m
raw spectral efficiency (16-QAM)	4.00				bits/s/Hz
data bit rate	5000.00				Mbits/s
total bit rate w/ RS(511,351)	7279.20				Mbits/s

Avail Data Rates	
max	6912
half	3456
qtr	1728
8th	864

Figure B.9: Spreadsheet link budget analysis for 16-QAM with RS(511,351) coding.