Design and Performance of Packet Retransmission Diversity Schemes for Wireless Networks

MIKAEL GIDLUND

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Doctoral Thesis in
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Abstract

High data-rate wireless access systems is currently under discussion since the demand for wireless multimedia communication is rapidly increasing due to strong advances in wireless Internet services. Reliable high-speed data communications is one of the major challenges on harsh conditions. With the need for high data rates, linear multi-level modulation schemes are becoming more and more important in wireless communication systems since they are bandwidth efficient.

In this thesis we design and evaluate protocols for improving system performance in combining ARQ-induced retransmissions through multipath channels in order to reduce the latency and improve the system throughput. We begin by showing that employing simple packet combining schemes to wireless LANs such as IEEE 802.11, a considerable performance gain can be achieved with a very small cost in complexity.

We evaluate a low-complexity method for enhancing and exploiting retransmission diversity by varying the bit-to-symbol mapping for each retransmission of a packet. The selected mappings are chosen to maximize a bit log-likelihood ratio (LLR) based metric. We also propose an ARQ-scheme that uses the modulation level as an extra dimension to improve the quality of the signal and to reduce the number of retransmissions needed for successful packet transfer. Obtained results show that by varying the bit-to-symbol mapping among retransmissions substantial performance gain can be achieved.

Multiple antenna systems with ARQ functionality are also evaluated. A space-time block coded hybrid ARQ scheme is considered which exploiting both the spatial and time diversity of the MIMO channel. We also consider bit-to-symbol mapping ARQ scheme suitable for multiple antenna systems.

List of Papers

Papers included in this thesis:

A. M. Gidlund and S. B. Slimane, "Performance enhancement of Wireless LANs through packet combining," *Proc. IEEE Vehicular Technology Conference,* Rhodes, Greece, May 2001.

B. M. Gidlund, "Receiver-based Packet Combining in IEEE 802.11a Wireless LAN," in *Proc. Radio and Wireless Conference,* Boston, USA, Aug. 2003.

C. M. Gidlund, "An Approach for Adaptive Error Control in Wireless LAN with CSMA/CA MAC protocol," *Proc. IEEE Vehicular Technology Conference*, Birmingham, Alabama, USA, May 2002.

D. M. Gidlund and Y. Xu, "Performance evaluation of different ARQ schemes in HIPERLAN/2 systems," *Proc. China Wireless Congress,* Hangzhu, China, October 2002.

E. M. Gidlund and P Åhag, "Enhanced HARQ scheme based on Rearrangement of Signal Constellations and Frequency Diversity for OFDM Systems," *Proc. Vehicular Technology Conference,* Milano, Italy, 17-19 May 2004.

F. M. Gidlund, "Retransmission Diversity Schemes for Multicarrier Modulations," *Submitted.*

G. M. Gidlund, "On packet retransmission diversity scheme with MQAM in fading channels," *Proc. Wireless 2005,* Calgary, Canada, July 2005.

H. M. Gidlund, "A novel combined packet retransmission diversity and multilevel modulation scheme," *Submitted.*

I. M. Gidlund, "Performance of coded packet retransmission diversity schemes," *Submitted.*

J. M. Gidlund, "Packet combined ARQ scheme utilizing unitary transformation in multiple antenna transmission," *Proc. 8th International Symposium on Wireless Personal Multimedia Communication,* Aalborg, Denmark, Sept. 2005.

K. M. Gidlund, "STBC-based ARQ scheme for multiple antenna system," *Proc. 2nd International Symposium on Wireless Communication Systems 2005,* Sept. 2005.

L. M. Gidlund, "An Improved ARQ scheme with application for multi-level modulation in MIMO systems," *Proc. International Symposium on Information Theory and its Applications,* Parma, Italy, Oct. 2004.

Papers by the author but not included in the thesis

1. M. Gidlund, "Precoded Closed-Loop MIMO-OFDM System Using Predefined Set of Rotation Matrices", *IEE Electronics Letters,* March 2005
2. M. Gidlund, *On Packet Retransmission Diversity Schemes for Wireless Networks,* Licentiate Thesis, TRITA-S3-RST0408, Royal Institute of Technology, Sweden, Dec. 2004.
3. M. Gidlund and Y. Xu, "Performance of Enhanced ARQ Scheme Suitable for Multi-Level Modulation Techniques," *Proc. IEEE ISCIT04*, Sapporo, Japan, October 2004.
4. M. Gidlund and P. Åhag, "A CRC-based Link adaptation Algorithm for IEEE 802.11a Wireless LAN," *Proc. Asia-Pacific Conference on Communications*, Penang, Malaysia, 2003.
5. M. Gidlund and P. Åhag, "Performance and Capacity Improvements of OFDM Wireless LANs with Multiple Antennas and Subchannel Power Control," *Proc. ICT'03*, Tahiti, French Polynesia, Feb. 24-28, 2003.
6. M. Gidlund and Y. Xu, "Enhancement of Throughput and Range in HIPERLAN/2 Systems using Space-Time Coding ," *Proc. ECWT'02*, Milano, Italy, Sept. 26-27, 2002.
7. M. Gidlund, "Enhancement of HIPERLAN/2 Systems using Space-Time Coding," *Proc. European Wireless 2002*, Florence, Italy, February 26-28, 2002.
8. J. Kirrander and M. Gidlund, "Progress in Wireless Radio Architecture," *Proc.* 10^{th} *Annual Virginia Tech Symposium on Wireless Personal Communications*, Blacksburg, Virginia, June 14-16, 2000.

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List of Abbreviations

3G	Third Generation
3GPP	Third Generation Partnership Project
ACK	Acknowledgment
ADSL	Asymmetric Digital Subscriber line
AM	Amplitude Modulation
AMC	Adaptive Modulation and Coding
AMPS	American Mobile Phone System
AP	Access Point
ARQ	Automatic Repeat reQuest
AWGN	Additive White Gaussian Noise
BCH	Bose-Chaudhuri-Hocquenghem
BER	Bit Error Rate
BICM	Bit-Interleaved Coded Modulation
BLAST	Bell-Labs Layered Space-Time
BPSK	Binary Phase Shift Keying
BSS	Basic Service Set
CDMA	Code Division Multiple Access
CRC	Cyclic Redundancy Check
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
DAB	Digitial Audio Broadcast
D-BLAST	Diagonal Bell-Labs Layered Space-Time
DECT	Digitial Enhanced Cordless Telecommunications
DS-CDMA	Direct Sequence CDMA
DVB	Digital Video Broadcasting
ETSI	European Telecommunication Standards Institute
FCS	Frame Check Sequence
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FER	Frame Error Rate
FH-CDMA	Frequency Hopping CDMA
GSM	Global System for Mobile Communication
HARQ-I	Type-I Hybrid ARQ
HARQ-II	Type-II Hybrid ARQ

HIPERLAN	High Performance Radio Local Area Network
HSDPA	High-Speed Downlink Packet Access
IEEE	Institute of Electrical and Electronics Engineers
ISI	Inter-Symbol Interference
IR	Incremental Redundancy
LA	Link Adaptation
LLR	Log-likelihood Ratio
MA	Multiple Access
MAC	Medium Access Control
MAI	Multiple Access Interference
MIMO	Multiple-Input Multiple-Output
MISO	Multiple-Input Single-Output
ML	Maximum Likelihood
MLM	Multi-Level Modulation
MMSE	Maximum Likelihood Sequence Estimate
MPDU	MAC Protocol Data Unit
MPSK	M-symbol Phase Shift Keying
MRC	Maximum Ratio Combining
MSDU	MAC Service Data Unit
MT	Mobile Terminal
NACK	Negative ACK
NMT	Nordic Mobile Telephony
OFDM	Orthogonal Frequency Division Multiplex
PAM	Pulse Amplitude Modulation
PER	Packet Error Rate
PEP	Pairwise Error Probability
PHS	Personal Handyphone System
PHY	Physical Layer
PLCP	Physical Layer Convergence Procedure
PPDU	PLCP Protocol Data Unit
PRMA	Packet Reservation Multiple Access
QAM	Quadrature Amplitude Modualtion
QoS	Quality-of-Service
QPSK	Quadrature Phase Shift Keying
RCPC	Rate Convolutional Punctured Codes
RMS	Root Mean Square
RS	Reed-Solomon
SIMO	Single-Input Multiple-Output
SINR	Signal-to-Interference plus Noise Ratio
SISO	Single-Input Single Output
SNR	Signal-to-Noise Ratio
STA	Station
STBC	Space-Time Block Coding
STC	Space-Time Coding

STTC	Spcae-Time Trellis Codes
TCM	Trellis Coded Modulation
TDMA	Time Division Multiple Access
UTRA	UMTS Terrestrial Radio Access
WCDMA	Wideband CDMA
V-BLAST	Vertical Bell-Labs Layered Space-Time
WLAN	Wireless Local Area Network
WSSUS	Wide Sense Stationary Uncorrelated Scattered
ZF	Zero Forcing

Part I

Chapter 1

Introduction

The use of wireless communication has literally exploded during recent years and not long a go was a mobile phone seen as a luxury item and status symbol affordable by only a few. Nowadays, wireless communication is taken for granted and a mobile phone a natural accessory for many people. Driven by the demand for land-mobile communication, wireless networks have been deployed around the world. So far, voice communications have been the major application. Current second generation networks such as the widespread GSM system have been designed with this primarily in mind. In the future, it is envisioned that data services providing, for example, Internet access will be another popular application. If the predictions come true, it is likely that there will be a strong demand for data rates dramatically higher than the rather limited communications speed provided by present second generation equipment. Infrastructure for WCDMA and other third generation networks have therefore recently started to be deployed with the hope of offering significantly higher data rates than what has been previously possible.

In parallel with the evolution of cellular systems, Wireless Local Area Networks (WLANs) has emerged as complementary service offering for mobile operators. The advent of the WLAN opens up a whole new definition of what a network infrastructure can be. No longer does an infrastructure need to be solid and fixed, difficult to move, and expensive to change. Instead, it can move with the user and change as fast as the organization does. Compared to a cellular system, WLANs can offer higher capacity within a smaller area and is particulary suitable form of alternative access at indoor public hot-spots, such as airport lounges, hotels, and conference areas.

In order for a wireless network to accommodate many users and provide high data rates within the typically limited radio spectrum available, it is important that the system is spectrally efficient. In essence, the system should provide as high data rates as possible using the least amount of bandwidth with the minimum of errors in the communication. The imperfections of the wireless communication channel, not to mention constraints on cost and size of equipment, make achieving this a challenging task.

In mobile wireless communications, the information signals are subjected to distortions caused by reflections and diffractions generated by the signals interacting with obstacles and terrain conditions. The above described phenomena is called *fading* and decreases the performance of the system. One kind of fading is frequency-selective fading which creates inter-symbol interference (ISI). Frequency-selective fading occurs when the transmitted signal is reflected at objects in the vicinity of the transmitter and receiver. The problem with ISI can be solved by employing an equalizer or the use of multi-carrier modulation such as Orthogonal Frequency Division Multiplexing (OFDM). In OFDM, the idea is to split the high transmission data rate into several low rates and transmit them in parallel, each on a different subcarrier which render in that the frequency-selective fading channel is transformed into a set of parallel flat fading channels which can be combated by insertion of guard interval between consecutive blocks. OFDM is now used is digital broadcasting, ADSL and in wireless LANs such as IEEE 802.11a/g and HIPERLAN/2.

To achieve low error rates in the transmitted data stream, error control techniques is employed to protect the digital data by selectively introduce redundancy in the transmitted data stream. Traditionally, we divide error control techniques in two approaches: 1) Forward error correction (FEC) is used for error correction and do not need any feedback link but one drawback is that FEC needs a lot of parity bits for providing reliable data transmission. 2) ARQ schemes are often used in data transmission where the transmission delay is not critical and a feedback channel is available.

Since FEC decoding errors are far more probable than undetected errors, ARQ protocols are sometimes preferred over FEC coding for systems that require low bit error rate. ARQ protocols also offer more flexibility with the choice of retransmission format, and often require less computational complexity at the receiver. Yet, FEC coding is prevalent, it is fairly common to include FEC coding with an ARQ protocol. This results in a hybrid ARQ (HARQ) protocol, where both error detection and correction are utilized. FEC coding alone can not guarantee the avoidance of decoder errors, but including ARQ in the system can guarantee this. Thorough analyses of ARQ protocols are available in the works of Lin *et al.* [52] and Wicker [79].

The development and exploitation of ARQ protocols has been a subject of much research. Most of this research is from a coding perspective, and many of the effects encountered at the physical layer are ignored and not exploited. The motivation of this work is to describe and propose new approaches for handling packet retransmission that exploit various aspects of the physical layer in order to enhance the robustness and enhance the overall capacity within the system. These approaches center upon combining multiple transmissions of a packet, focusing on the signal processing at the physical layer. In this chapter, we first discuss some of the basic principles that govern ARQ protocols. This is followed

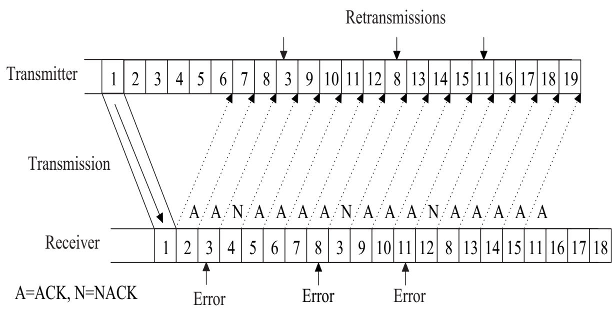


Figure 1.1: Selective-repeat ARQ scheme.

by a summary of some popular packet combining schemes.

1.1 Fundamentals of ARQ

For any erroneous packet, there are two fundamental aspects that all ARQ protocols must consider.

First, while retransmission of a packet is requested and transmitted, some strategy for handling subsequent packets are necessary. Three primary strategies exist in the literature: stop-and-wait (SW), go-back-N (GBN), and selective repeat (SR). These strategies was first discussed by Benice and Frey [5]. The SW strategy requires the transmitter to transmit a packet and wait idly until either a confirmation of successful reception or a request for retransmission is made by the receiver. This provides very low throughput, but requires no buffering of packets. With the GBN strategy, the transmitter continually sends packets until a retransmission request comes from the receiver, the transmitter then halts, backtracks to the desired packet, and resumes transmission from that point. No buffering is done at the receiver, and packets received after the erroneous packet is discarded until a retransmission of the erroneous packet is received. This improves the throughput provided by SW, but there are substantial numbers of transmitted packets that are ignored and thus retransmitted unnecessarily. The SR strategy is the GBN strategy except that the receiver do not discard packets received after the retransmission request (see Fig. 1.1). Throughput is only affected by the necessary retransmissions, at the expense of some type of buffer for erroneous packets at the receiver. Several strategies exist in the literature that mix two or three of these strategies; they usually involve SR with switching to GBN when receiver buffer overflows occur [57], [83].

The second fundamental aspect of ARQ is that most modern ARQ protocols exploit information from previous transmissions of a packet in detecting the current retransmission of a packet. Packet combining for ARQ was first introduced by Sindhu, who suggested that all copies of a packet should be combined into a single, more reliable packet [70]. Most combining schemes are categorized as either a code combining or diversity combining scheme. In code combining schemes, multiple transmissions of a packet is concatenated to form a single, much longer packet. This concatenation is viewed as a very long codeword from a low-rate encoder. The first code combining scheme was proposed by Chase, who developed a maximum-likelihood combining scheme for an arbitrary number of coded packets, concatenating M copies of a codeword into a single codeword [12]. Harvey and Wicker proposed several ARQ strategies, including an approach where soft-decoded codewords from multiple packet transmissions are combined into a single soft codeword [40]. In these schemes, it is sometimes advantageous to not retransmit an identical copy of a packet, but additional parity or code bits that correspond to a lower-rate code.

Diversity combining schemes avoid concatenating altogether; they usually involve some joint processing of all transmissions. Due to the delay between the retransmission request and the retransmission itself, the retransmitted packet is corrupted by an independent set of noise samples. Additionally, the effects of the transmission channel may vary so that each transmission appears to experience an independent channel. The diversity effect produced at the receiver, by these independent channel and noise realizations, leads to better detection of the packet of interest. A simple example involves summing together L noise-corrupted packets, producing a single packet whose signal-to-noise ratio (SNR) is L times that of any of the constituent packets. Haugenauer, Rowitch, and Milstein, have developed combining schemes involving rate-compatible codes, where retransmitted copies of a packet are each uniquely punctured to improve throughput [39], [68].

There are other concerns, sometimes overlooked, that must be addressed with ARQ protocols. Requests for retransmissions imply three properties of the system:

- there is a feedback channel available from the receiver back to the transmitter,
- the transmitter and receiver can effectively identify and/or reference packets and
- the receiver has error detection capabilities.

Typically, low throughput is needed from the feedback channel, and very powerful FEC coding is implemented. Thus, feedback channels are usually considered to be error-free which is also the case in this work. In cases where feedback channels incur errors, the transmitter and/or receiver uses a timer to ensure that retransmission is performed. To easily identify packets, Lin and Costello suggest several schemes for numbering packets [52]. Finally, a very common error detection mechanism employs a cyclic redundancy check (CRC) code by appending the parity bits, produced by CRC coding the message bits, to the packet. CRC leads to very efficient encoding and decoding algorithms, and the probability of undetected error for 16-bit and 32-bit CRC codes is approximately 10^{-5} respectively 10^{-10}. Another criteria for retransmission requests, specific to some type of soft detection or decoding, could be the estimated SNR of the receivers soft bit estimates. Wicker detailed a third criteria for HARQ protocols, where retransmission requests are made when FEC decoder failures occur [79].

With hybrid ARQ protocols, they generally fall into two categories or types. Type I HARQ protocol are fairly simple: the packet is retransmitted without modification and no packet combining is performed. Type II HARQ protocols are distinguished by their use of incremental redundancy (IR). In [55], Mandelbaum introduced incremental redundancy and describes the production of additional parity bits (of the packet) that constitute the retransmissions. The receiver appends these parity bits to the previously received transmissions to form one long codeword. Thus incremental redundancy is a form of code combining. One major difference with IR and Chase combining is that in IR every retransmission must be separately demodulated and buffered at the receiver side.

1.2 Motivation

The objective of this work is the development of diversity combining ARQ schemes that concentrate on the various features at the physical and MAC layer of communication systems. These features will include signal modulation/demodulation, interleaving, detection algorithms and access protocols. This objective is motivated by two observations. First, as evident from the discussion on ARQ fundamentals, there is a strong relationship between FEC coding and ARQ protocols. As a result, most ARQ protocols resemble some sort of delayed coding strategy, as is the case with code combining. For most part, retransmissions are restrictively viewed as additional parity information. Most diversity combining techniques only consider the independence of noise realizations and some alternatives have been proposed. Second, the signal processing and communication community is replete, with diversity enhancing methods that improve system performance. A prime example is space-time coding, where spatial and temporal diversity are combined to increase system capacity. FEC coding is a form of time diversity. Another example is fractional sampling or oversampling communications, with the receiver sampling the transmitted signal at some multiple L of the symbol rate [64]. It will be shown in this work that by varying the bit-to-symbol mapping a substantial performance gain can be achieved. For fading channels spatial diversity is utilized by multiple receiver antennas. This also is equivalent to receiving L independent copies of a transmitted packet. Similarly, packet retransmission are a form of time diversity (retransmission diversity) that can be exploited via pre-processing at the transmitter and/or postprocessing at the receiver. While some work exists that join signal processing and retransmission diversity, many capabilities of this partnership have yet to be studied. This serves as the motivation and underlying theme of this work.

1.3 Main Contributions

The contributions of this thesis are:

- A study of the usefulness of utilizing different packet combining methods in wireless local area networks. It was shown that system performance is increased with packet combining without significantly increase in complexity. Related publications are enclosed in appendix A-E.
- A study about mapping diversity where the optimum mappings are chosen to maximize a bit log-likelihood ratio (LLR) based metric. The analytical results are shown to agree very well with the simulation results. Furthermore, we also discuss generalized mapping diversity to allow for greater flexibility in retransmission formatting and the presence of error control coding. The symbol mapping diversity method is also evaluated for multicarrier modulation. Related publications are enclosed in appendix F-G.
- A study of combined orthogonal transmitter diversity and multi-level linear modulation techniques. The idea is to view the signal constellations of the modulation in an augmented signal space formed by the modulation signal dimension and the number of branches of the transmitter diversity scheme. The obtained results show that this combined scheme is effective in fading channels and also bandwidth efficient. Related publication is enclosed in appendix H.
- A study of three different ARQ protocols in MIMO systems. Unitary transformation prior to the encoding is considered to create an artificially diversity in flow fading channels. Furthermore, an Alamouti-based HARQ scheme is evaluated. Related publications are enclosed in appendix I-K.

1.4 Thesis Outline

In Part I, Chapter 2 gives a brief introduction to the communication system, and how to combat signal fading in an effective way. Furthermore, we discuss different packet combining methods and performance measures. Chapter 3 treats the performance of different packet combining methods in wireless LANs. The mapping diversity in retransmissions are discussed in Chapter 4. The last contribution area is hybrid ARQ transmission in MIMO system, which is covered in Chapter 5. Chapters 3, 4, 5 are all structured in a similar way. First the problem area is introduced introduced to the reader, then comes a review of previous work followed by detailed description of the contribution of the author. Chapter 6, summaries the work and discusses it applicability and extensions to further work.

Part II provides copies of the original papers presented here.

Chapter 2

Preliminaries

In this chapter we summarize some modeling assumptions and performance measure. We start with a general description of the radio link and the radio channel. The effects of the channel on the system performance and the achievable data rate through the channel is then discussed. Two different classes of modulation is considered, namely single carrier modulation and multi-carrier modulation.

Signal manipulations at the receiver play an important role on the reliability of the communication link. We describe some packet combining methods that can be used at the receiver to take advantage of the possible diversity obtained from the replicas of the transmitted signal available.

2.1 Transmitter Model

Considering a general baseband model shown in Fig. 2.1. The source encoder outputs one bit every T_b seconds and we can form a binary message

$$m(t) = \sum_{n=-\infty}^{\infty} d_n g_t(t - nT_b),$$

where $d_n \in \{0, 1\}$ is the digit and g_t is a pulse shaping filter. Depending on the modulation scheme employed, every k consecutive information bits are grouped to form a symbol. With k bits per symbols, there will be a total number of $M = 2^k$ possible symbols in the entire signal constellation Ω ($I_n \in \Omega$). With channel coding, the encoder adds some extra redundancy to the transmitted symbols. The added redundancy is intended to protect the transmitted symbols from interference and fading. Every symbol is then mapped by the digital modulator into a waveform to form the quadrature components of the analog transmitted signal. The equivalent lowpass of the transmitted signal can be written as

$$s_l(t) = \sum_{n=-\infty}^{\infty} I_n g_t(t - T_s),$$

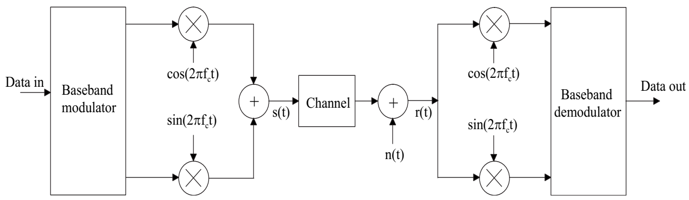


Figure 2.1: Baseband model of transmitter and receiver.

where $I_n = A_n + jB_n$ is the baseband modulated symbol, T_s is the symbol duration and g_t is the transmitted pulse shape. For unfiltered signals, g_t is a rectangular pulse of duration T_s. The equivalent lowpass signal is then upconverted to the carrier frequency to form the transmitted radio signal

$$s(t) = Re\{s_l(t)e^{j2\pi f_c t}\} = A(t)\cos(2\pi f_c t + \theta(t))$$

where $A(t)$ is the amplitude function and θ is the phase function of $s(t)$. We define f_c as the carrier frequency.

2.2 Modulation Techniques

In this thesis we limit ourselves to linear modulation techniques. Linear modulation techniques are bandwidth efficient and therefore well suited for wireless communication where the bandwidth is a scarce resource. Although, one should also consider that these modulation schemes are power demanding and has a required transmitted power that increases when the modulation level M is increasing. Later on, we will see that the modulation level M can be used very well in conjunction with diversity system to reduce the required power without any increase in complexity with comparison to other methods.

The waveforms used by the channel encoder can be represented as vectors in a linear vector space dimension of n, where n is related to the bandwidth and duration of the waveforms.

2.2.1 Pulse Amplitude Modulation

For Pulse Amplitude Modulation (PAM), the equivalent lowpass of the transmitted signal is given by

$$s_l(t) = \sum_{n=-\infty}^{+\infty} A_n g_t(t - nT_s),$$

where $A_n \in \{(2m-1-M)d,\ m = 1, 2, \cdots, M\}$, d is a constant related to the average energy per symbol, and M is the modulation level. Since, PAM signals are one-dimensional, they do not take full advantage of the used bandwidth. Although, the reason for studying M-PAM is its important relation to the practically much more appealing quadrature modulation described in the next section.

2.2.2 Quadrature Amplitude Modulation

Quadrature Amplitude Modulation (QAM) is a modulation scheme that tries to remedy the problem of pulse amplitude modulation. QAM modulation uses the two quadrature components of the carrier signal by transmitting a PAM signal on each component. Since the quadrature components of the carrier signal are orthogonal, QAM allows a doubling in the transmission rate without any extra bandwidth needed. Thus, quadrature amplitude modulation can be seen as a two $\sqrt{M}$-PAM modulation schemes in parallel, one on the inphase component and one on the quadrature component of the carrier signal. The baseband modulated M-QAM signal is given by

$$s_l(t) = \sum_{n=-\infty}^{+\infty} (A_n + jB_n)\, g(t - nT_s),$$

where $A_n \in \{(2m - 1 - \sqrt{M})d,\ m = 1, 2, \cdots, \sqrt{M}\}$ and $B_n \in \{(2m - 1 - \sqrt{M})d,\ m = 1, 2, \cdots, \sqrt{M}\}$.

2.2.3 Phase Shift Keying

Phase Shift Keying (PSK) is another linear modulation scheme that has been considered and used in wireless applications. PSK modulation has been used extensively in satellite communication and in second generation cellular systems. In PSK modulation all the information is within the carrier phase and the transmitted signal is a constant amplitude signal. With their constant amplitude characteristics, PSK schemes allow the amplifiers at the transmitter to operate near saturation which provides good power efficiency as compared to non-constant envelope signalling. The baseband modulated signal for MPSK signal is given by

$$s_l(t) = A_c \sum_{n=-\infty}^{\infty} e^{j[\theta_n + \phi_m]} g_t(t - nT_s),$$

where A_c is the carrier amplitude and the carrier phase θ is defined as $\theta_n \in \left\{m\frac{2\pi}{M},\ m = 0, 1, \cdots, M - 1\right\}$.

2.2.4 Multi-Carrier Modulation

Recently, another linear modulation technique, known as Orthogonal Frequency Division Multiplexing (OFDM), have gained a lot of attention and have been considered in several wireless applications. OFDM is today used in Digital Audio Broadcasting (DAB), Digital Video Broadcasting (DVB), Wireless Local Area Networks (WLANs), Wireless Local Loop, and others. OFDM allows for high data rate applications and has the capability to operate reliably in severe multipath fading conditions. The idea behind OFDM modulation is to divide the wideband bandwidth into several narrowbands and transmit a low data rate on each narrowband. This procedure gives the possibility to transform a frequency fading channel into flat fading channels in parallel. With the help of a guard time interval, inter-symbol interference can be completely removed and time domain equalization can be completely avoided or reduced to a simple one-tap equalizer in the case of coherent detection. OFDM is a very flexible scheme and can adapt very well to different interference situations. Infact, OFDM is a modulation scheme that gives the possibility to save power where one can easily allocate power only where it is needed.

OFDM can be seen as a second modulation applied to the already baseband modulated signal before signal transmitted. When OFDM modulation is used, the signal is modulated again to give the baseband OFDM modulated signal as

$$s_l(t) = \sum_{n=-\infty}^{\infty} \sum_{k=0}^{N-1} I_{k+nN} g_k(t - nT),$$

where $T = nT_s$ is the duration of the OFDM block, T_s is the symbol duration, I_{k+nN} is the modulated symbol of subcarrier k during the nth OFDM block interval, and $g_k(t)$ is the waveform modulating the data stream k with

$$g_k(t) = \begin{cases} \frac{1}{\sqrt{T}} e^{j2\pi f_k t} & 0 \leq t < T \\ 0 & \text{otherwise} \end{cases},$$

where $f_k = f_0 + k/T$ is the frequency of subcarrier k and f_0 is a constant. Note that each low rate data stream is transmitted over a different subcarrier frequency. These subcarriers overlap in frequency but exhibit orthogonality over each OFDM block interval. This orthogonality property allows the separation and detection of the different symbols of every transmitted OFDM block at the receiver.

In a multipath fading environment the orthogonality property is destroyed by the different delays of the multipath components. A simple procedure to preserve the orthogonality property of OFDM in multipath environment is by introducing a time guard interval between consecutive OFDM blocks. This guard interval is introduced at the transmitter side and then removed at the receiver side before signal demodulation and detection. Having a guard interval larger than the maximum delay spread of the channel we eliminate almost all inter-symbol interference introduced by fading multipath channels. This added guard interval requires some extra transmitted power but in general this extra power is quite small even for moderate number of subcarriers. With a guard interval, the equivalent of the OFDM signals becomes

$$s_l(t) = \sum_{n=-\infty}^{\infty} \sum_{k=0}^{N-1} I_{k+nN} g_k(t - nT_t),$$

where $T_t = T + T_g$ is the total OFDM block duration, T_g is the duration of added time guard interval, and the subcarrier waveform is now given by

$$g_k(t) = \begin{cases} \frac{1}{\sqrt{T_t}} e^{j2\pi f_k t} & -T_g \leq t < T \\ 0 & \text{otherwise .} \end{cases}$$

with f_k as earlier defined.

In wireless communication, the transmitted signal is exposed to external interference, thermal noise, and fading multipath channels. All these effects contribute to the destruction of the wireless communication link and put a limit on the transmission rate and the achieved signal quality. To better design wireless communication systems, good models for these different effects are needed. Having good models give the possibility to study the system performance and the possibility to design good solutions for countering these negative effects.

2.3 Distinctive Properties of the Wireless Channel

Unfortunately, the wireless propagation medium is far from ideal. Additive thermal noise disturbs the information carrying signals. Interference from other wireless users may also plague the transmission. If the noise and interference are sufficiently strong compared to the information carrying signal, it becomes difficult for the receiver to correctly detect the transmitted message. Hence, the signal-to-noise-ratio (SNR) and the signal-to-interference-plus-noise-ratio (SINR) are two relevant parameters. These power ratios are important since they give an indication of the performance of the system and are often relatively easy to measure.

Wireless systems are especially prone to errors in the communication since the signal attenuation incurred by the channel may be very large. This problem is made worse by the fact that the transmitted radio signal interacts with objects in the physical environment [8], [9]. As a result, the signal usually propagates along several different paths before it arrives at the receiver. The phenomenon is termed *multipath* and is illustrated in Fig. 2.2, where only two propagation paths are indicated. Each propagation paths affect the signal differently which means that the received signal is a superposition of different, possibly delayed, versions of the original signal. These multipath components add constructively or destructively, depending on the surrounding terrain and the positions of the transmitter and the receiver. The signal level at the receiver may therefore

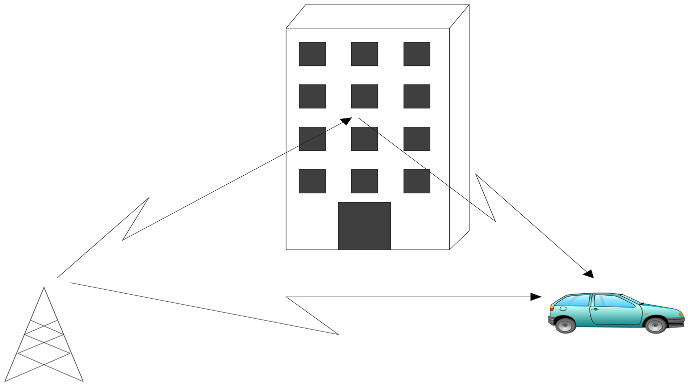


Figure 2.2: The radio signal arrives at the receiver along several different paths, so-called multipath propagation.

fluctuate wildly over time due to changes in the environment and movement of the transmitter/receiver. In the worst case, such channel fading make the attenuation so large that the receiver is unable to obtain a useable signal.

If the *delay spread* [64] of the multipath is small relative to the inverse bandwidth of the transmitted signal, in the individual multipath components are not resolvable and the effective communication channel is therefore essentially frequency-nonselective of flat fading. Consequently, the different frequency components of the information bearing signal undergo the same attenuation and phase shift when propagating through the channel. The channel, including the up- and downconversion in frequency as well as transmit and receive filtering, may then be modeled by a filter with only one complex valued tap, or coefficient. A common assumption is that single channel coefficient that determines the attenuation and phase shift fades according to a complex Gaussian random process [64]. Such fading is also known as flat *Rayleigh* fading, since the magnitude of the channel coefficient is Rayleigh distributed. High data rate communication usually requires such a large bandwidth that at least some of the multipath is resolvable. The result is a frequency-selective fading channel that can be modeled by a finite impulse response filter with several complex-valued taps. In general, the equivalent lowpass of the channel impulse response can be expressed mathematically as follows:

$$h(t, \tau) = \sum_{l=0}^{P-1} \alpha_l(t)\delta(\tau - \tau_l(t)),$$

where P is the total number of paths, $\tau_l(t)$ is the time delay path l and $\alpha_l(t)$ is its attenuation factor.

This way of absorbing the up- and downconversation into an effective channel is common practice in the field of communication theory and leads to so-called complex baseband equivalent model of the system [85], [64]. When using such a model, both the transmitted and received signals, as well a the channel itself, are potentially complex-valued. Also the additive noise may be complex-valued and is often modeled as a wide sense stationary complex Gaussian random process.

2.4 Receiver Model

At the receiver, the received equivalent lowpass signal can be expressed as

$$r_l(t) = \sum_{l=0}^{P-1} \alpha_l(t) e^{-2j\pi f_c \tau_l(t)} s_l(t - \tau_i(t)) + z(t),$$

where $s_l(t)$ is the equivalent lowpass of the transmitted signal, f_c is the carrier frequency, and $z(t)$ is complex Gaussian random variable with zero mean and variance N_0 representing the additive noise.

Assuming a receive filter matched to the transmit filter, the demodulator output sample during the nth symbol interval for single carrier systems can be written as follows:

$$y_n = \alpha_0(n) I_n + \sum_{l=1}^{P-1} \alpha_l(n) I_{n-l} + z(n),$$

where we can see the presence on intersymbol interference. Hence, one has to solve two problems: the ISI problem and the signal fading problem. We assume, in this thesis, that this intersymbol interference has been taken care of with the use of a proper time domain equalizer and we consider possible solutions for solving the problem of signal fading. Here, signal fading is directly related to the fading coefficient $\alpha_0(n)$.

For multicarrier system, intersymbol interference is solved through the use of a proper guard interval. Assuming a time guard interval larger than the maximum delay spread of the channel, the OFDM demodulator output at subcarrier k can be written as follows:

$$y_k(n) = H_k(n) I_{k+nN} + z_k(n),$$

where $H_k(n)$ is the channel transfer function sampled at subcarrier k, i.e.,

$$H_k(n) = \sum_{l=0}^{P-1} \alpha_l(n) e^{-j2\pi\tau_l(n)/T}.$$

Since the coefficients $\alpha_l(n)$ are complex Gaussian, the channel transfer function $H_k(n)$ is also complex Gaussian with normalized variance. We notice that multicarrier modulation techniques can solve the problem of intersymbol interference but do not solve the problem of signal fading. Signal fading is a major problem in wireless communication as it introduces fading dips into the received signal and degrades the link error probability considerably. For instance, the instantaneous signal-to-noise ratio can be written as follows:

$$\Gamma = \frac{a^2 E_s}{N_0},$$

where a is the fading amplitude, E_s is the average energy per symbol, and N_0 is the noise variance. For a flat Rayleigh fading channel, the probability density function of the instantaneous SNR is given by

$$p_\Gamma(\gamma) = \frac{1}{\gamma_0} e^{-\gamma/\gamma_0},$$

where $\gamma_0 = \frac{2\sigma^2 E_s}{N_0}$ is the mean signal-to-noise ratio. In average, 63% of the time the instantaneous SNR is below the average. Hence, to ensure a reliable communication system a high fade margin is needed. Such a solution is not suitable for wireless communication as the size, weight, and power saving are important factor to consider in designing these systems.

2.5 Solving the Problem of Signal Fading

Although the problem with inter-symbol interference can be solved through the employment of time domain equalization or by using multi-carrier modulation techniques with proper time guard interval, we still have to deal with the problem of signal fading. The presence of channel fading is one of the major difficulties associated with wireless communication. An often used strategy for dealing with the fading problem is to employ so-called *diversity* techniques. The basic idea behind diversity is to provide the receiver with several versions of the same information bearing signal where the various versions has been affected by different, preferably independent fading, channels. Hopefully, at least one of the received signals has experienced a channel with little attenuation, thereby increasing the chance that the message can be correct detected at the receiver. It can be shown that the probability of an error in the communication generally decreases with increasing number of signal replicas (assuming that the signal replicas have undergone reasonable independent fading). There exists several methods of providing independent diversity branches to the receiver. These methods try to exploit the space correlation properties of the wireless channel; its frequency correlation properties; its time correlation properties, or a combination. Three examples of common diversity techniques are listed below.

- *Time diversity*: The same information-bearing signal is transmitted in different time slots, with the interval between successive time slots being equal to or greater than the *coherence time* of the channel [64]. If the interval is less than the coherence time of the channel, we still can get some diversity, but at the expense of performance. In any event, time diversity may be likened to the use of repetition code for error-control coding.

- *Frequency diversity*: In the case of frequency-selective fading channel, diversity can be obtained by transmitting the same information on different carrier frequencies. As long as the carrier separation is large compared with the *coherence bandwidth* of the channel [64], the signals experiences roughly independent fading. A more direct but less obvious diversity approach is to transmit on a single carrier but with a bandwidth large enough for some of the multipath components to be resolvable at the receiver. The resulting distortion of the information carrying signal can be handled by appropriate processing at the receiver. In any case, the frequency-selectivity of the channel serves to protect against fading and should hence not only be seen as a problem

- *Space Diversity*: In space diversity, multiple receive or transmit antennas, or both, are used to provide diversity branches to the receiver with the spacing between adjacent antennas being chosen so as to ensure the independence of possible fading events occurring in the channel. In practice, however, we find that antenna spacings which results in correlations as high as 0.7 may incur performance degradation of at most half a decibel, compared with the ideal case of independent channels. Depending on which end of the wireless link is equipped with multiple antennas, we may identify different forms of space diversity.

In wireless data transmission where the delay requirements are not very restrict, adaptive diversity can be used. With adaptive diversity, the receiver can decide on the number of replicas of the transmitted data packet that ensures the required quality. Having a feedback channel between the receiver and the transmitter, the transmitter checks the quality of the received packet and asks for retransmission (replica) only if the quality of the received packet does not satisfy the required quality. Such a procedure is repeated until the packet is properly decoded or ignored (dropped) if the maximum delay has been reached. Hence, we can see ARQ schemes as a diversity scheme with adaptive number of branches. Such scheme is well suited for wireless data communication since it only uses bandwidth and power when needed.

2.6 Different forms of Space Diversity

The use of antenna arrays is seen as a promising approach for coping with many of the problems associated with wireless communication [63]. An array of multiple antennas may be placed at the receiver, the transmitter, or at both sides of the communication link. The antennas in the antenna array are placed at different physical positions in space. Alternatively, the polarization may vary among the antennas. In any case, an antenna array gives the system access to an extra spatial dimension that can be utilized in conjunction with its temporal counterpart for increasing the performance beyond what is possible with single antenna transmission and reception.

2.6.1 Receiver Diversity

The classic use of multiple antennas is to utilize them on the receiver side. The resulting single-input-multiple-output (SIMO) channel provides the receiver with several versions of the transmitted signal. The signals at the receiver can be combined in a way so as to suppress noise and increase the SNR. If the antennas are spaced sufficient far apart for the fading of the individual channels to be reasonable uncorrelated, the antenna outputs may be used to obtain spatial diversity. Well-known techniques that provide maximum possible spatial diversity include antenna selection and maximum ratio combining [45]. In the former method, the antenna output with the strongest signal is selected while in the latter both diversity as well as array gain is obtained by adjusting the phase and amplitude of each signal so that the antenna output add coherently and maximize the SNR. Maximum ratio combining is designed for flat fading scenario and can be seen as implementing a simple spatial filter that is matched to the SIMO channel's coefficients. After the combining, a one-dimensional signal is input to the detector. Thus, an equivalent SISO channel is created with properties better than those of individual SISO channels. In a frequency-selective scenario, the coefficients of a more general spatio-temporal filter structure can be optimized to increase the SNR while equalizing the distortion caused by the channel [3].

2.6.2 Transmit Diversity

Placing multiple antennas at the transmitter and using a single receive antenna creates a multiple-input-single-output (MISO) channel. Multiple signals are now transmitted, instead of received. Because the signals are combined before they are available for receiver processing, schemes for exploiting the spatial domain must be placed on the transmit side. In the downlink it is difficult to utilize receive diversity at the mobile since it is for instance difficult to place more than two receive antennas in a small-sized portable mobile. Therefore it is more practical to install multiple transmit antennas in the base station and provide extra power for multiple transmissions.

The difficulties with utilizing transmit diversity mainly include: 1) since the transmitted signals from multiple antennas are mixed spatially before the arrive at the receiver, some additional signal processing is required at both the transmitter and receiver in order to separate the signals and exploit diversity; and 2) unlike the receiver that can usually estimate fading channels, the transmitter does not have instantaneous information about the channel unless the information is feedback from the receiver to the transmitter [53].

For system with feedback, modulated signals are transmitted from multiple transmit antennas with different weighting factors. The weighting factors are then chosen adaptively so that the received signal power or channel capacity is maximized.

For system without feedback the transmitter is effectively blind since it cannot predict how the channel will affect the transmission. Despite this fact, an antenna array may provide spatial diversity of the same order as when the there is perfect channel knowledge or when the array is placed at the receiver. In [42], phase shifted versions of the same information carrying signals are multiplexed to the different antenna elements. By making the phase shifts time-varying, a possibly static MISO channel is transformed into a fast fading SISO channel. The artificially created time-varying channel is used together with conventional time diversity methods such as coding combined with interleaving [64]. Thus, spatial diversity is transformed into time diversity.

Another way producing similar time-variations is to transmit on only one antenna at a time a let the antennas taka turn to transmit. The effective SISO channel coefficient thus alternates among the coefficients in the MISO channel. Such a time division approach was proposed in [69] where a simple repetition code was used to exploit the resulting temporal variations of the channel. A more bandwidth efficient technique is called delay diversity and was original proposed in [81] and offers diversity by multiplexing time-delayed versions of the same information carrying signal onto the different antennas. The time delay increases linearly from no delay at the first antenna to some maximum delay at the last antenna. Usually, the time delay differs with one symbol period between two consecutive antennas. The result is a tapped delay line SISO channel or, in other words, a frequency-selective channel. Decoding the received signal through the use of a maximum likelihood sequence estimator captures the frequency diversity of the synthetic SISO-system.

Vector codes in transmit antenna array applications are more popularly known as space-time codes and has recently received considerable attention because of the high data rates and reliable communication they may provide. Most of the literature on the design of space-time codes focuses on flat fading scenario in which the receiver is assumed to know the channel state parameters perfectly. An extremely simple yet novel space-time block code for two transmit antennas was given in [2]. The code is commonly known as Alamouti code, which is a simple two branch transmit diversity scheme and has the appealing property that the two antenna signals are orthogonal in time (as well as in space) without the bandwidth expansion normally associated with orthogonal signaling. Another key feature of the scheme is that it achieves full diversity gain with a simple maximum-likelihood decoding algorithm. It is worthwhile to mention that delay diversity schemes can also achieve a full diversity, but they introduce inference between symbols and complex detectors are required at the receiver.

2.6.3 MIMO System

A wireless channel using multiple antennas at both ends is commonly referred as multiple-input multiple-output (MIMO) channel and represent a natural extension of the previously described MISO case. Such dual antenna array system offer more degrees of spatial freedom for the spatio-temporal environments, these extra degrees of freedom lead to a channel capacity substantially higher than when only a single antenna array is used [73], [18].

The use dual antenna arrays in rich scattering environments gives rise to a multiplicative effect that makes the channel capacity increase essentially a constant integer factor faster with respect to the SNR than comparable SISO, MISO or SIMO systems [18]. The numerical value of the factor is given by the minimum of the number of antennas at the transmitter and receiver, respectively. Intuitively speaking, the MIMO channel broadens the channel in the sense that many parallel "data pipes" are available for communication. The number of data pipes corresponds to the multiplicative factor mentioned above. This explains the improvement in capacity compared with systems that do not use MIMO setup. The encouraging capacity results exhibited by MIMO systems suggest that reliable and high data rate communication may be accomplished in ways that do not incur significant bandwidth expansion.

2.7 Packet Combining Techniques

As we are dealing with wireless data transmission we will mainly focus on combining methods for data packets. Transmitted packets usually carry some kind of redundancy (channel coding) and hence the combining method used should take that into account. There exist different techniques of combining retransmitted packets to improve the probability of acceptance of a packet. In this section we will review some of the most familiar combining methods and describe them briefly. In general, we find two classes of packet combining methods: soft packet combining and hard packet combining. As the name indicates, soft combining consists of combining the received soft values of the different elements of the packet followed by decoding and decision. For hard combining, quantization (binary decision) is carried out first followed by decoding and decision. Which method to use depends on the designer. Here going from one combining method to the other we see a tradeoff between performance and complexity.

2.7.1 Majority Logic Combining

Majority logic combining is a hard combining scheme that makes a vote for every symbol of packet by using all the received versions of the packet. The obtained packet after the majority voting is decoded using the decoder of the regular FEC scheme employed. Majority logic combining simply sees the retransmitted packets as a repetitive code with a code block length equals to the number of transmissions at that time instant. Thus, the overall decoder for this scheme is a concatenation of a hard decision repetitive decoder followed by the regular scheme decoder. If decoding fails, a retransmission is requested and the repetitive code length is increased by one and so on until the transmitted packet is successively decoded or dropped due to some delay requirements.

As just mentioned the principle of majority logic combining is quite simple. Let us consider the transmission of a certain binary data packet, $X = \{x_1, x_2, \cdots, x_N\}$ with $x_k \in \{-1, +1\}$, of length N over the wireless communication channel. Denoting by the binary packet $V_i = \{v_{i1}, v_{i2}, \cdots, v_{iN}\}$, with $v_{ik} \in \{-1, +1\}$, the received packet at the detector output corresponding to the ith replica of the transmitted packet X, the decoder input is then given by the packet $Y_i = \{y_{i1}, y_{i2}, \cdots, y_{iN}\}$ with $y_k = \text{majority}\{y_{1k}, y_{2k}, \cdots, y_{ik}\}$ for all possible values of i. After decoding, if the packet is still not reliable a new retransmission is requested and the procedure is repeated until the packet is successfully accepted or dropped if the delay requirements have been reached and the packet is still corrupted.

The advantage of majority logic combining appears in its low complexity and the saving in buffer memory at the receiver. However, this advantage comes at the expense of a poor performance since with hard decision combining we do loose a lot of information about the received data . Variations of majority logic decoding have been considered in the literature but the main idea is similar to the above description [79], [80].

2.7.2 Diversity Combining

Diversity combining is another hard packet combining technique similar to the previous combining method where every element of the combined packet is obtained through a simple linear combination of the different replicas of that elements within the different received packets. Again, we will denote $X = (x_1, x_2, \cdots, x_N)$ with $x_k \in \{-1, +1\}$ the transmitted packet through the wireless communication channel. The received signal corresponding to X is demodulated, deinterleaved, decoded, and checked for errors. If the received packet is corrupted, it is stored in a buffer and a new retransmission is requested. After each retransmission, the stored packets are fed into a combiner. In order to get diversity gain, the stored packets are combined to a packet Y_i which contains likelihood information about the different elements of the packet where i refers to the number of packets (corresponding to $i - 1$ retransmissions). In the combiner, a likelihood calculator calculates the likelihood information by averaging the kth bit in the i received packets. Therefore, the combiner output $Y_i = \{y_{i1}, y_{i2}, \cdots, y_{iN}\}$ may be expressed as follows:

$$y_{ik} = \frac{1}{i} \sum_{n=1}^{i} y_{nk}, \qquad k = 1, 2, \cdots, N.$$

The packet Y_i is then fed to the decoder and checked for possible errors.

Note that the combiner output is $i+1$ levels, that is, $+1, (N-2)/N, (N-4)/N, \cdots$, and -1. Basically, this simple combining procedure generates soft values for elements of the packet from the hard values obtained from the retransmitted packet. Clearly, this combining method has the same complexity as the majority logic combining but should provide much better performance especially for large values of retransmissions.

2.7.3 Chase Combining

Chase combining or code combining is a form form of soft packet combining similar to maximal ratio combining in diversity systems. The fundamental idea with code combining is to combine the different elements of retransmitted packets using some properly chosen combining coefficients. If we denote by $X = (x_1, x_2, \cdots, x_N)$ with $x_k \in \{-1, +1\}$ the transmitted packet through the wireless communication channel. The received signal corresponding to X is first demodulated, deinterleaved, decoded, and checked for errors. If the received packet is corrupted, its soft value r_1 is stored in a buffer and a new retransmission is requested. After each retransmission, the stored packets are fed into a combiner. In order to get diversity gain, the stored packets are combined to a packet Y_i which contains likelihood information about the different elements of the packet where i refers to the number of packets (corresponding to $i-1$ retransmissions). In the combiner, a likelihood calculator calculates the likelihood information by linearly combining the soft values of each symbol in the packet using the i receiver packets (i.e. after $i-1$ retransmissions). Therefore, the combiner output $Y_i = \{r_{i1}, r_{i2}, \cdots, r_{iN}\}$ may be expressed as follows:

$$y_{ik} = \sum_{n=1}^{i} \alpha_{nk} r_{nk}, \qquad k = 1, 2, \cdots, N$$

where $\{\alpha_{nk}\}$ are the combining coefficients and $\{r_{nk}\}$ are soft values. The packet Y_i is then fed to the decoder and checked for possible errors. The combining coefficients are determined based on maximizing the signal-to-noise ratio of the different symbols of the packet which is the basic principle of maximum ratio combining.

Here the combiner output is a soft value. Clearly, this combining method is an improved version of the diversity combining method described earlier and has superior performance. It can easily be seen that optimum code combining is equivalent with maximum-ratio packet combining [7]. A simplified version of Chase combining could be to add the different replicas of each symbol coherently. That is, an equal gain combining method where the replicas of the symbol are co-phased and added. This will give a reduction in system complexity with a slight degradation in performance.

2.7.4 Reliability of Packet Combining Techniques

The idea of packet combining is to try to take advantage of the different replicas of the transmitted packet available at the receiver side. The outcome of this process will of course depend on the kind of packet combining technique used and the wireless channel behavior. There is always a trade-off between performance and complexity. Opting for a simple combining method may cause more harm and results in worse performance than the case of no combining. This could be the case of slowly varying fading multipath channels where one version of the packet could be completely faded and another version with good signal level. A simple hard combining method in this case could introduce more errors than the non-combining case. Hence, the choice of the packet combining method plays an important role in the design of wireless communication systems.

2.8 Performance Measures

We know make some comments in relation to the performance measures we use in this work. It is actually quite easy to come up with a wide range of performance measures, but we will focus on following: *System throughput, packet delay, symbol error probability* and *bit error probability.* System throughput and packet delay are two performance measure that in a sense are complementing to each other. The throughput for a system may be high, and consequently look very good for an operator, while corresponding packet delay may also be high not satisfying the QoS requirements for subscribers.

2.8.1 System Throughput

The throughput is generally defined as the amount of data that is transmitted over the channel during a unit time. In multiple access systems where only one transmission can be successful at any time the throughput is commonly defined as the fraction of time there is a successful transmission on the channel. The throughput is therefore a figure between zero and one.

2.8.2 Packet Delay

An important figure of merit for packet switched systems is the average packet delay. We define the random variable packet delay D_i for a mobile station i as the time between the packet is generated for transmission in the corresponding base station and its successful reception. The average packet delay in a system is defined as

$$E\{D\} = \frac{1}{N} \sum_{i=0}^{N-1} E\{D_i\}, \tag{2.1}$$

where N is the number of stations within the cell.

2.8.3 Symbol Error Probability

The symbol error probability is a natural performance measure with respect to our model setting. It is simply the probability with which a symbol is selected by the channel encoder is not decoded into the same symbol by the channel decoder. Such an event is called a *symbol error* and is important as it measures how well we have succeeded to place our points in the signal space, which is central in any transmitter design.

2.8.4 Bit Error Probability

Although the symbol error probability is a highly relevant performance measure in many communication applications, we pay more attention in this work to a related measure: the bit error probability.

In the two-dimensional signal space that we study, each symbol represents a block of m bits. Assume that a block of m bits, $\mathbf{c}$, is mapped to a signal vector $\mathbf{s}$ and transmitted over the channel. The receiver makes a decision based on the the received signal vector and outputs a decision, $\hat{\mathbf{c}}$, on what block the received vector represents. If $\hat{\mathbf{c}} \neq \mathbf{c}$, a symbol error has occurred and at least one and at most m of the bits in $\hat{\mathbf{c}}$ are in error. The average number of bits that are in error in $\hat{\mathbf{c}}$ is mP_b, where P_b is the bit error probability.

Chapter 3

Packet Combining in Wireless LANs

Wireless LANs is getting a lot of attentions and are being used more and more in public places, airports etc. One drawback with most of todays WLAN system is their lack of robustness in interference and fading multipath channels. It has been proven by employing packet combining in WLAN the system performance is enhanced. This chapter summarize papers **A-D** in the appendix which deals with different approaches of packet combining in WLAN systems.

3.1 Introduction

Wireless local area networks (wireless LANs, or WLANs) are changing the landscape of computer networking. The use of mobile computing devices, such as laptops and personal digital assistants, coupled with the demand for continual network connections without having to "plug in," are driving the adoption of enterprise WLANs. Wireless networks are continuing to advance and are providing high speed and possible alternatives to wired networks. WLAN can provide a completely wireless workplace. The future may see complete high-speed wireless coverage for metropolitan areas with service providers just like mobile phone networks. Several wireless LAN standards have appeared in the last decade. The wireless LAN that dominates the market today is the IEEE 802.11. The current standard does not support specific quality of service needs. It has two different Medium Access Control (MAC) schemes.

The main job of the MAC protocol is to regulate the usage of the medium, and this is done through a channel access mechanism. A channel access mechanism is a way to divide the main resource between nodes, the radio channel, by regulating the use of it. It tells each node when it can transmit and when it is expected to receive data. Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) is the channel access mechanism used by most wireless LANs of today.

The basic principles of CSMA/CA are listen before talk and contention. This is an asynchronous message passing mechanism, delivering a best effort service, but no bandwidth and latency guarantee. The main advantages are that it is suited for network protocols such as TCP/IP, adapts quite well with the variable condition of traffic and is quite robust against interferences. However, its throughput is in general quite low.

CSMA/CA is derived from CSMA/CD (Collision Detection), which is the base of Ethernet. The main difference is the collision avoidance: on a wire, the transceiver has the ability to listen while transmitting and so to detect collisions (with a wire all transmissions have approximately the same strength). But, even if a radio node could listen on the channel while transmitting, the strength of its own transmissions would mask all other signals on the air. So, the protocol can not directly detect collisions like with Ethernet and only tries to avoid them.

The protocol starts by listening on the channel, and if it is found to be idle, it sends the first packet in the transmit queue. If it is busy (either another node transmission or interference), the node waits the end of the current transmission and then starts the contention (wait a random amount of time). When its contention timer expires, if the channel is still idle, the node sends the packet. The node having chosen the shortest contention delay wins and transmits its packet. The other nodes just wait for the next contention (at the end of this packet). A direct consequence of this is that the effective throughput is lower than the channel's actual bandwidth.

The contention in CSMA/CA is usually slotted where a transmission may start only at the beginning of a slot. This makes the average contention delay larger, but can reduce collisions. However, the wireless channel is a severe channel and transmitted packets will be corrupted even in the absence of collision. Because of that, most MAC protocols also implement positive acknowledgement and MAC level retransmissions to avoid losing packets on the air. Here, each time a node receives a packet; it sends back immediately a short message (an ACK) to the transmitter to indicate that it has successfully received the packet without errors. If after sending a packet the transmitter does not receive an ACK, it knows that the packet was lost, so it will retransmit the same packet again (after contending again for the medium). Most MAC protocols use a stop and go mechanism where they transmit the next packet of the queue only if the current packet has been properly acknowledged. This makes the protocol simpler, minimizes latency and avoids retransmission of packets.

MAC level retransmission can solve the problem of loosing packets, but does not provide really good performance. If the packet to transmit is long and contains only one error, the transmitter needs to retransmit it entirely. If the error rate is significantly high, we could come to some situation where the probability of error in large packet is dangerously close to 1, so we can not get packet through. Fragmentation can partially solve such a problem. Fragmentation is sending big packets in small pieces over the medium. Of course, this adds some overhead, because it duplicates packet headers in every fragments. Each fragment is individually checked and retransmitted if necessary. In this case, the transmitter needs only to retransmit one small fragment and a small packet has a higher probability to get through the channel without errors. However, such a procedure still does not take full advantage of the wireless channel and the replicas of the transmitted packets after retransmission.

Clearly, the feature of MAC retransmission in wireless LANs is quite attractive and provides a good diversity scheme where packet combining can be easily implemented at the receiver without considerable modifications. In fact by storing corrupted packets the receiver can combine the retransmitted versions of each packet until the packet is successfully received or dropped. Such a procedure combines well with MAC retransmission and can help in solving the problem of loosing packets in wireless LANs. This will of course require some buffering space at the receiver and signal combining before detection. The complexity in combining will depend on the combining method to be used. As indicated in Chapter 2, packet combining can improve the packet acceptance probability and can improve the system effective throughput.

3.2 Related Work

In the current IEEE 802.11 MAC standard there exist no attempt to correct erroneous packets. However, there exist some recent work on packet combining in wireless LANs. In [56], Masala *et al.* studied different combining techniques in IEEE 802.11 which required no change within current standard. For instance, they investigated an XOR combining scheme which relies on a brute-force bit-by-bit inversion of the located bit error positions which was first presented by Chakraborty *et al.* in [11]. Masala also considered majority combining similar to the one Liang *et al.* used in [51]. Packet combining has also been considered for multi-carrier modulation techniques. In [48], Kumagi *et al.* presented a maximal ratio combining frequency diversity ARQ scheme for OFDM systems, where at every new retransmission, the different symbols of the OFDM block are transmitted on different subcarriers (frequency interleaving), and then maximum ratio combining with the previous versions of each packet is performed followed by a detection attempt until the packet is accepted or ignored after a certain number if retransmissions. The advantage of the proposed method is that one can take advantage of the frequency variations of the radio channel and add frequency diversity to the time diversity. The drawback is that it requires the identity of the subcarrier symbol since at every retransmission the symbol is transmitted on a different subcarrier. The problem of hidden terminals and how to model them has been discussed in several papers. The main approach in those papers was to us a predefined probability for the hidden terminal problem.

The employment of hybrid ARQ in WLAN's has been considered sparse. In [53], Liu *et al.* proposed a generalized type-II hybrid ARQ scheme with rate-compatible convolutional codes (RCPC) for and IEEE 802.11b network. In [24], the author considered a type-II hybrid ARQ scheme with BCH codes over an IEEE 802.11 WLAN system, but the adaptive modulation and coding (AMC) functionality was neglected. In [34], AMC was considered and they used an rate-adaptive algorithm was used to handle the AMC functionality. Another simple method to handle the AMC functionality is to always start at the highest signal constellation size and then gradually reduce the constellation size during retransmissions and continue until the packet is successfully received. This strategy suits perfect if the MAC overhead is negligible, but unfortunately the MAC overhead has big impact on IEEE 802.11 system performance [46]

3.3 Receiver-based Packet Combining in Wireless LANs

Considering a packet based system like IEEE 802.11a which is relying on error-correcting codes, cyclic redundancy check (CRC) and ARQ schemes to guarantee nearly error-free transmission of data packets in hostile wireless environments. A simple stochastic model for reflecting the problem of hidden terminal was proposed in paper [22]. The rationale behind that proposed model is that the environment decide whether the mobile is hidden or not without any predefined probability.

The rationale behind receiver-based packet combining is that only the receiver structure needs to be changed to support packet combining functionality. A buffer is needed to store the erroneous packets which should be combined later on. Furthermore, a signal combining device is need to be added and the complexity is depending on the employed combining technique.

3.3.1 Majority Voting Combining

When a decoded packet is deemed erroneous at the receiver, the hard bit decisions of the decoder are stored in a buffer and a retransmission is requested. If the ith transmission of a packet is detected in error, the corresponding bit decisions $d_0^1, d_1^i, \cdots, d_{N_p}^i$ are stored, where $d_0^1 \in [0, 1]$ corresponds to the decision on the jth bit during the ith transmission and N_p is the length of the data packet. When a packet is detected in error during the third subsequent transmissions ($i \leq 3$), a bit-by-bit majority voting decision is made according to the rule

$$\hat{d}_j = \begin{cases} 1 & \text{if } \sum_{n=1}^{i} d_j^i \geq \frac{i}{2} \\ 0 & \text{otherwise.} \end{cases}$$

Then the new decisions are checked for errors using CRC check. If the packet is still erroneous a retransmission is requested, this procedure continues until the packet is correct decoded or a the time limit has been reached.

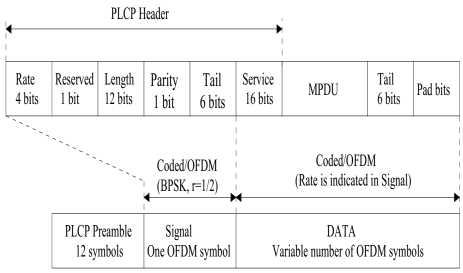


Figure 3.1: IEEE PPDU frame.

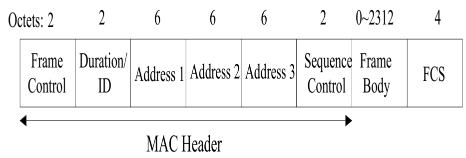


Figure 3.2: IEEE MAC Header format.

The technique of majority combining is very simple to implement and imposes only small storage requirements on the receiver. For five retransmissions a maximum of $5N_p$ binary numbers (decisions of the decoder) has to be stored.

3.3.2 Chase Combining

Instead of majority voting, let us consider Chase combining for IEEE 802.11a [23]. According to the 802.11 standard, the information bits are scrambled before encoding, so they are not exactly the same. The scrambling sequence $\mathbf{c}$ is obtained from the first seven bits of the 16-bit SERVICE field in the PLCP header, which is transmitted in the beginning of each packet. With this in mind, we can express the log-likelihood ratio Λ for the L repeated versions of a given code bit $y_{i,k}$, with $0 \le i \le L$, as follows:

$$\Lambda_{i,k}^{L} = \sum_{l=0}^{L-1} (2c_{i,k,l} - 1)\Lambda_{i,k,l},$$

where $c_{i,k,l}$ corresponds to the kth subchannel of the ith symbol of the lth coded scrambled sequence.

In the beginning of each packet there is a MAC header which contains packet target address and packet sequence number, this implies that both these properties must be the same as the stored packets to enable packet combining. Furthermore, the last four bytes of a packet which corresponds to the frame check sequence (FCS) may be different. With this is in mind we can conclude that

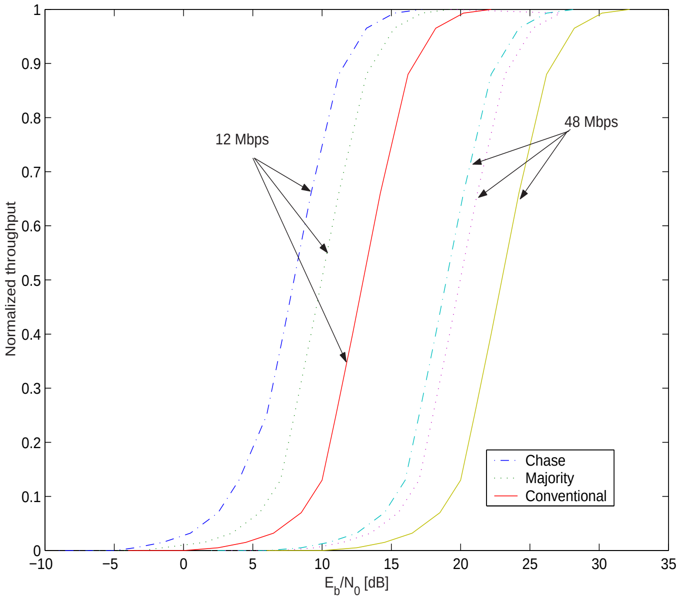


Figure 3.3: Performance comparison between Chase combining and majority voting for 802.11a

packet combining is only available on the user data, but can still provide a good performance enhancement.

3.3.3 Results

The numerical results are evaluated by means of computer simulation over a frequency-selective Rayleigh fading channel. The obtained results shows, as expected, that packet combining enhances both the throughput and decreases the number of retransmissions. For small packet sizes the gain is not that large, mainly due to the fact that most part of the errors occurs in the MAC header, which mentioned before cannot be combined. For larger packet sizes the performance gain is substantial when packet combining is employed. From Fig. 3.3 it can be seen at a data rate of 12 Mbps the throughput for a standard IEEE 802.11a system is $\eta = 0.18$ and for the system with packet combining functionality offers a throughput of $\eta = 0.72$. Obtained results also show that the number of retransmissions rapidly decreases with utilizing packet combining.

3.4 Type-II Hybrid ARQ in Wireless LAN

Wireless LANs are know to suffer from location-dependent, time-varying and burst errors. Hybrid ARQ has been considered very sparse in WLAN environments and in paper **C** and paper **D** we have implemented HARQ schemes in both IEEE 802.11 and HIPERLAN/2 systems and evaluated their performances.

3.4.1 IEEE 802.11

One major problem in 802.11 is the lack of feedback information to accurate estimate the channel in order to make a good decision on what modulation order and coding rate to use for the specific channel quality [44]. One simple way to deal with this problem is to rely on a rate-control algorithm that use some form of statistics-based feedback, for example user-level throughput. In [35], Gidlund and Åhag presented a CRC-based link adaptation algorithm to control the choice of modulation rate and coding rate. The approach was to use FER-based rate control and by counting the number of received ACK frames and the number of transmitting frames during a rather short time window, the FER can be computed as the ratio of the two. It was shown in [34] that this algorithm works well to handle the AMC functionality.

In [24], we simplified the model and used a error-free feedback channel. The type-II hybrid ARQ scheme uses two linear codes: one is a high rate (n, k) code C_0 and which is designed only for error detection, and the other is a half-rate *invertible* $(2k, k)$ code C_1 which is designed for simultaneous error correction and error detection, e.g., correcting t or fewer errors and simultaneously detecting $d(d \geq t)$ or fewer errors. Generally speaking, a $(2k, k)$ code is invertible if, knowing only the k parity-check bits of a codeword, the corresponding k information bits can be uniquely determined by a inversion process. This process can for instance be achieved by using a linear sequential circuit. In [52], it was shown that an invertible BCH code can be designed by shortening a regular BCH code.

Due to the invertible property of code C_1, a message D can be reconstructed uniquely from the parity block by inversion. Hence, the parity block contains the same amount of information as the message D. The overhead per transmission or retransmission is then simply the number of parity-check bits $n - k$ needed for error detection based on the $(n - k)$ code C_0, which is required by any ARQ scheme. By using the inversion process when the error rate is high, the number of retransmissions are reduced while maintaining high throughput. For channels with low error rate there is no difference compared to simple selective-repeat ARQ.

3.4.2 HIPERLAN/2

In HIPERLAN/2 there is no problem with lack of feedback information since that system employs TDMA/TDD as MAC-protocol which makes it easier to measure

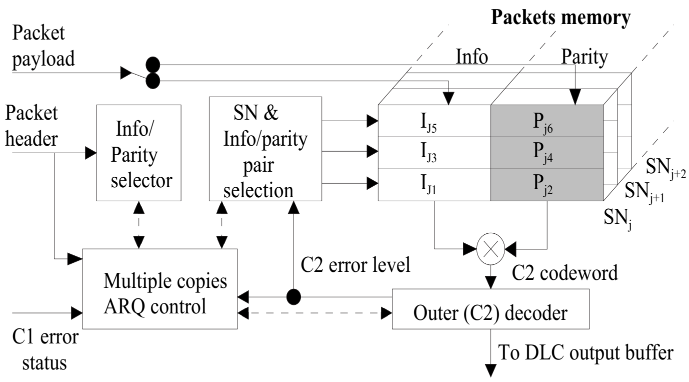


Figure 3.4: Multiple copies combination for type-II/III HARQ schemes.

P-type 2 bits	SN 10 bits	DLC-SDU 396 bits	CRC 24 bits

DLC USER-PDU

Figure 3.5: HIPERLAN/2 Frame.

on the feedback link. In HIPERLAN/2 the ARQ function is based on selective-repeat ARQ with partial bitmap (SRBP) [50]. Here the signaling of erroneous packets use partial bitmap acknowledgements, i.e., correct and erroneous packets are acknowledged in form of a bitmap.

Instead of using SRBP, we have employed an type II/III hybrid ARQ scheme with multiple copies combining [25]. The major problem in type II/III HARQs is how to provide the receiver with correct data, concerning the very important packet control information. We propose for each DLC connection, that information is condensed in to a "forwarding direction packet list" and transported in one or more SCHs aside with the corresponding LCHs containing the U-PDUs. This will assure that packet control information has an increased protection and still guaranteeing the normal operation of type II/III hybrid ARQ. Furthermore, at the receiver we implement a new mechanism to combine the retransmitted packet payload. For each packet with same sequence number, the mechanism enables the existence of multiple copies for the information and redundancy parts, guaranteeing the testing of more codewords for each copy arrival. With M memories for each packet we use $M/2$ memories to save "information" packets; the other $M/2$ memories are used to save "parity" check packets.

Hence, when the inner code states an unrecovered error, it passes the received packet payload to this second level of decoding. Having several copies memorized, it is possible to combine more "information" and "parity" parts.

3.4.3 Results

For both different cases (IEEE 802.11 and HIPERLAN/2), performance gains was obtained by employing type-II hybrid ARQ scheme. In the case of IEEE 802.11, we can conclude that for good channel conditions there is no difference between the compared schemes, but for bad conditions the proposed scheme works better. If the PER performance of the current channel is worse than average, there will still be a gain since the scheme uses incremental redundancy which systematically reduces the mode at each attempt.

For the scenario with HIPERLAN/2, the same observation is made. At high SNR there is no difference between SRBP and the proposed scheme, while at lower SNR the gain is quite substantial. We can also note that both the hybrid ARQ scheme with multiple copies combining and SRBP ARQ provides higher throughput and lower delay than PRIME ARQ. The reason is that PRIME ARQ need more capacity compared with the other two schemes due to the Go-Back-N function. [61].

3.5 Concluding Remarks

We have found that by implementing simple packet combining methods in Wireless LAN a substantial gain in system performance can be achieved. The obtained results showed that throughput increases and packet delay decreases within the system. The complexity is mainly depending on what signal combining device is implemented at the receiver and the buffer size to store the corrupted packets to be combined later. Not surprisingly, simulation results show that soft packet combining outperforms hard packet combining. For hybrid ARQ, it is of importance that an accurate link adaptation algorithm is employed to avoid unnecessarily switching of transmission modes.

As expected a bigger performance gain was obtained for larger packet sizes, because for lower error rates most errors are likely to occur in the data sequence. Although, this does not implies that the packet size could be increased in parallel with increasing data rate to obtain higher throughput performance in WLANs. The reasons are: 1) at the MAC layer, we do not have control over the length of the packets coming from higher applications and 2) the drawback for increasing the packet size is that the packet-error probability increases due to higher transmission error probability or a higher number of collision probability. This in turn results in a higher number of retransmissions, which leads to a reduction of the overall capacity.

An other feature that improves the system performance is to consider MAC-level FEC with retransmission combining. This was shown in [34] to provide a substantial performance gain. Note that the IEEE 802.11 do not apply any MAC-level protection except a CRC-32 code in the frame check sequence (FCS).

Chapter 4

Packet Retransmission Diversity Schemes

A method to achieve packet combining diversity that has been recently investigated is the *bit-to-symbol mapping diversity* which is suitable systems that employ higher-order modulation such as PSK or QAM. By varying the bit-to-varying mapping for each packet (re)transmission, the diversity is enhanced among L transmissions. It can be shown that such a system enhance the diversity among the multiple (re)transmissions and provide improved error performance compared to a system where L packet (re)transmissions are made using the same mapping. That type of combining scheme is called *Maximum-Likelihood (ML) combining diversity.*

One motivation for the use of bit-to-symbol diversity scheme is to compare the error performance between ML combining diversity and and a simple bit-to-symbol diversity scheme based on *random mappings*, where the mapping function is chosen randomly from an available set of $M!$ mappings. From Fig. 4.1 it can be seen that the symbol diversity scheme with random mappings performs better than the ML approach, which indicates the superiority of the symbol mapping diversity approach. The explanation to this performance gain is that bits are assigned to adjacent symbols in one mapping may be assigned symbols that are spaced further apart in subsequent mappings. A key question is how to design good mappings for different (re)transmissions. For instance, for an M-ary constellation, there are $M!$ possible mapping to choose between.

4.1 Related Work

There exist schemes that adjust the mappings available in literature. Benelli conducted the first known work that considered the effects of modulation; an ARQ protocol for continuous-phase modulation [6]. In [62], Otnes and Maseng

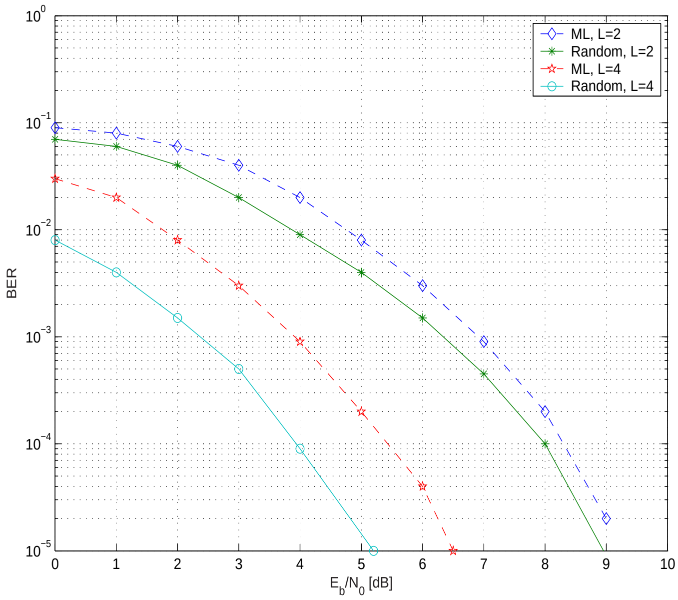


Figure 4.1: Bit error performance of ML combining diversity versus symbol mapping diversity with random mappings for 8-QAM on AWGN channels.

proposed the use of uniform constellations for retransmitted packets in a system that requires unequal error protection. Wengerter *et al.* presented a HARQ scheme that employ code combining and adapting among Gray mapping for retransmissions [77]. Their approach can be seen as an ad hoc type. In [26], Gidlund *et al.* proposed a hybrid ARQ scheme which take advantage of changing the bit interleaving mode in such manner that the data sequence is changed. That approach exploits both frequency- and time diversity.

In the past, the problem of finding optimal symbol mappings for a single transmission has been studied. A prime example is the work of Ungerboeck on trellis-coded modulation (TCM), with development of set-partitioning mapping [75]. Wesel *et al.* developed mappings for linear encoders that minimize a constellations edge profile [78]. In [74], ten Brink *et al.* proposed an algorithm which employs iterative demapping to improve the performance of anti-Gray mappings. Recently, Chindapol and Ritcey experimented with several mapping schemes for error correction coded transmissions through AWGN and Rayleigh fading channels [13].

4.2 Preliminaries

Let us consider a bandwidth efficient M-ary modulation scheme where a symbol s consisting of $b = \log_2 M$ bits, which are mapped to a point in the signal constellation via a bit-to-symbol mapping function ψ, and this signal point $\psi(s)$ is transmitted over the channel. In order to achieve packet combining diversity, the same bits may be transmitted more than once. Let L be the number of retransmissions. The data packet can either be retransmitted by using the same bit-to-symbol mapping in all transmissions, or vary the bit-to-symbol mapping in each transmission $\psi_1(s), \psi_2(s), \cdots, \psi_L(s)$. Assuming that the transmitted symbol s undergoes fading, the received signal y_L (after multiple transmissions) can then be written as

$$y_i = h\psi_i(s) + n_i, \quad i = 1, 2, \cdots, L, \tag{4.1}$$

where h is the complex fading coefficient with $E\{||h||^2\} = \Omega$, and the r.v's $||h||$'s for different symbols are assumed to be i.i.d. Rayleigh distributed. A received and combined symbol is first converted into $\log_2 M$ bit metrics by a soft demodulator. Assuming perfect knowledge of the CSI at the receiver, the combined signal output for symbol s_k is given by $\hat{s}_k = hs_k + n_k$, we define n as a complex gaussian random variable with zero mean and variance $h\sigma^2$.

A common used method to combine packets is to employ ML combining diversity where all the L mappings are the same, i.e., $\psi_1 = \psi_2 = \cdots = \psi_L = \psi$. The mapping function ψ is repeatedly used in all L transmissions of the data symbol s. Assuming an AWGN channel and given the observations $y_1, y_2, \cdots, y_L$ in (4.1), the ML combining diversity receiver decides that symbol $\hat{s}$ was transmitted according to the ML rule

$$\zeta(\hat{s}) = \min_{0,1,\cdots,M-1} \sum_{i=1}^{L} |y_i - h\psi(\hat{s})|^2. \tag{4.2}$$

4.3 Mappings based on BER Upper Bound

One way to obtain good mappings is to choose the mappings that minimize the BER of the system. To be able to use that kind of method, an expression for the BER of the diversity scheme with L transmissions is required. Although, it is difficult to obtain a exact BER expression for this scheme, an upper bound on the BER can be used to obtain the mappings. The union bound, using the metric $\zeta_L(s)$ defined in (4.1) states that [64]

$$Pr\{\hat{s} \neq s|s\} \leq \sum_{k=0}^{M-1} Pr\{\zeta_L(k) < \zeta_L(s)|s\}.$$

Assuming independence of the Gaussian noise variable n_i, the pairwise error probability (PEP) of the transmitted symbol s is being decoded as symbol k can be described as follows:

$$P(\zeta(s) \to \zeta(k)) = Q\left(\sqrt{\frac{1}{4\sigma^2}\sum_{i=1}^{L=1}\mathcal{D}^2[\psi_i(s),\psi_i(k)]}\right) \tag{4.3}$$

where $\zeta_L(s)$ is the minimization metric given in (4.2), $\mathcal{D}[a,b]$ is the Euclidean distance between points a and b. The Q-function is defined as

$$Q(x) = \frac{1}{2\pi}\int_x^{\infty} e^{-t^2/2}dt.$$

To be able to determine the BER upper bound we denote the variable $\chi(s,k)$ as function that accounts for the number of bit errors caused by the block error. Including (4.3) and $\chi(s,k)$ we can express the upper BER bound as following [34]

$$P_b(L) \leq \frac{1}{M}\sum_{a=0}^{M-1}\sum_{\substack{b=0\\b\neq a}}^{M-1}\chi(s,k)Q\left(\sqrt{\frac{1}{4\sigma^2}\sum_{i=1}^{L=1}\mathcal{D}^2[\psi_i(a),\psi_i(b)]}\right). \tag{4.4}$$

Our problem is to determine the L optimal symbol mappings $\psi_1(s) = \psi_2(s) = \cdots = \psi_L(s)$, which minimize the BER upper bound in (4.4). This optimization is stated as

$$\min_{\psi_L\in\Psi}\frac{1}{M}\sum_{s=0}^{M-1}\sum_{\substack{k=0\\\neq s}}^{M-1}\chi(s,k)Q\left(\sqrt{\frac{1}{4\sigma^2}\sum_{i=1}^{L=1}\mathcal{D}^2[\psi_i(s),\psi_i(k)]}\right),$$

with Ψ denoting the set of all possible mappings. This minimization will become a massive combinatorial optimization problem whose solution space contains $(M!)^L$ solutions. To overcome this problem, a simpler sub-optimal iterative solution can be used by computing the Lth mapping from the previous $L-1$ mappings, where the optimization problems simplifies to

$$\min_{\psi_L\in\Psi}\frac{1}{M}\sum_{s=0}^{M-1}\sum_{\substack{k=0\\k\neq s}}^{M-1}g[s,\psi_L(s),\psi_L(k)],$$

where $g[s,a,k,b]$ is the pairwise BER that results by mapping s to symbol a and k to symbol b in the Lth mapping, given by

$$g[s,a,k,b] = \frac{\chi(s,k)}{M}Q\left(\sqrt{\frac{1}{4\sigma^2}(h[s,k]+\mathcal{D}^2[a,b])}\right),$$

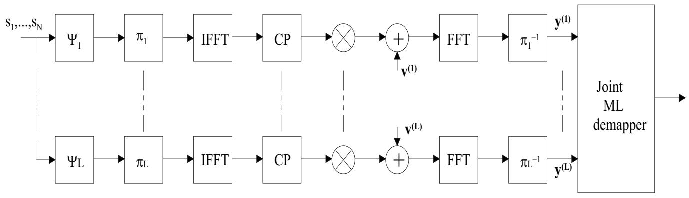


Figure 4.2: System model of multiple OFDM transmissions of a packet.

where $h[s,k] = \sum_{i=1}^{L-1} \mathcal{D}^2[\psi_i(s), \psi_i(k)]$ denotes the sum of the squared Euclidean distances in previously chosen $L-1$ mappings. As the combined squared Euclidean distance (CSED) increases between labels a and b, the likelihood of error decreases.

4.3.1 Mappings for Multicarrier Modulation

Multicarrier modulation such as OFDM and DMT have become a topic of great interest in research and practice. In [48], the authors presented ARQ packet combining scheme that involves subcarrier reassignment for OFDM, where symbols are retransmitted through different subchannels.

To enhance the diversity among the L retransmissions, we interleave the symbols within a packet and using different bit-to-symbol mapping. The interleaving process allows for symbols that were initially transmitted over poor subchannels to be later transmitted over better subchannels. Moreover, symbols that initially went through good subchannels can afford to experience poor subchannels in subsequent transmissions. Effectively, over all transmissions, interleaving provides a label with a Rayleigh fading channel rather than a fixed AWGN-only channel. By adapting the mapping for retransmissions increases the average Euclidean distance between any two labels, thereby significantly reducing the bit error rate.

Considering the system model in Fig. 4.2, where a packet of N symbols is uniquely interleaved and then mapped for the lth transmission, the symbols $\psi(s_{\pi_1}), \ldots, \psi(s_{\pi_L})$ is transmitted using OFDM through a frequency selective channel. OFDM uses an N-point IFFT and a cyclic prefix (CP) at the transmitter with an N-point FFT at the receiver to transform the channel into a set of parallel,flat subchannels. The gains, $h_1, \ldots, h_N$ of the particular subchannels correspond to the FFT of the channel response. After deinterleaving, the receiver obtains $y_i^{(l)} = y_i^{(l)} - h_{\pi_l^{-1}} \psi_l(s_n) + v^2_{\pi_l^{-1}}$ for detection of the nth symbol of the packet. The noise $v^2_{\pi_l^{-1}}$ is assumed white Gaussian with zero mean and variance σ_v^2. The ML decoding rule in (4.2) can now be written as

$$\zeta(\hat{s}) = \min_{0,1,\cdots,M-1} \sum_{i=1}^{L} |y_i^{(l)} - h_{\pi_l^{-1}} \psi_l(s_n)|^2,$$

where the deinterleaver is specified by π_l^{-1}.

For OFDM transmissions, the PEP for any label is given by

$$E_{\mathbf{f}} \left\{ Q \left(\sqrt{\frac{1}{2\sigma_v^2} \sum_{l=1}^{L} |f_l|^2 |d_l(s,k)|^2} \right) \right\}. \tag{4.5}$$

where $f_l = h_{\pi_l^{-1}}, d_l[s,k] = \psi_l(s) - \psi_l(k)$ and $\mathbf{f} = \{f_1, \ldots, f_2\}$. The variable f_l represents the Rayleigh fading gain of the l^{th} transmission of a label. The expectation over $\mathbf{f}$ is necessary since these fading gains are not known to the transmitter.

In DMT, symbol interleaving is avoided as symbols in high-SNR subchannels have large constellations and performance suffers when such symbols are retransmitted over lower-SNR subchannels. Fortunately, mapping diversity is highly effective, particular since the subchannel SNR is fixed for all transmissions.

4.3.2 Results

Obtained results show that both mapping diversity and symbol interleaving provides significant performance gains compared to a system employing identical mapping for all transmissions (Chase combining). From Fig. 4.3, it is shown that for two transmissions, symbol mapping diversity produces about 2 dB gain. When both methods are used the gain is even more significant.

4.4 LLR-Based Selection of Signal Constellations

In the case for ML combining diversity scheme, all the L mappings are the same, i.e., $\psi_1 = \psi_2 = \cdots = \psi_L = \psi$. For the bit-to-symbol mapping diversity scheme, a key question is to how to obtain optimum mapping functions $\psi_1 = \psi_2 = \cdots = \psi_L$. Consequently, we present the bit LLR expressions for Rayleigh fading channel in the following subsection, the LLR expressions for AWGN channel can be obtained by simply ignoring the channel fade coefficient in the system model.

4.4.1 Log-likelihood Ratios of the Bits

Let us define the log-likelihood ratio of bit $b_i,\ i = 1, 2, \cdots, b_i$ as following:

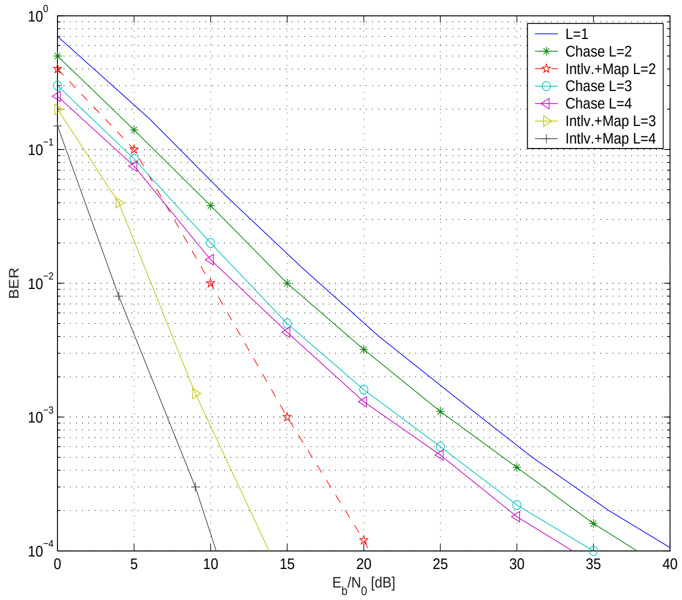


Figure 4.3: BER result for OFDM applying symbol mapping diversity and interleaving compared to retransmission same packet in every transmission (Chase).

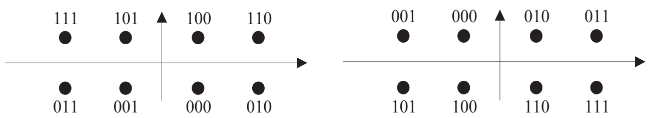
$$\begin{aligned} \Lambda_{s_k}(b_i) &= \log\left(\frac{Pr(b_i=1|y,h)}{Pr(b_i=0|y,h)}\right) \\ &= \log\left(\frac{Pr(b_i=1|\hat{s}_k,h)}{Pr(b_i=0|\hat{s}_k,h)}\right). \end{aligned} \tag{4.6}$$

The optimum decision rule is to decide $\hat{b}_i = 1$ if $\Lambda(b_i) \geq 0$, and 0 otherwise. Furthermore, we also assume that all symbols are equally probable and that fading is independent of the transmitted symbols. According to Bayes' rule, we can rewrite (4.6) as:

$$\Lambda_{s_k}(b_i) = \log\left(\frac{\sum_{\alpha\in S_i^{(1)}} f_{\hat{s}_k|s,h}(\hat{s}_k|s,h=\alpha)}{\sum_{\beta\in S_i^{(0)}} f_{\hat{s}_k|s,h}(\hat{s}_k|s,h=\beta)}\right), \tag{4.7}$$

where S_i^1 and S_i^0 is defined as the set partitions that compromises symbols with $b_i = 1$ and $b_i = 0$, respectively. We know from [64], that $f_{\hat{s}_k|s,h}(\hat{s}_k|s,h=\alpha) = \frac{1}{\sigma\sqrt{\pi}}\exp(1/\sigma^2||\hat{s}_k - h\alpha||^2)$, then we can rewrite (4.7) as

$$\Lambda_{s_k}(b_i) = \log\left(\frac{\sum_{\alpha\in S_i^{(1)}} \exp(-1/\sigma^2||\hat{s}_k - h\alpha||^2)}{\sum_{\alpha\in S_i^{(0)}} \exp(-1/\sigma^2||\hat{s}_k - h\alpha||^2)}\right). \tag{4.8}$$



(a) First transmission. (b) Second transmission.

Figure 4.4: 8QAM mappings for first and second transmission.

This expression in (4.8), can be further simplified by suing the approximation $\log(\sum_j \exp(-x_j)) = \min_j(x_j)$. By defining $z = \frac{\hat{s}_k}{h} = s+\hat{n}$, where $\hat{n}$ is a complex Gaussian r.v with variance $\sigma^2/||h||^2$ and using the above approximation we can simplify (4.8) to the following:

$$\Lambda_{s_k}(b_i) =$$
$$\frac{||h||^2}{4}\left[\min_{\beta\in S_i^{(0)}}(||\beta||^2 - 2z_I\beta_I - 2z_Q\beta_Q) - \min_{\alpha\in S_i^{(1)}}(||\alpha||^2 - 2z_I\alpha_I - 2z_Q\alpha_Q)\right]$$

where $z = z_I + z_{jQ}, \alpha = \alpha_I + j\alpha_Q$ and $\beta = \beta_I + j\beta Q$. If considering a square or rectangular QAM constellations, the set partitions $S_i^{(1)}$ and $S_i^{(0)}$ is delimited by horizontal or vertical boundaries. To find the optimum mappings for bit-to-symbol mapping diversity we take advantage of the soft information given by the LLRs of the bits forming the QAM symbol. We will iteratively compute the Lth mapping from the $L-1$ previous mappings. We define the sum of LLRs of a given bit in the previous $L-1$ mappings as

$$\epsilon(i,j) = \sum_{l=1}^{L-1} \bar{\Lambda}_{ij}^{(l)}, \tag{4.9}$$

where $\bar{\Lambda}_{ij}^{(l)}$ is defined as the averaged Λ computed for the ith bit of the jth symbol in the mapping of the lth transmission and the averaging over the noise samples. Furthermore, We define Ψ as the set of mappings ($|\psi| = M!$). To choose the Lth mapping we need to solve the following optimization problem

$$\max_{\psi_L\in\Psi} \sum_{j=1}^{M} \sum_{i=1}^{\log_2 M} |\epsilon(i,j) + \bar{\Lambda}_{ij}^{(L)}|. \tag{4.10}$$

By using the above optimizing procedure we can construct new constellations for next retransmission. We obtained the optimum mappings for 8QAM by carrying out the optimization in (4.10). The resulting mappings is shown in Fig. 4.4. We observe that the newly obtained signal constellation is still Gray mapped.

4.4.2 Results

Results show that using LLR based mappings give a good performance gain in an AWGN environment as well as in Rayleigh fading channel compared to a conventional diversity scheme. For instance, at a BER of 10^{-3}, the LLR based mapping results in about 2 dB of E_b/N_0 advantage compared to a Chase combined scheme. The obtained mappings are all Gray mapped, which was not the case with the BER upper bound approach.

4.5 Combined Packet Retransmission Diversity and Multi-Level Modulation

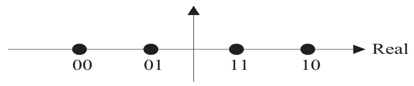
Important parameters in wireless communications are bandwidth efficiency, power efficiency and signal reliability. By increasing the signal quality or reducing the bit error rate of digital modulated signals in fading channels without any efficiency loss is quite difficult.

By combining retransmissions and multi-level bandwidth efficient modulation techniques with changing the symbol mapping in every (re)transmission we can enhance the error probability and increase the power efficiency. The main idea is to take advantage of the extra dimension provided by the retransmission diversity scheme in improving the power efficiency of the used modulation without altering the diversity order of the system. Considering the overall scheme as one entity we can obtain a transmission scheme that can perform very well in both additive Gaussian and fading multipath channels without any increase in receiver complexity.

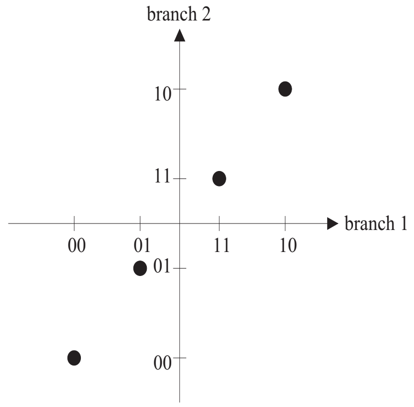
The performance gain obtained from packet transmission and packet combining depends only on the number of retransmissions and is completely independent from the modulation scheme used. This is not optimum since the combination does not take full advantage of the available signal space. With packet combining we basically adds an extra dimension to the used modulation scheme. Hence, with a proper interaction between retransmission and signal mapping we can obtain a better mapping of the modulation signal points within the signal space. This better spread of signal points, can improve the error probability and hence reduce the number of retransmissions within the system. The interaction and design will be dependent of the modulation level used and its signal dimension.

4.5.1 The Proposed Scheme

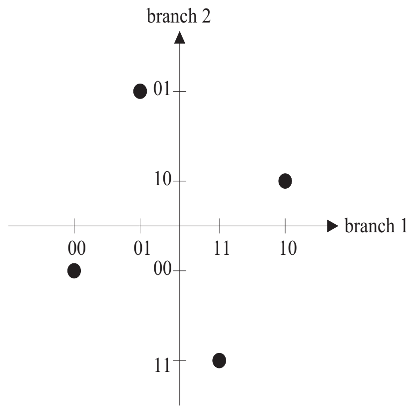
To illustrate the proposed scheme, we consider for simplicity the case of 4-level pulse amplitude modulation (4PAM) with the signal constellation shown in Fig. 4.5(a) where Gray mapping has been assumed. Using conventional orthogonal transmit diversity with signal combining according to (4.2) then the signal constellations of the combined signal becomes two-dimensional as shown in Fig.



(a) 4PAM signal constellation for the first transmission



(b) 4PAM signal constellation after two transmission utilizing Chase combining



(c) 4PAM optimum signal constellation.

Figure 4.5: Different signal constellations for 4PAM.

Table 4.1: Optimum signal mapping sets for 4-level PAM scheme.

Level	Set 1	Set 2	Set 3	Set 4	Set 5	Set 6	Set 7	Set 8
$-3d$	00	01	10	00	00	10	00	01
$-d$	01	10	00	10	11	00	01	00
$+d$	11	00	11	01	10	01	10	11
$+3d$	10	11	01	11	01	11	11	10

4.5(b). Note, in an AWGN environment, the signal space still appears as a one-dimensional space even though we are using two dimensions. This indicates that this retransmission procedure does not take full advantage of the system dimension. This also explains why orthogonal transmitter diversity does not give any advantages when there is no difference between the channel amplitudes of the different channel branches. By taking advantage of the available system dimension we may enhance the system performance and this increase in dimension of the signal space will ensure that the distance is increased between the signal points and improving the bit error probability over different channels.

By simple manipulation the signal points in next transmission, the combined signal can be optimized to use the complete signal space as shown in Fig. 4.5(c). It can clearly be seen that the obtained signal points are now better spread in this augmented signal space with a minimum squared Euclidean distance between the signal points 4 dB better than that of the conventional case. If a third transmission is required, our signal space will have a dimension equal to three and in the case of 4PAM form a cube in the signal space. The new signal constellations can be easiest be found by computer search. The above process can be repeated for finding the mapping sets. In Table I, we have listed the optimum mappings sets for eight retransmissions [1]. After eight we stopped since it was found that set 9 was equal to set 1.

Our methodology can be readily extended to other high level modulation techniques. For instance, it also applies for MQAM since we know that a square 2^{2m}-QAM constellation is the sequence of complex numbers where the real and imaginary part are both taken from the obtained 4PAM constellations. Some optimum constellations found by this method for MQAM and MPSK can be found in [29], [34].

4.5.2 Performance Analysis

We will shortly give some performance analysis of the proposed scheme. A more extended analysis can be found in [29]. Given an AWGN channel the an upper bound of the average symbol error probability can be found as

[1]Note that there are other signal mapping sets that give the same distance distribution between the different signal points of the modulation scheme.

$$P_s \leq \frac{1}{M} \sum_{s_n=1}^{M-1} \sum_{\hat{s}_{l,n} \neq s_{l,n}} Q\left(\sqrt{\frac{\lambda^2(s_{l,n}, \hat{s}_{l,n})}{2N_0}}\right).$$

For the 4PAM scheme discussed in previous section an upper bound on the SEP can be derived an is given by

$$P_s \leq \begin{cases} 2Q\left(\sqrt{\frac{4E_b}{5N_0}}\right) & L{=}1 \\ 2Q\left(\sqrt{\frac{2E_b}{5N_0}}\right) + 2Q\left(\sqrt{\frac{4E_b}{N_0}}\right) & L{=}2 \\ 2Q\left(\sqrt{\frac{2.4E_b}{N_0}}\right) + 2Q\left(\sqrt{\frac{3.6E_b}{N_0}}\right) + 2Q\left(\sqrt{\frac{4.4E_b}{N_0}}\right) + 4Q\left(\sqrt{\frac{5.6E_b}{N_0}}\right) & L{=}3 \end{cases}$$

while the upper bound for the symbol error probability over a Rayleigh fading channel can be given as

$$\begin{aligned} P_s \leq & \frac{1}{M}\left[\sum_{j=1}^{L} \binom{2L-j-1}{L-1} \frac{2^{j-2L}}{(1+x_{min})^2}\right] \\ & \times \sum_{s_n=1}^{M-1} \sum_{\hat{s}_{l,n} \neq s_{l,n}} \prod_{i=0}^{L-1} \left(\frac{1}{1+\frac{2\sigma^2|s_{l,n}-\hat{s}_{l,n}|^2}{4LN_0}}\right) \end{aligned}$$

where

$$x_{min} = \min_{\forall s_n \neq k} \sqrt{\frac{2\sigma^2|s_n - s_k|^2/(4N_0)}{L + 2\sigma^2|s_n - s_k|^2/(4N_0)}}$$

where the product distance is depending on the selected set. When the modulation signal constellation sets are properly selected, a better product distance is obtained and the overall system performance is improved.

4.5.3 Results

The performance of the proposed scheme has been evaluated over both AWGN and Rayleigh fading channels. The performance measures considered are average symbol error probability, bit error probability and throughput. The fading multipath channel is assumed slowly varying Rayleigh distributed and uncorrelated between the retransmissions. The proposed scheme is compared to a Chase combined scheme.

Figure 4.6 shows simulation results and upper bounds for the averaged symbol error probability of the combined scheme with 16QAM over additive white Gaussian noise channels as a function of E_b/N_0 and for different number of

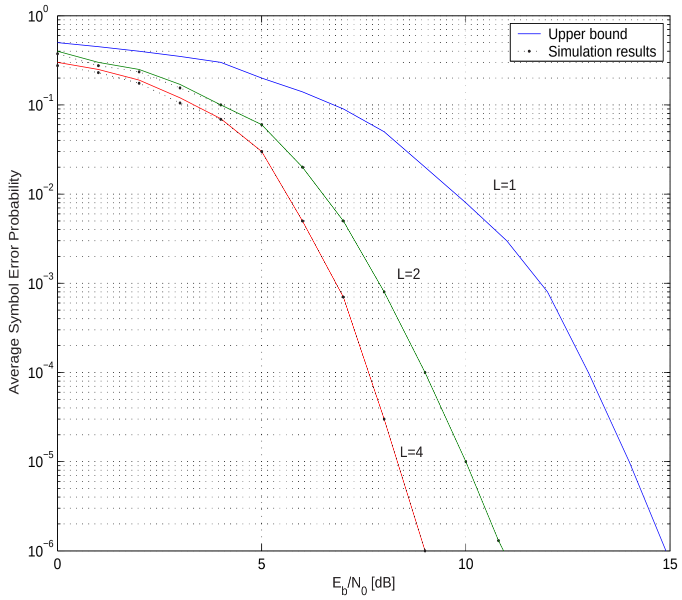


Figure 4.6: Average symbol error probability of combined scheme with 16QAM over AWGN fading channels and for different number of transmissions.

transmissions (branches). It is observed that by increasing the number of transmissions, better error probability performance is obtained. Compared to conventional transmitter diversity case[2], a gain about 4 dB is obtained when two transmissions are used. This gain is then increasing to about 4.7 dB for four transmissions. We also notice that the upper bound on the average symbol error probability is very tight and can be used to predict the performance of the combined MQAM scheme without the need for extensive simulations.

Figure 4.7 illustrates the average bit error probability of the combined scheme over Rayleigh fading channels. Also included in the figure is the bit error probability for conventional Chase combining. We notice that both schemes have the same diversity order but the proposed combined scheme outperforms the conventional scheme due to the nice spread of signal constellations of the proposed scheme that gives a larger product distance.

[2] As indicated earlier, the performance of conventional orthogonal transmitter diversity over AWGN channels is identical to that of non-diversity case (one transmission only) regardless of the number of transmissions

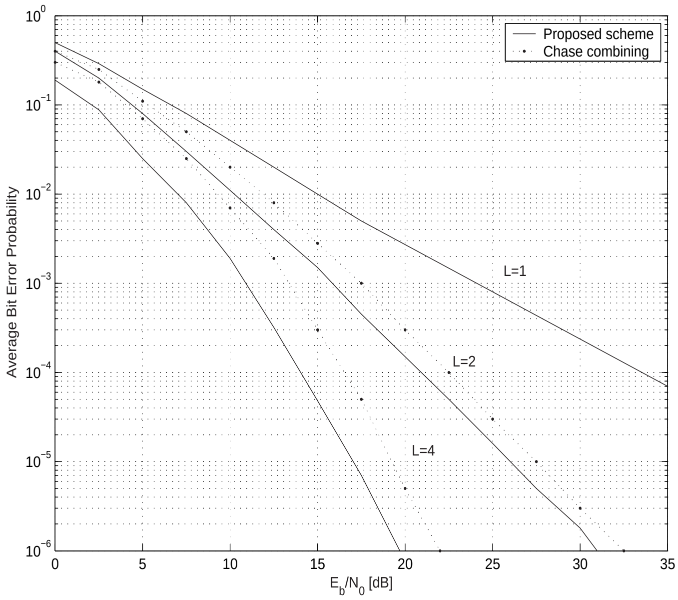


Figure 4.7: Average bit error probability of combined scheme with 16QAM over Rayleigh fading channels and for different number of transmissions.

4.6 Coded Retransmission Diversity

Bit-interleaved coded modulation (BICM) is a bandwidth efficient coding technique based on serial concatenation of binary error-correcting coding, bit-by-bit interleaving, and multi-level modulation. Let us consider that the BICM symbols from the mapper are similarly divided into multiple blocks for ARQ use.

The performance of the BICM depends on how the bit metrics are generated by the soft demodulator. It is optimal to use the log *a posteriori* likelihood of the MRC output symbol conditioned a particular bit label c_l. Considering a sub-optimal LOG-MAX demodulator, the effective rate of the bit channel is given by

$$C_{l,LOGMAP}(SNR) = \\ 1 - \int_{v\in\mathbb{C}} \frac{e^{-|v|^2}}{\pi M} \sum_{s\in M} \log_2 \left(1 + \frac{\max_{\hat{s}\in M; B_l(\hat{s})=1-B_l(s)} e^{-|v+\sqrt{SNR}(s-\hat{s})|}}{\max_{\hat{s}\in M; B_l(\hat{s})=B_l(s)} e^{-|v+\sqrt{SNR}(s-\hat{s})|}} \right).$$

It has been known that Log-Max demodulation achieves the same performance as LOG-MAP demodulation for high coding rate cases but slightly losses for medium or low coding rates. However, this slightly performance difference can sometimes be amplified by the HARQ processes.

4.7 Concluding Remarks

We have presented different methods for enriching the diversity among multiple packet transmissions by adapting the bit-to-symbol mapping for each transmission. This method requires a minimal increase in transmitter complexity while receiver complexity remains constant as the number of transmissions increases. Results reveal that the method leads to very substantial gains for several constellation types when applied to AWGN and Rayleigh fading channels.

We have presented combined transmitter diversity and multi-level bandwidth bandwidth efficient modulation techniques. The idea was to take advantage of the extra dimension provided by the diversity scheme in improving the power efficiency of the used modulation without altering the diversity order of the system. By considering the overall scheme as one entity we can obtain a transmission scheme that can perform very well in all kind of channels. This combining procedure does not increase the complexity at the receiver and consecutive received symbols can still be treated independently.

Chapter 5

Hybrid ARQ Transmission in MIMO Systems

The use of multiple-input multiple-output (MIMO) in wireless communication systems together with the recently developed space-time coding and signal processing techniques, has been shown to provide dramatic capacity increase over traditional single-input single-output (SISO) channels, especially over rich scattered environments. As a result, MIMO systems have become important and popular research subjects.

A major concern in packet data communication system is how to control the transmission errors caused by the channel noise and interferences such that data can be transmitted with a minimum error. As mentioned before, the most common error control method used in data communication is ARQ which intends to ensure an extremely low packet error rate.

Combined with hybrid ARQ, MIMO can potentially provide higher throughput packet data services with higher reliability. A simplistic way to utilize HARQ and MIMO is to consider a single antenna HARQ for each data stream.

In general we are talking about two different MIMO systems, namely BLAST and space-time coding. Bell-Labs layered space-time (BLAST) system [18], [19], [37] which transmits different symbols from all transmitting antennas simultaneously, and is aimed for high data rate transmissions such as WLAN and WMAN. On the other hand, the space-time coding (STC) [2], [72] exploit the transmission diversity by sending the same symbols from different transmit antennas and achieves high reliable data transmissions in severe mobile wireless systems with scattering, shadowing, reflection and diffraction, which makes them specially useful for 3G cellular with high mobility.

BLAST

BLAST systems are designed for high data rate transmission, and are particular effective when a large number of antennas are deployed at both the transmitter and receiver. In BLAST systems, the data stream is demultiplexed into independent substreams that are referred to as layers. These layers are then simultaneously transmitted through multiple transmit antennas, and at the receiver they are successively detected using the so-termed interference cancellation and nulling algorithms. Depending on how the layers are transmitted in space and time, two layering structures, namely, diagonal layering and vertical layering, have been proposed. Accordingly, BLAST systems can be categorized as Diagonal BLAST (D-BLAST) and Vertical BLAST (V-Blast). D-BLAST spreads each layer diagonally in space and time, and relies on layer encoding to achieve transmit diversity. In V-BLAST, each layer is transmitted through a particular transmit antenna.

Space-Time Coding (STC)

Space-time codes employ redundancy for the purpose of providing protection against channel fading, noise and interference. Space-time codes are divided into two types: 1) space-time trellis codes (STTC) which permits the serial transmission of symbols by combining signal processing at the receiver with coding techniques that are appropriate to the use of multiple antennas at the transmitter. STTC are designed for two or four transmit antennas and performs extremely well in a slow-fading environment. 2) In space-time block codes (STBC), the transmission of the signal take place in blocks. The code is defined by a transmission matrix and for efficient transmission, the transmitted symbols are expressed in complex form. Moreover, in order to facilitate the use of linear processing to estimate the transmitted symbols at the receiver and thereby simplify the receiver design, orthogonality is introduced in to the design of the transmission matrix.

5.1 Related Work

Employing packet retransmission in MIMO systems is a relative new research area and there exist a few recent articles. In [59], Nguyen and Ingram investigated hybrid ARQ protocols for systems that uses recursive space-time codes. The obtained result in that article showed that employing a hybrid ARQ protocol with diversity and code combining outperform schemes employing pure ARQ and HARQ with transmit diversity. In [60], Onggasnusi *et al.* investigated possibilities to enhance the efficiency of HARQ in MIMO systems by employing either Zero-forcing or MMSE receiver before (pre-combining) and after (post-combining) the interference-resistant detection. Their result showed that a pre-combining scheme performs better than post-combining. Zhang *et al.*

proposed in [85] a new ARQ scheme for MIMO systems where the substreams emitted from various transmit antennas encounter different error statistics. They found by using per-antenna encoders, separating the ARQ process among the the substreams, they obtained some throughput improvements. In [47], Koike *et al.* presented two different ARQ strategies. One method is referred as trellis-coded modulation reassignment, where different TCM codes assigned for multiple transmitters are periodically rearranged upon retransmissions. The other method was antenna permutation, where they proposed to change connections between transmitters and and transmit antennas upon retransmission.

In this chapter we use the following *Notation:* Column vectors (matrices) are denoted by boldface lower (upper) case letters. Superscripts $(\cdot)^T, (\cdot)^*$ and $(\cdot)^H$ stand for transpose, conjugate, Hermitian transpose, respectively. We will use $\mathbf{I}_N$ to denote the $N \times N$ identity matrix.

5.2 HARQ-Scheme in Static Channels

For slow fading channels, the signal and interference components remain approximately constant ($\mathbf{H}_1 = \mathbf{H}_2 = \cdots = \mathbf{H}_l$) upon retransmission which limits the ARQ gain. To increase the ARQ gain we consider to use a precoder to create an artificially diversity. One method which is effective in both SISO and MIMO systems, is to employ a Vandermonde matrix as precoder and create artificially diversity. Other precoding options is to consider a permutation matrix, which shuffles the label-transmit antenna assignments for each transmissions. A third option is to consider a FFT (or IFFT) matrix, which is both unitary and Vandermonde. That method spreads the symbol energy evenly among the L transmit antennas so that the effect of any deep fades (i.e. small values in $\mathbf{H}_l$) are alleviated.

By considering an unitary transformation Θ prior to the encoder, we can as mentioned before create artificially diversity. The transformation is taken from a set of predetermined matrices $\mathcal{S} = \{\mathbf{\Theta}_0, \mathbf{\Theta}_1, ..., \mathbf{\Theta}_{L-1}\}$ which is changing upon retransmission request. The generation of real unitary rotation can be achieved by applying a sequence of $P(P-1)/2$ Givens rotations [38], [36] to the channel matrix as follows

$$\mathbf{V}(\theta) = \prod_{i=1}^{P-1} \prod_{k=i+1}^{P} \mathbf{G}(i, k, \theta),$$

where the Givens rotation matrix is given as

$$\mathbf{G}(i,k,\Theta) = \begin{pmatrix} 1 & \cdots & 0 & \cdots & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & & \vdots & & \vdots \\ 0 & \cdots & \cos(\theta) & \cdots & \sin(\theta) & \cdots & 0 \\ \vdots & & \vdots & \ddots & & & \vdots \\ 0 & \cdots & -\sin(\theta) & \cdots & \cos(\theta) & \cdots & 0 \\ \vdots & & \vdots & & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & 0 & \cdots & 1 \end{pmatrix}$$

since $\mathbf{G}(i,k,\theta)$ is orthogonal, it is clear that the resulting rotation matrix is unitary. It is of great importance that $\boldsymbol{\Theta}$ is unitary to avoid any increase in the transmitter power.

At the receiver in paper **I** [31], a MMSE detection algorithm with ordered interference cancellation is employed and the combined decision can now be expressed as

$$z_i = \sum_{l=1}^{L} w_i(l) z_i(l),$$

where z_i denotes the decision statistic corresponding to the ith symbol s_i and the lth transmission. If equal packet combining scheme are used, $w_i(l) = 1$ for all $l = 1, 2, \ldots, L$. In a maximal ratio combining, the combining weight $w_i(l)$ is proportional to the SNR, i.e;

$$w_i(l) = \frac{1}{\{\boldsymbol{\Omega}_{\mathbf{k_i},\mathbf{k_i}}\}},$$

where $\boldsymbol{\Omega}$ is the MMSE criterion and k_i is the current min SNR symbol index.

5.2.1 Results

Obtained simulation results show that using unitary transformation prior to encoding provides a performance gain compared to a system without transformation. For instance, a performance gain of more than 2 dB is achieved between second and third transmission. The complexity can be kept fairly low if zero-forcing detection will be used instead of MMSE detection.

5.3 Alamouti-based HARQ-Scheme

For simplicity, we consider two transmit antennas and that the transmitted coded data stream is split into two sub-packets which are sent from the two transmit

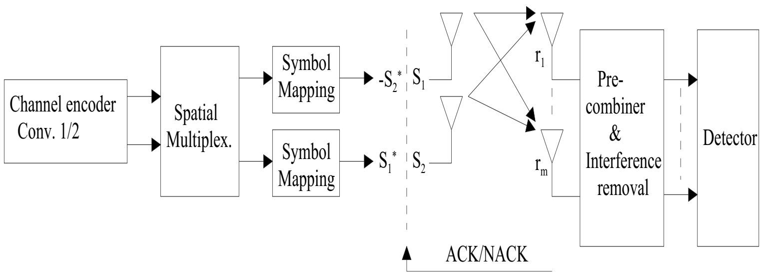


Figure 5.1: System model for Alamouti MIMO HARQ Scheme.

antennas. In order to remove the interference, we separate the two decoded packets and perform decoding. We consider both zero-forcing and MMSE receivers. The information bits are encoded with a high rate code c_0 for error detection and then with a half rate $(2, 1, m)$ convolutional code for error correction. The coded packet is then demultiplexed into two separate data streams transmitted from the two individual transmit antennas. The two data streams are digitally modulated and simultaneously transmitted from the two antennas.

If the received packet is correct decoded an ACK is sent to the transmitter, if an error is detected the receiver sends a NACK and a new transmission is requested using Alamouti STC scheme, i.e., the newly sent packet is composed as $[-s_2^* s_1^*]^T$. By taking the conjugate of the newly received packets we can write the ith signal at the receiver as:

$$\mathbf{r}^*_{(i+1)} = \mathbf{H}^*\Theta\mathbf{s}_{(i)} + \mathbf{n}^*_{(i+1)}, \quad i = 1, \ldots, L \tag{5.1}$$

from (5.1), it can be seen that this is equivalent to re-sending the previous vector signal through the new channel $\mathbf{H}^*\Theta$ that add time diversity. At the receiver, we employ symbol level combining to provide the soft symbol decision for $\mathbf{s}_i$. If the combined packets does not contain any error after decoding an ACK is sent, otherwise the transmitter resend the packets as in the i-th transmission, i.e., $\mathbf{s}_{i+2} = [s_1 s_2]^T$ and then combined [32]. This retransmission procedure proceeds until the packet is correct decoded or until the number of maximum retransmissions are exceeded.

When the number of transmission is even, the performance with zero-forcing and MMSE performance is the same and we can express the soft decision statistics as

$$\hat{\mathbf{s}} = (\mathbf{C} + \alpha\mathbf{I}_2)^{-1}\mathbf{C}\mathbf{s} + \mathcal{N}_{\mathcal{C}}[\mathbf{0}_2, \sigma^2(\mathbf{C} + \alpha\mathbf{I}_2)^{-1}\mathbf{C}(\mathbf{C} + \alpha\mathbf{I_2})^{-1H}], \tag{5.2}$$

where $\mathbf{C} = \sum_{i=1}^{L} \mathbf{H}_l^H \mathbf{H}_l$. Moreover, no matrix inversion is needed which reduces the complexity of the decoding. When the total number of transmissions is odd, despite having non orthogonal combination, the processing by the linear or

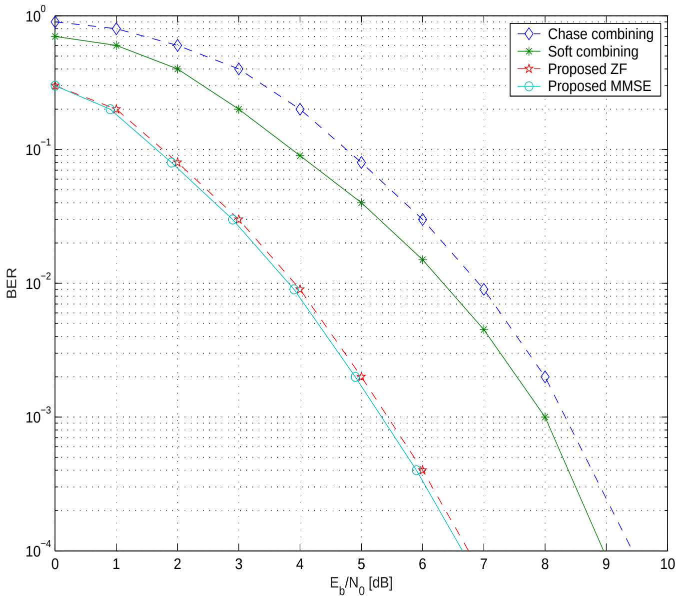


Figure 5.2: BER Performance for the proposed scheme compared to Chase combining and soft packet combining for $L = 2$ transmissions

MMSE take care of the cross interference though with extra decoding complexity due to the matrix inversion [64]. In fact, when N is even the linear ZF and MMSE are not needed since the Alamouti space-time coding remove the interference.

5.3.1 Results

The proposed scheme was simulated over a slowly fading channel with two transmit and two receive antennas (2×2 MIMO system). We have chosen to compare the scheme to basis hopping scheme in [60] for both ZF and MMSE receivers. For even number of transmissions there is no difference between ZF and MMSE detection, and no matrix inversion is needed which reduces the decoding complexity.

5.4 ARQ Scheme for Multi-Level Modulation

As been seen previously, rearrangement of signal constellations can provide good performance gain in SISO-channel. In this paper, we try to implement the same methodology for a MIMO-system. We consider to view the system like a single-antenna HARQ scheme for each data stream. Although, this setup does not fully exploit the characteristic of the MIMO channel. Furthermore, the proposed scheme requires that the receiver extracts the substreams independently. The decision metric can now be expressed as

$$\zeta(\hat{s}) = \min_{0,1,\cdots,M-1} \sum_{i=1}^{L} |\mathbf{y}_i - \mathbf{H}_i \hat{\mathbf{s}}|^2. \tag{5.3}$$

At a first glance, minimizing the metric in (5.3) appears to require an exhaustive search over all candidates. Fortunately, through some algebraic manipulations, the metric can be expressed so that an exhaustive search is avoided. By defining $\kappa_l = \mathbf{H}_l^H \mathbf{y}_l$, the metric can be written as

$$\sum_{l=1}^{L} (\hat{\mathbf{s}}_l - \kappa_l)^H \mathbf{H}_l^H \mathbf{H}_l (\mathbf{s}_l - \kappa_l).$$

Now we can apply sphere decoding to the above expression. In ML detection, sphere decoding has become a low cost alternative to exhaustive brute-force search [41], [43]. The primary strategy in search reduction is the removal of all points outside of a hypersphere centered about the received data point. Several techniques exist that quickly enumerate all symbols/labels within the hypersphere [43].

5.4.1 Finding Good Mappings

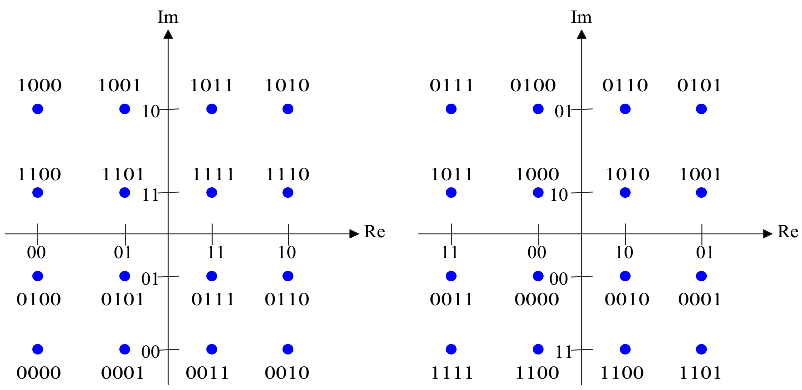
To find some good mappings there exist some heuristic approaches in the literature. In [6], the design of 16PSK modulation is obtained using the authors intuition and experiences. Another approach is called binary switch algorithm (BSA) [84], which - thanks to multiple random initializations is hoped to yield a solution close to optimum. To remedy this problem we will use set partition and partition to find good mappings.

To minimize the BER, the first transmission should be Gray mapped, which is optimal both for high and low SNR [1]. The signal points s_i in the first transmission are spread such they maximizes the squared Euclidean distance which is defined as

$$d^2 = \min\{||s_i - s_j||^2 : \; s_i, s_j \in \Omega\}. \tag{5.4}$$

To map the signal points of the second transmission we consider both set partition and permutation. The fundamental idea of set partitioning is to group the points of the signal constellation into sub-sets to achieve the maximum Euclidean distance between the points. The designing of good mappings can be described by the following procedure:

Let $k = 1, 2, \ldots, k$ represent the partition level, $\Omega_j^{(k)} = w_L$, the jth subset in the kth partition level and $\Omega^0 = \Omega$. We denote $M_j^{(k)}$ as the size of Ω_j^k and $M^0 = \sum_i^L M^{(j)}$. Then Δ_j^k is the minimum distance within the subset $\Omega_j^{(k)}$. The



(a) 16QAM first transmission (b) 16QAM second transmission

Figure 5.3: 16QAM mappings for first and second transmissions.

principle of set partitioning was proposed by [75] and the key is to partition the signal constellation into series of subsets of diminishing size

$$\Omega_j^{(k-1)} = \bigcup_{i=1,\dots,s} \Omega_{(j-1)s+i}^{(k)}, \quad j = 1, \dots, Ks$$

$$M^{(k)} = \frac{1}{s} M^{(k-1)},$$

in such way that the minimum Euclidean distance within the subsets increases while increasing the partition level, that is

$$\Delta^{(0)} < \Delta^{(1)} < \cdots < \Delta^{(K)}.$$

The iteration continues until the each sub-set only contains one signal point. Then, we define π to be a squared permutation matrix consisting of zeros and ones with the property that every row, and column has a single one. This permutation process ensures that the symbols obtained in the set partition process maximizes the Euclidean distance between the signal points. An example of obtained signal constellations for 16 QAM is shown in Fig. 5.3.

The complexity Υ of the search is roughly proportional to the number of times the criterion (5.4) has to be evaluated. An exhaustive search, i.e., explicit enumeration of all possible labellings has the complexity of $\Upsilon = M!$, where ! denotes factorial.

5.4.2 Results

To assess the performance of HARQ in MIMO system, we have simulated a 2×2 MIMO system using 16 QAM modulation. We chose to compare our proposed scheme with Chase combining. For instance, after two transmissions and a BER value of 10^{-2} we gain approximately 2.5 dB. This performance gain is due to the better spread of symbols in the signal space.

5.5 Concluding Remarks

By combining MIMO retransmissions at the receiver, the spatial diversity of MIMO systems is combined with the temporal diversity of retransmissions. Usually in discussing multiple transmissions for MIMO systems, the effect of the channels $\mathbf{H}_1 \ldots, \mathbf{H}_l$ has been ignored which intuitively say that if there is more variation among these channels we end up with a stronger diversity effect. This effect can be achieved by employing precoding. One example of precoding is to employ unitary precoders that are based on Given rotations. The purpose of this precoding is to avoid correlated interference between transmissions and artificially create a time diversity effect.

We have presented a hybrid ARQ scheme which exploits the space-time coding gain of Alamouti STC and also simplifies the computation of decision statistics since the Alamouti space-time coding take care of the cross interference. The proposed scheme is less complex than a system using precoding.

By combining distinctly mapped transmissions through MIMO channels, significantly gains are achieved. The mappings for different transmissions are designed such that they maximize the squared Euclidean distance. The obtained results show a significant performance gain compared to system employing Chase combining.

Chapter 6

Summary and Future Work

6.1 Summary

This thesis discuss different aspects of packet retransmission diversity in wireless networks.

In Chapter 3, we discussed the usefulness of employing simple packet combining in wireless LANs which today don't have this kind of technical feature. It was shown that packet combining increases the system performance in terms of higher throughput and lower packet delay. The complexity can be kept fairly low in a receiver-based packet combining approach where a signal combining device and a buffer is needed. We also investigated the performance of employing type-II hybrid ARQ scheme in wireless LAN. The obtained result show that a big performance gain can be achieved, although at the expense of increased complexity in the system. Furthermore, the performance also depends on the how accurate the channel statistics are at the transmitter in order to make an adequate selection of modulation and code rate for current channel conditions in order to avoid unnecessarily retransmission.

In Chapter 4, we presented some methods enriching diversity among multiple packet transmissions by adapting the mapping for each transmission. The proposed methods requires a minimal increase in transmitter complexity while the receiver complexity remains constant as the number of transmissions increase. A general framework, independent of signal constellation and channel characteristics, is introduced for finding optimal symbol mappings that maximizes the Euclidean distance. Results reveal that mapping diversity leads to very substantial gains for several constellation types when applied for AWGN and several types of flat-fading channels.

It was also found that by viewing the modulation dimension and the number of branches of the diversity scheme as an augmented signal space for the modulation signal points, good bit error rate performance was obtained. Furthermore, the combined scheme can be used to solve the problem of bandwidth efficiency loss seen in regular orthogonal transmitter diversity without increase in receiver complexity.

In Chapter 5, we studied MIMO-ARQ systems. We investigated a Alamouti-based HARQ scheme which exploits the space-time coding gain of Alamouti STC [2]. The proposed scheme simplifies the computation of the decision statistics especially when the total number of transmissions are even since the Alamouti space-time coding take care of the cross interference.

By employing unitary transformation prior to encoding, an artificially diversity gain can be obtained in quasi-static fading channels. The unitary matrices are constructed by Givens rotations. This method demands more complexity than the Alamouti-based HARQ scheme. Another approach was to employ the method of mapping diversity in MIMO system. This approach produced significant gains in both BER and computational complexity. We note that retransmissions in MIMO environments is very similar to space-time coding, and that our retransmission combining serves as simple, flexible, and efficient code.

6.2 Future Work

Many of the combining schemes, though indented for ARQ protocols, could be efficient as stand-alone FEC techniques. While trellis coded modulation (TCM) and Turbo coding have proven to be extremely effective techniques, mapping diversity provides reasonable coding gains with lesser complexity demands. Bigger gains may be archived trough joint mapping than using the iterative process.

In choosing mappings for retransmissions, standard constellations like QAM and PSK were typically considered. However, no restrictions were made on the constellation other than the constellation size. Thus, unconventional constellations may produce larger gains.

Further studies regarding the combined transmitter diversity and multi-level modulation scheme is of big interest. Since the results presented in this dissertation is for uncoded linear modulation schemes only, the natural extension of this work is to consider combined Trellis coded modulation and transmitter diversity and the interaction between coding and diversity branches.

For MIMO-ARQ system there is still much work to do. An interesting venue for future work is to design more sophisticated list decoders inspired by the elegant framework of Forney in [17]. Another interesting area is to investigate the performance of employing incremental redundancy for mapping diversity in MIMO systems. It may be advantageous to not retransmit all N labels, but instead to puncture or retransmit a subset of these labels. A simple puncturing is to use only one subset of the transmit antennas.

Finally, all protocols and combining schemes in this dissertation operate in the broader context of a communication system or network. Most of the simulations and analyses herein are concentrated on physical layer issues measures, like BER and FER. Studies that measure the impact of these schemes on the higher layers of the system should be of great value.

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Part II

Included Papers