Linköping Studies in Science and Technology
Dissertations, No. 1526

HARQ Systems: Resource Allocation, Feedback Error Protection, and Bits-to-Symbol Mappings

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Linköping 2013

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ISBN 978-91-7519-574-2
ISSN 0345-7524
Printed in Sweden by LiU-Tryck, Linköping 2013

Abstract

Reliability of data transmission is a fundamental problem in wireless communications. Fading in wireless channels causes the signal strength to vary at the receiver and this results in loss of data packets. To improve the reliability, automatic repeat request (ARQ) schemes were introduced. However these ARQ schemes suffer from a reduction in the throughput. To address the throughput reduction, conventional ARQ schemes were combined with forward error correction (FEC) schemes to develop hybrid-ARQ (HARQ) schemes. For improving the reliability of data transmission, HARQ schemes are included in the present wireless standards like LTE, LTE-Advanced and WiMAX.

Conventional HARQ systems use the same transmission power and the same number of channel uses in different ARQ rounds. However this is not optimal in terms of minimizing the average transmit power or the average energy spent for successful transmission of a data packet. We address this issue in the first part of the dissertation, where we consider optimal resource allocation in HARQ systems with a limit on the maximum number of allowed transmissions for a data packet. Specifically, we consider the problem of minimizing the packet drop probability (PDP) under an average transmit power constraint or equivalently minimizing the average transmit power under a fixed PDP constraint. We consider both incremental redundancy (IR)-based and Chase combining (CC)-based HARQ systems in our work. For an IR-HARQ system, for the special case of two allowed transmissions for each packet, we provide a solution for the optimal number of channel uses and the optimal power to be used in each ARQ round. For a CC-HARQ system, we solve the problem of optimal power allocation in i.i.d. Rayleigh fading channels as well as correlated Rayleigh fading channels. For the CC-HARQ case, we also provide a low complexity geometric programming (GP) solution using an approximation of the outage probability expression.

HARQ systems conventionally use one bit acknowledgement (ACK)/negative ACK (NACK) feedback from the receiver to the transmitter. In the 3GPP-LTE systems, one method for sending these HARQ acknowledgement bits is to jointly code them with the other control signaling information using a specified Reed-Muller code consisting of 20 coded bits. Even though the resources used for sending this control signaling information can inherently provide a diversity gain, the Reed-Muller code

with such a short block size is not good at extracting all of the available diversity. To address this issue, in the second part of this dissertation, we propose two new methods: i) based on complex-field coding (CFC), and ii) using repetition across frequency bands, to extract the inherent diversity available in the channel resources and improve the error protection for the HARQ acknowledgement bits along with the other control signaling information. In the second part of the dissertation, we also propose a new signal space diversity (SSD) scheme, which results in transmit signals having constant envelope (CE). The proposed CE-SSD scheme results in a better overall power efficiency due to the reduced back-off requirements on the radio frequency power amplifier. Moreover, the proposed CE-SSD technique can be useful for application scenarios which require transmission of a small number of information bits, such as in the case of control signaling information transmission.

In conventional HARQ systems, during the retransmission phase, the channel resources are exclusively used for the retransmitted data packet. This is not optimal in terms of efficient resource utilization. For efficient utilization of channel resources during the retransmissions, a superposition coding (SPC) based HARQ scheme was proposed in the literature. In an SPC based HARQ system, erroneous packets are transmitted together with a new data packet by superposition in the Euclidean space. In the final part of this dissertation, we study performance of different bits-to-symbol mappings for such an SPC based HARQ system.

Populärvetenskaplig Sammanfattning

De senaste åren har vi bevittnat en snabb utveckling av området trådlös kommunikation. Radiospektrum som används för cellulär kommunikation är, liksom alla andra naturresurser, också begränsad. Man förutspår att datatrafiken i de trådlösa näten kommer att följa en exponentiell tillväxt åtminstone i ytterligare fem år. För att hålla jämna steg med denna ökade efterfrågan, måste man utnyttja det tillgängliga radiospektrumet på ett effektivt sätt och samtidigt garantera tillförlitlig dataöverföring.

Fädning i trådlösa kanaler orsakar varierande signalstyrka hos mottagaren och detta resulterar i förlust av datapaket. För att förbättra tillförlitligheten, har paketomsändning system föreslagits i litteraturen. I dessa paketomsändningssystem, skickar sändaren ett datapaket till mottagaren. Efter mottagandet av paketet, försöker mottagaren att avkoda det. Om paketet mottagits felaktigt, sänder mottagaren en återkopplingssignal (negativ bekräftelse) som uppmanar sändaren att skicka mer information om det felaktiga paketet. Om paketet tas emot korrekt, skickar mottagaren en återkopplingssignal (positiv kvittering) och efterfrågar sändning av ett nytt datapaket. I denna avhandling, betraktar vi olika aspekter av dessa befintliga system för paketomsändning och föreslår några förbättringar.

Konventionell paketomsändning är inte optimalt när det gäller effektivt resursutnyttjande (effekt eller energi). I den första delen av avhandlingen, beskriver vi två varianter av sådana paketomsändningssystem och föreslår lösningar för optimal effektfördelning, vilket resulterar i betydande energibesparingar.

Återkopplingssignalen spelar en viktig roll i paketomsändningssystem. Det är viktigt att denna återkoppling- (kontroll-) information har ett starkt felskydd. I den andra delen av avhandlingen, föreslår vi två nya metoder för att förbättra felskyddet av styrsignaleringsinformationen i dagens LTE system.

Ett sätt att utnyttja resurserna på ett effektivt sätt med hjälp av omsändningssystem är att återsända ett felmottaget paket tillsammans med ett nytt datapaket. Detta kan man göra med hjälp av överlagringskodning. I den sista delen av avhandlingen, föreslår vi tekniker för att förbättra prestanda för sådana system.

Acknowledgments

When I look back at the time from finishing my Masters degree in 2005 to the present day, a lot of people have helped me in this long and fulfilling journey.

First and foremost, I would like to express my sincere gratitude to my supervisor Prof. Erik. G. Larsson for giving me the opportunity to pursue my doctoral studies in Sweden. I am thankful to him for his constant support, enthusiasm, and immense knowledge. He has encouraged me to pursue my own research ideas, and he has guided me with his critical comments and suggestions which improved the quality of my research work. His constructive feedback helped me develop as a researcher during the past 4+ years. Among other things, I have also learned from him about presenting research results and how to be a good teacher.

I am thankful to my co-supervisor Dr. Danyo Danev for the research discussions, where we tried to solve some interesting mathematical problems. I am grateful to my research collaborators Dr. Niclas Wiberg, Ericsson Research and Dr. Fredrik Brännström, Chalmers University of Technology for generously sharing their time and knowledge. I am also thankful to the anonymous reviewers who carefully read my manuscripts and provided useful and instructive comments.

A special acknowledgement goes to my colleagues Reza, Mirsad and Hien for their help and many interesting technical and non-technical discussions. They each helped make my time as a Ph.D. student more fun and interesting. I hope we can continue football discussions in future as well!

I would like to sincerely thank all present and past colleagues at Communication Systems division for the mentoring and support they have given me during my stay here in Sweden. I have really enjoyed working with them and learned many new things. A special thanks to Mirsad and Danyo for organizing the wonderful after work get together events.

I would also like to thank Dr. Gunnar Bark, Ericsson Research and Dr. Pål Frenger, Ericsson Research for facilitating the technical discussions, where I learned many important things about LTE systems.

A special thanks goes to my former colleagues at Beceem communications Dr. Erik Lindskog, Dr. Harold Artés, and Dr. Bhavani Shankar for their help during my search for Ph.D. studies in Sweden.

Finally, I would like to thank my parents, brother, sister, and friends for their endless support.

Linköping, August 2013
T. V. K. Chaitanya

Abbreviations

3GPP	Third Generation Partnership Project
ACK	Acknowledgment
AMC	Adaptive Modulation and Coding
ARQ	Automatic Repeat Request
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BLER	Block Error Rate
BPSK	Binary Phase Shift Keying
BW	Bandwidth
CC	Chase Combining
CCI	Control Channel Information
CE	Constant Envelope
CFC	Complex-Field Coding
CMA	Cooperative Multiple Access
CNR	Channel-to-Noise Power Ratio
CP	Cyclic Prefix
CQI	Channel Quality Indicator
CRC	Cyclic Redundancy Check
CSI	Channel State Information
CSIT	Channel State Information at the Transmitter
DL	Downlink
DPC	Dirty Paper Coding
eNodeB	Evolved Node B (Base station)
FEC	Forward Error Correction
FFT	Fast Fourier Transform
GPP	Geometric Programming Problem
GLRT	Generalized Likelihood Ratio Test
HARQ	Hybrid Automatic Repeat Request
IR	Incremental Redundancy
KKT	Karush-Kuhn-Tucker
L1/L2	Layer 1/Layer 2
LDC	Linear Dispersion Codes

LDPC	Low-Density Parity-Check
LLR	Log-Likelihood Ratio
LS	Least Squares
LTE	Long Term Evolution
MAC	Medium Access Control
MCS	Modulation and Coding Scheme
MIMO	Multiple-Input Multiple-Output
MISO	Multiple-Input Single-Output
MMSE	Minimum Mean Square Error
ML	Maximum Likelihood
MLM	Multiple Level Modulation
MRC	Maximum Ratio Combining
MSC	Multiple Source Cooperation
NACK	Negative Acknowledgment
NMT	Nordic Mobile Telephony
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PAM	Pulse Amplitude Modulation
PAPR	Peak-to-Average Power Ratio
PCFICH	Physical Control Format Indicator Channel
PDCCH	Physical Downlink Control Channel
PDP	Packet Drop Probability
PEP	Pairwise Error Probability
PHICH	Physical HARQ Indicator Channel
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
QAM	Quadrature Amplitude Modulation
R-PDCCH	Relay-Physical Downlink Control Channel
SC-FDMA	Single Carrier Frequency Division Multiple Access
SIC	Successive Interference Cancellation
SISO	Single-Input Single-Output
SNR	Signal-to-Noise Power Ratio
SPC	Superposition Coding
SSD	Signal Space Diversity
TDD	Time Division Duplexing
UE	User Equipment
UL	Uplink
UL-SCH	Uplink Shared Channel
WiMAX	Worldwide Interoperability for Microwave Access

Contents

Part I

Introduction

Chapter 1

Background

Wireless networks have inherent advantages over wired networks in terms of facilitating user mobility, cost effectiveness and coverage even in remote areas and harsher environmental conditions. Because of these advantages, many new application scenarios are emerging daily where wireless communication plays a significant role. For example, communication in smart grids [1] and vehicle-to-vehicle communications [2]. In the past three decades, the wireless communications field has seen a rapid growth in terms of technology evolution from the analog Nordic mobile telephony (NMT) system to broadband wireless systems like third-generation partnership program (3GPP)-long-term evolution (LTE) and LTE-Advanced. During this evolution, new transmission techniques were developed, which have led to increase of data rates by many orders of magnitude, see Figure 1.1. Some of the techniques contributing to the increased data rates are the multi-carrier modulation, fast modulation and coding adaptation, channel-dependent scheduling and multiple-input-multiple-output (MIMO) transmission.

The earlier versions of wireless technology mainly focused on speech and text applications. However, with the emerging broadband wireless technologies, applications which require large amounts of data transfer are taking precedence over speech and text applications. In current wireless networks, the data traffic is growing at an exponential rate, whereas the speech traffic is growing linearly with time. It is predicted that there will be 50 billion connected devices by the year 2020. While many new communication devices are being connected using wireless technology, the radio resources like frequency spectrum and transmit power available for wireless communication are limited like any other natural resource. Hence it is becoming increasingly important to efficiently utilize the radio resources. Another important aspect of communication over wireless networks is the reliability of the data. Often, reliability over wireless networks is affected by fading, which causes the signal strength to vary at the receiver and this results in a loss of data packets.

Generation	Peak data rate	Example Technology	Applications	Time line
1G	1.9 kbps	**NMT**, AMPS	Analog Voice	1980's
2G	9.6 kbps	**GSM**, CDMA	Digital Voice, SMS	1990's
2.5G	384 kbps	GPRS**, EDGE**	Internet, MMS	Late 1990's
3G	2 Mbps	**WCDMA,** CDMA 2000	Multimedia over wireless	2000's
3.5G	~300 Mbps	HSPA, **LTE**	Mobile TV, Video chat	Late 2000's
4G	1 Gbps	**LTE-Advanced**	Interactive applications	2010's

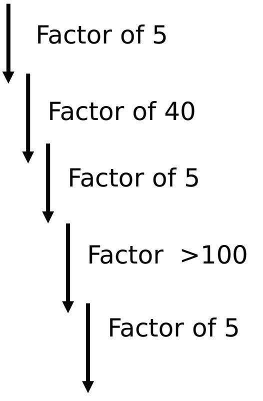


Figure 1.1: List of different wireless communication technologies. Peak data rates shown in the figure are for the technologies in bold-font.

To overcome the reliability issue in fading channels and for efficient utilization of radio resources, wireless systems like worldwide interoperability for microwave access (WiMAX) [3] and 3GPP-LTE [4] employ adaptive transmission techniques. One of the important factors in adaptive transmission systems is the channel state information (CSI) feedback from the receiver. In the presence of CSI at the transmitter, a common adaptive transmission technique used at the physical layer is dynamic link adaptation. In link adaptation, the transmitter dynamically adapts the modulation order, coding rate and/or other signal transmission parameters [5, 6]. Commonly used link adaptation strategy in practical wireless systems is adaptive modulation and coding (AMC). In AMC, when the channel quality is good, higher order modulation and coding scheme (MCS) is used to increase the throughput, and if the channel quality degrades, the transmitter switches to lower MCS level to maintain a fixed target error probability. To further improve the robustness of the wireless systems against the link adaptation inaccuracies caused by errors in channel measurement and feedback delays, hybrid automatic repeat request (HARQ) schemes are also adopted at the medium access control (MAC) layer in systems like WiMAX and 3GPP-LTE.

In HARQ schemes, forward-error correction (FEC) schemes are combined with automatic repeat request (ARQ) schemes. If a data packet is received in error, the transmitter sends again the information about the erroneous packet to the receiver. Upon receiving additional information about the erroneous packet, the receiver makes another try to decode the erroneous packet and it may or may not combine the information received across different transmissions of the same data packet. HARQ systems use acknowledgment (ACK) and negative acknowledgement (NACK) signal feedback to determine whether retransmission of a data packet is required or not. Because of their wide usage in current wireless broadband systems, presently there is a lot of attention on the research related to HARQ systems. Even though HARQ schemes exist in literature for more than three decades, many research problems related to both theoretical and practical aspects of HARQ systems are still open. In this dissertation, we focus on three aspects of HARQ systems described below.

Resource Allocation for HARQ Systems: Although retransmission schemes consume additional radio resources in terms of channel uses and transmission power, they are necessary to improve the transmission reliability in fading channels. Most HARQ systems studied in literature assume the same transmission parameters (transmission power, channel uses) during retransmission of an erroneous data packet, and many theoretical results have been derived using this assumption. Recently, adaptive and optimal resource allocation for HARQ systems are being studied extensively to improve the efficiency. In this dissertation, we consider the resource allocation problem for both Chase combining (CC) and incremental redundancy (IR) based HARQ schemes. Our objective is to find the optimal channel usage and power allocation for IR-HARQ schemes and optimal power allocation for CC-HARQ schemes in Rayleigh fading channels.

Feedback Error Protection for HARQ Systems: Another important aspect of adaptive transmission systems is the transmission of control signaling information between the transmitter and the receiver. To facilitate the use of link adaptation techniques, and HARQ schemes as well as to improve the system performance, information about channel quality and HARQ acknowledgment bits should be sent from the receiver on a dedicated feedback channel. In general, this control signaling information consists of a small number of information bits and it is transmitted using weak channel codes. Typically the coded control signaling information is spread across the channel resources (in time or in frequency) to overcome the effects of fading. However, weak (inefficient) channel codes used for encoding control signaling information are not good enough to extract all of the diversity available in the channel resources. Hence it is important to come up with new methods for efficient transmission of control signaling information in current wireless systems. In this dissertation, we specifically consider the problem of improving error protection for uplink control signaling transmission in LTE systems. We also propose a new power efficient transmission method which can be useful for application scenarios involving transmission of a small number of information bits.

Bits-to-Symbol Mappings for HARQ Systems: In traditional HARQ systems, during the retransmission phase, channel resources are exclusively used for transmitting an erroneous data packet to the receiver. However, such a transmission scheme is not efficient from radio resource utilization point of view. To improve the throughput efficiency of HARQ schemes, a superposition coding (SPC) based multiplexed HARQ scheme was proposed in [54]. In an SPC-HARQ scheme, during retransmissions, erroneous data packets are superimposed along with a new data packet and sent to the receiver. The conventional way of superimposing data packets results in an inherent natural mapping of bits-to-superimposed symbols, which may not be optimal in terms of the performance metric of interest. In this dissertation, we look at the problem of finding good bits-to-symbol mappings in terms of maximizing the mutual information for SPC-HARQ systems.

In the following, we give a brief introduction to link adaptation and different HARQ schemes in Chapter 2. In Chapter 3, we describe the control signaling mechanisms used in 3GPP-LTE systems. A brief introduction to superposition coding and its applications in various communication systems is presented in Chapter 4. We list the specific contributions of this thesis with a short description of the included papers in Chapter 5 and finally we discuss some future research directions in Chapter 6.

Chapter 2

Link Adaptation and HARQ Systems

In this chapter, we first look at information theoretic results concerning the availability of CSI knowledge at the transmitter in slow fading channels. Later, we describe how link adaptation, ARQ and HARQ schemes are used in limited feedback systems to improve reliability and efficiency.

Let us consider the complex baseband representation of a flat fading channel as:

$$y(n) = h(n)\,x(n) + w(n)\,, \tag{2.1}$$

where $y(n)$, $h(n)$, $x(n)$ and $w(n)$ denote the received signal, the fading coefficient, the component of the transmitted codeword and the additive white Gaussian noise (AWGN) sample at time index n, respectively. We assume that $h(n) \sim \mathcal{CN}(0,1)$ and that $w(n)\,, \forall n$ are independent and identically distributed (i.i.d.) with distribution $\mathcal{CN}(0, N_0)$. The components of the codewords are assumed to be independent and satisfy the condition that $\mathbb{E}\left(|x(n)|^2\right) = P$. We define the signal-to-noise power ratio (SNR) as

$$\mathrm{SNR} = \frac{P}{N_0}. \tag{2.2}$$

In a slow fading scenario, $h(n) = h, \forall n$. If the receiver has perfect knowledge about h, conditioned on the channel gain h, this system model corresponds to an AWGN channel with received SNR of $|h|^2\,\mathrm{SNR}$. The spectral efficiency of this channel is $\log\left(1 + |h|^2\,\mathrm{SNR}\right)$ bits/s/Hz. If the transmitter also has perfect knowledge about h, the capacity of this channel is given by [8]:

$$C = \log\left(1 + |h|^2\,\mathrm{SNR}\right) \text{ bits/s/Hz} \tag{2.3}$$

However, if the transmitter does not have the knowledge of h, from the transmitter point of view, the fading coefficient h is random. If the transmitter encodes the data at a rate of R bits/s/Hz, and if R is larger than $\log\left(1 + |h|^2 \,\mathrm{SNR}\right)$, then the decoding error probability cannot be made arbitrarily small for whatever code chosen by the transmitter. In such scenarios, the system is said to be in outage [8]. The probability of an outage event can be written as [8]:

$$p_{\mathrm{out}}(R) = \Pr\left\{\log\left(1 + |h|^2 \,\mathrm{SNR}\right) < R\right\}. \tag{2.4}$$

One of the design targets in slow fading channels when no CSI is available at the transmitter is to achieve a fixed target outage probability. While considering the optimum resource allocation problem in HARQ systems in this dissertation, we use outage probability as a performance metric.

Practical wireless systems use finite-dimensional constellations for modulation, and providing the transmitter with perfect CSI is also not possible in practice. CSI has to be either estimated at the receiver and then fed back or the transmitter has to use the estimated channel of the reverse-link and use the reciprocity of wireless channel in time division duplexing (TDD) systems. In the following sections, we discuss how wireless systems use the limited CSI knowledge at the transmitter to improve the efficiency and reliability of communication.

2.1 Link Adaptation

Traditional communication systems were nonadaptive. These systems were designed for worst-case channel conditions, resulting in insufficient utilization of the full channel capacity [5]. When the channel can be estimated and fed back to the transmitter on a dedicated feedback channel, the transmitter can utilize this information and adapt the transmission scheme relative to the current channel state. The idea behind these adaptive transmission (link adaptation) schemes is to maintain a constant packet error rate by changing transmission parameters such as transmission power, modulation order, coding rate, spreading factors, signaling bandwidth, and more. For example, in practical wireless systems, the different MCS levels to be supported in a system are predefined. When channel conditions are favorable, the transmitter exploits them by selecting a higher order modulation and coding rate for the transmission. But when the channel quality degrades, the transmitter adapts by choosing a lower order modulation and a lower coding rate for data transmission. By selecting the best MCS level for a given channel quality, the link adaptation results in higher average throughput performance compared to the nonadaptive systems [9].

The first adaptive transmission scheme was proposed in [10], where the transmitter power level was adjusted relative to channel variations. Later, various link adaptation schemes were proposed, in which different transmission parameters were adapted to improve the performance in fading channels. For example, symbol transmission rate [11], coding rate/scheme [12], constellation size [13], or a combination of these parameters [14] were adapted based on channel conditions.

The gains that can be realized by link adaptation very much depend on the accuracy of CSI available at the transmitter and the feedback delay. If the user mobility is high, imperfect CSI and large feedback delays make the CSI information less useful at the transmitter. Choosing a wrong MCS level based on imperfect CSI may result in a degradation of throughput performance. In order to make the wireless systems more robust against the link adaptation inaccuracies, retransmission mechanisms such as ARQ and HARQ can be used at MAC layer. One disadvantage of retransmission schemes in practice is that additional delays are introduced in the system. However, in many practical systems, the number of retransmissions allowed is limited to avoid an unacceptable time delay before the successful transmission of a packet. This limit on the number of allowed retransmissions introduces residual packet errors.

2.2 ARQ Schemes

The conventional way of controlling transmission errors is to use FEC schemes. In an FEC system, error-correcting codes are used. When the receiver detects the presence of errors, it attempts to detect the location of errors and correct them. Even if the receiver is not able to correct the errors, the erroneous data will be delivered to the upper layer. Alternatively, when a feedback channel from the receiver to the transmitter is available, ARQ schemes can be used for overcoming the transmission errors. In an ARQ system, a code with good error-detection capability is used. Data packets are appended with error detection bits and sent to the receiver. After receiving the data packet, the receiver checks for errors in the received data. If there are errors, the receiver sends a NACK signal on the feedback channel asking for a retransmission, and this process is continued until the data is successfully received. If the packet is received without any errors, the receiver sends an ACK signal to the transmitter. Cyclic redundancy check (CRC) codes are the commonly used codes for error-detection [15]. There are three basic types of ARQ schemes proposed in literature. They are the stop-and-wait ARQ, the go-back-N ARQ and the selective-repeat ARQ.

2.2.1 Stop-and-wait ARQ

An example for the stop-and-wait ARQ protocol is shown in Figure 2.1. After the packet is encoded using an error-detection code and sent to the receiver, the transmitter waits for the feedback from the receiver. If the transmitter receives an

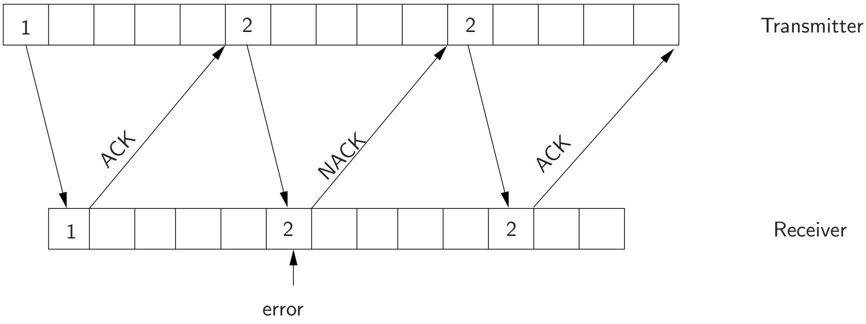


Figure 2.1: Stop-and-wait ARQ protocol.

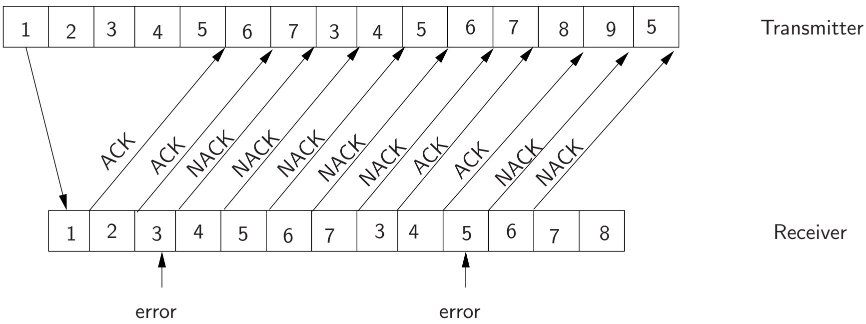


Figure 2.2: Go-back-N ARQ protocol with N = 5.

ACK message, it sends the next packet. If the transmitter receives a NACK message on the feedback channel, it retransmits the erroneous packet. This stop-and-wait ARQ scheme is inefficient when there is a large delay (round-trip delay) between the time each packet is transmitted and the time ACK or NACK feedback message is received. The advantage of this protocol is that it is easy to implement, and that the transmitter or the receiver needs to store only one packet at any given time.

2.2.2 Go-back-N ARQ

The operation of the go-back-N ARQ scheme is shown in Figure 2.2. In this ARQ protocol, the transmitter does not wait for an ACK message to transmit the next packet, the packets are transmitted continuously. The ACK/NACK message for a transmitted packet will be received after the round-trip delay. During this time, the transmitter sends another $N-1$ packets. When a NACK message is received, the transmitter backs up the erroneous packet and resends it along with the $N-1$ packets that were sent during the round-trip delay. The transmitter must be provided with buffers to store N packets at any given time. Whereas, on the receiver side, $N-1$ packets following an erroneously received packet are discarded regardless

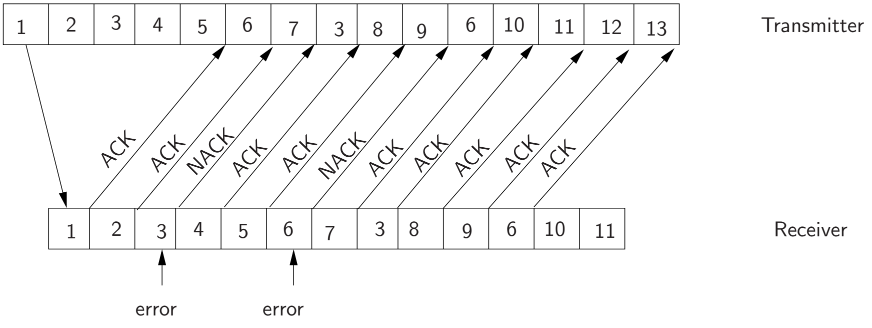


Figure 2.3: Selective-repeat ARQ protocol.

of whether they are in error or not. Because of the continuous transmission of packets, this protocol is more efficient than the stop-and-wait protocol. The go-back-N protocol also becomes inefficient if the round-trip delay is large and data transmission rate is high. The inefficiency of this protocol lies in the fact that many error-free packets will be discarded at the receiver following a packet detected in error [15].

2.2.3 Selective-repeat ARQ

The selective-repeat ARQ protocol is shown in Figure 2.3. In this protocol also, the packets are continuously sent from the transmitter. The transmitter keeps sending new packets as long as ACK messages are received. When a NACK message is received, the transmitter resends only the erroneous packet. Since packets should be delivered in correct order to higher layers at the receiver, a buffer must be provided at the receiver to store the packets which are received error-free following a packet which has been in error. When the first negatively acknowledged packet is successfully received, the receiver then releases the error-free packets in consecutive order until the next erroneously received packet is encountered. Selective-repeat ARQ is the most efficient of the three ARQ protocols [15]. The main drawback of selective-repeat ARQ scheme is the increased complexity it induces as both the transmitter and the receiver have to be equipped with buffers. The throughput efficiency study of the three ARQ protocols is available in [15].

Since the probability of decoding error is much higher than the probability of an undetected error, systems using only FEC schemes cannot guarantee high reliability. Moreover, to obtain high reliability using FEC, long powerful codes must be used and a large number of errors must be corrected. However, using long codes make the decoding hard to implement and computationally expensive. Compared to systems using only FEC, ARQ systems are simple and provide more reliability. ARQ schemes have a drawback in the sense that their throughput degrades significantly under severe fading conditions. The drawbacks in both the ARQ and FEC schemes could be overcome if the two error control schemes are properly combined. Such a combination of the two basic error control schemes is referred to as HARQ [15].

2.3 HARQ Schemes

A HARQ system consists of an FEC subsystem contained in an ARQ system. The role of the FEC subsystem is to reduce the frequency of retransmissions by correcting the errors in the received packets. This increases the throughput performance. When the FEC cannot correct the errors, ARQ takes over and this improves the reliability. Thus a proper combination of FEC and ARQ would provide higher reliability than only an FEC system and a higher throughput than the system using only ARQ. An FEC scheme can be incorporated with any of the three basic ARQ schemes described in Section 2.2. There are different types of HARQ schemes proposed in literature, and they are mainly classified into type-I and type-II HARQ schemes [16]:

2.3.1 Type-I HARQ Schemes

In these schemes, a code capable of simultaneous error-correction and error-detection is used. If the number of errors in a received packet is within the error correcting capability of the code, the errors will be corrected. If the receiver is unable to correct the errors, it discards the received packet and asks for a retransmission. When the retransmitted packet is received, the receiver again attempts to correct the errors (if any). If the decoding is not successful, the receiver again discards the received packet and asks for another retransmission. This process continues until the packet is correctly received. Since the code must be able to both detect and correct errors, more parity-check bits are required. This increases the overhead associated with transmissions. Because of this, type-I HARQ schemes result in a lower throughput than the ARQ schemes if the channel conditions are good. However, if the channel conditions are not good and the error correcting capability of the FEC code is good, a type-I HARQ scheme can achieve a higher throughput than an ARQ scheme [15].

2.3.2 Type-II HARQ Schemes

In these schemes, the receiver combines the information from different (re)transmissions to decode the packet. These schemes are sometimes called HARQ schemes with soft combining. They are further classified into two types:

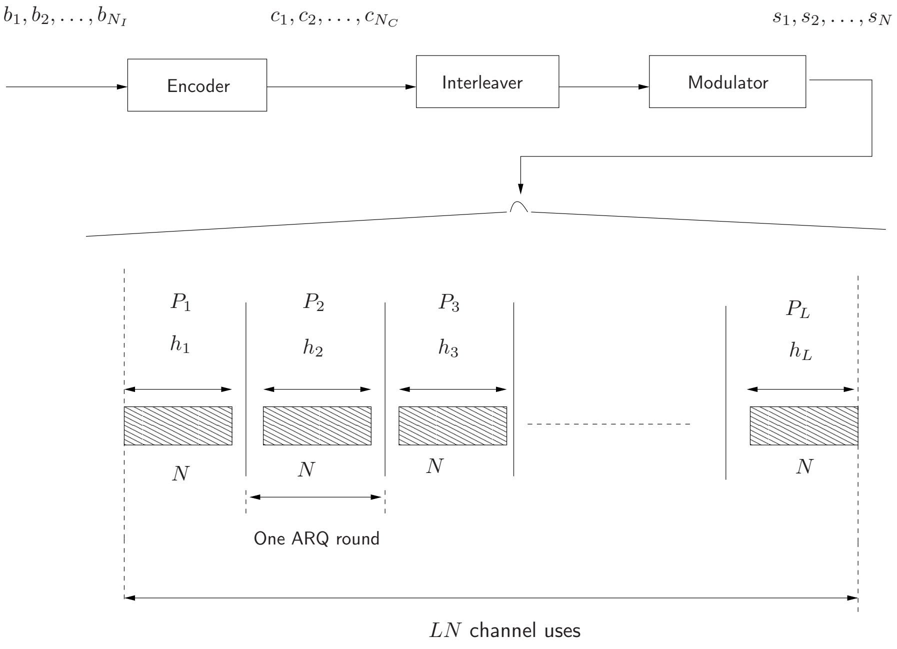


Figure 2.4: System model for the CC-HARQ scheme.

- ***Chase Combining (CC) Schemes:*** These are the type-II HARQ schemes in which all the retransmissions carry the same information, i.e., the packet is encoded using the same channel code during each transmission and the transmitted signal contains the same coded bits [17, 18]. The receiver uses maximum-ratio-combining (MRC) to decode the data packet. The combining is usually done after the demodulation but before the decoding. Since each retransmission is identical to the first transmission, these schemes are also known as repetition diversity HARQ schemes. Since no additional redundancy is transmitted during retransmissions, Chase combining schemes do not give any additional coding gain. With each retransmission, these schemes only result in an increase of the accumulated received E_b/N_0, where E_b denotes the energy per information bit.

  The system model considered in this dissertation for a CC-HARQ scheme is shown in Figure 2.4. A set of N_I information bits are encoded to obtain N_c coded bits. The N_c coded bits are then mapped onto a constellation $\mathcal{S}$ to obtain N modulation symbols $s_1, \cdots, s_N$. The N modulation symbols are sent to the destination in N channel uses. If the receiver is not able to decode the packet, the same N modulation symbols $s_1, \cdots, s_N$ are transmitted during the retransmission phase. If the maximum number of retransmission for each data packet is limited to L, then the maximum number of channel uses for the transmission of each packet is given by LN.

  Several variations of Chase combining schemes are proposed in literature. For

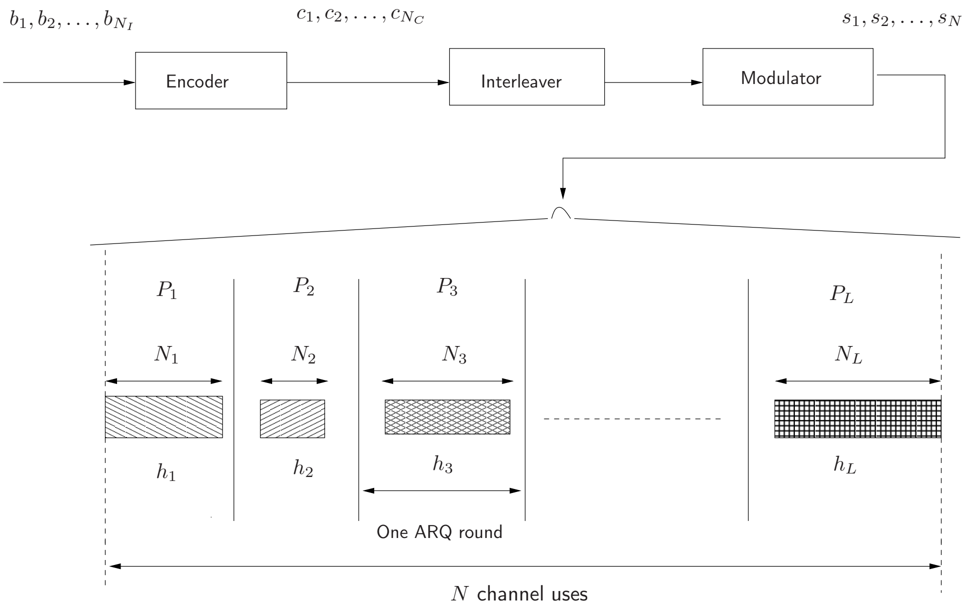


Figure 2.5: System model for the IR-HARQ scheme.

example, instead of transmitting the whole codeword during retransmissions, only a part of the codeword can be transmitted and such schemes are called *partial Chase combining HARQ* schemes.

- ***Incremental Redundancy (IR) Schemes:*** In these type-II HARQ schemes, successive retransmissions carry 'new' information to the receiver. Typically during retransmissions, additional parity bits are sent to the destination [19, 20]. The receiver combines the information from the current retransmission with information from previous transmission attempts of the same packet. Since each transmission contains information which was not transmitted previously, the resulting code rate at the receiver is lowered by each retransmission. One can view Chase combining schemes as a special case of incremental redundancy schemes [4]. We note that the term *type-III HARQ schemes* is sometimes used in literature to refer to IR-HARQ schemes where each retransmission is self decodable [21].

The system model considered in this dissertation for an IR-HARQ scheme is shown in Figure 2.5. It is similar to the one shown for a CC-HARQ scheme in Figure 2.4, except that during retransmissions, modulation symbols corresponding to new parity bits are sent to the destination. Assuming that the lth ARQ round uses N_l channel uses, and that the number of transmissions is limited to L, the maximum number channel uses for each packet is given by $\sum_{l=1}^{L} N_l = N$.

2.4 Information Outage Analysis of Type-II HARQ Schemes

In this section, we give an information theoretic understanding of HARQ schemes involving CC and IR. As described with the system models for CC-HARQ and IR-HARQ in Section 2.3.2, during each ARQ round, in case of IR-HARQ scheme, a new block of modulation symbols consisting of additional parity bits is transmitted. Whereas in case of CC-HARQ scheme, the same modulation symbols are transmitted during each ARQ round. The discrete-time received signal model for a HARQ system in the ith channel use of an lth ARQ round can be written as:

$$y_{l,i} = \sqrt{P_l} h_l s_{l,i} + e_{l,i}, \quad l = 1, 2, \ldots, L,\ i = 1, 2, ..., M \tag{2.5}$$

where P_l and h_l denote the transmit power used and the complex fading coefficient during the transmission of lth ARQ round. The additive white Gaussian noise (AWGN) samples $e_{l,i}$ are assumed to be i.i.d. and independent across the ARQ rounds with distribution $\mathcal{CN}(0, 1)$. The modulation symbols $s_{l,i}$ are assumed to have zero mean and unit average energy. The channel gain h_l is assumed to be constant for the transmission during the lth ARQ round. The parameter M in (2.5) takes on different values depending on the type of HARQ scheme used. For CC-HARQ schemes, $M = N$ and for IR-HARQ schemes, $M = N_l$.

Let SNR_l denote the received SNR during the transmission of lth ARQ round. We have $\mathrm{SNR}_l \triangleq |h_l|^2 P_l$. Assuming a Gaussian codebook with encoding, decoding and error detection procedures described in [22], for a sufficiently large value of N, the probability of a decoding error at the end of each ARQ round can be well approximated by the information outage probability. The information outage probability is defined as the probability that the instantaneous spectral efficiency is smaller than the target spectral efficiency or equivalently the total accumulated mutual information is smaller than the total number of information bits [25]. Hence the information outage probability after l ARQ rounds for IR-HARQ schemes can be written as:

$$P_{\mathrm{out,IR}} \triangleq \Pr\left(\sum_{k=1}^{l} N_k \log_2\left(1 + \mathrm{SNR}_k\right) \leq N_I\right), \tag{2.6}$$

whereas for CC-HARQ schemes, we have:

$$P_{\mathrm{out,CC}} \triangleq \Pr\left(N \log_2\left(1 + \sum_{k=1}^{l} \mathrm{SNR}_k\right) \leq N_I\right). \tag{2.7}$$

The exact expression for the outage probabilities in (2.6) and (2.7) depend on the distribution of $\mathrm{SNR}_k, 1 \leq k \leq l$.

2.5 Overview of Research on HARQ Systems

Previous work on HARQ systems has focused on different aspects of system performance. For example, an information theoretic throughput and delay analysis of HARQ schemes for the Gaussian collision channel was presented in [22]. Throughput analysis of IR-HARQ in the block-fading AWGN channel with low-density parity-check (LDPC) codes was carried out in [23]. Coding performance of HARQ systems was studied in [24], and a rate adaptation scheme for IR and CC HARQ systems to maintain fixed outage probability was studied in [25].

As HARQ schemes can easily be extended to MIMO systems [8] and cooperative communication systems [26], significant research work has been done in terms of studying the performance of HARQ schemes in these systems. For example, the tradeoff between throughput, diversity, multiplexing gain and delay for MIMO ARQ systems was studied in [27, 28]. Similarly, performance of HARQ schemes in relaying systems was studied in [29].

HARQ schemes are used when perfect CSI information is not available at the transmitter. Most research results on HARQ systems use one bit ACK/NACK feedback from the destination. It is possible to improve the performance of HARQ schemes by providing more knowledge about CSI at the transmitter. This, however, leads to more information transfer on the feedback channel, therefore increasing the overhead. There are previous works which have considered this research problem. In [30, 37], average rate performance of HARQ schemes in terms of quantized CSI feedback was studied for single-input-single-output (SISO) systems. The trade-off in terms of providing the amount of received channel output feedback and the throughput performance of SISO, multiple-input-single-output (MISO) and MIMO HARQ systems was studied in [31]. Outage performance of IR-HARQ schemes with multibit feedback for MIMO systems was studied in [32].

Many previous works on HARQ systems did not consider the resource optimization to minimize the energy consumption. The studies in [22, 23, 24, 25, 27, 28, 29, 31] assume the same transmit power in all the transmission rounds of associated HARQ schemes, i.e., $P_1 = P_2 = \cdots = P_L = P$ in Figures 2.4 and 2.5. While analyzing IR-HARQ schemes, previous works also assumed that the channel uses in different ARQ rounds are also the same, i.e., $N_1 = \cdots = N_L = \frac{N}{L}$ in Figure 2.5. However, the importance of energy savings in telecommunication networks has led to the research on optimal resource allocation for HARQ systems. Towards this, for CC-HARQ schemes, an ad-hoc power ramping scheme was proposed in [33] to improve throughput performance. In [34], a cross-layer optimization problem to maximize the average system goodput with HARQ was studied under the assumption of outdated CSI at the transmitter, and an asymptotic cross-layer policy involving power allocation, rate allocation and user selection was derived. Similarly, an optimal power allocation scheme to minimize the asymptotic packet drop probability (PDP) for a space-time coded HARQ scheme was presented in [35]. In [36, 37], optimal power allocation for maximizing the average rate performance of HARQ schemes was studied under short-term and long-term average power constraints.

For CC-HARQ schemes, a power optimization problem to minimize PDP in quasi-static ($h_1 = \cdots = h_L = h$ in Figure 2.4) Rayleigh fading channels under an average transmit power constraint was studied in [38]. However, in a quasi-static fading scenario in which the channel gain remains constant for all ARQ rounds, it might be better to spend resources on learning the channel at the receiver and then use the bits allocated for HARQ acknowledgements to send information about CSI to the transmitter. We believe that this approach might be better than performing power optimization.

2.6 Contributions Related to Resource Allocation for HARQ Systems

In Paper A, we consider the problem of optimal power allocation for IR-HARQ systems by assuming equal number of channel uses for each ARQ round. We specifically consider the problem of minimizing PDP under an average transmit power constraint when one additional retransmission is allowed. Our contribution is novel in the sense that we provide a closed-form root-finding solution for determining power values to be used in the two ARQ rounds. In Paper B, we relax the equal channel uses assumption and consider optimal power and channel uses allocation problem.

For CC-HARQ schemes, we consider the power allocation problem by relaxing the quasi-static fading channel assumption of [38]. In Paper C, we consider the problem of minimizing PDP of a CC-HARQ scheme under an average transmit power constraint in i.i.d. Rayleigh fading channels and then we generalize the results to correlated Rayleigh fading channels in Paper D.

Chapter 3

Control Signaling in LTE Systems

To improve reliability of data transmission and efficient utilization of radio resources, many advanced transmission techniques like AMC, channel-dependent scheduling, MIMO transmission and packet retransmissions are introduced in present broadband wireless systems like WiMAX and LTE [3, 4]. To facilitate the use of these techniques, there is a need for certain associated control signaling transmission both in downlink and uplink. The LTE system has separate channels both in the downlink and the uplink to carry control channel information (CCI). For example, the base station (eNodeB in LTE terminology) schedules different user equipments (UEs) in a single downlink frame. This scheduling information has to be sent to each of the UEs in a separate control channel to enable them to decode their data. In the uplink, the information about ACK/NACK for received downlink packets and also certain channel quality indicator (CQI) information have to be sent from each of the UEs to the eNodeB. The error performance of CCI is an important factor to improve the overall system performance, especially for cell-edge users who experience large path losses and high inter-cell interference. In LTE, the control signaling in the downlink is called downlink Layer 1/Layer 2 (L1/L2) control signaling and in the uplink it is called uplink L1/L2 control signaling [4].

3.1 Downlink L1/L2 Control Signaling

The downlink L1/L2 control signaling is transmitted in the control region located at the beginning of each subframe. The reason for transmitting control signaling information at the beginning of a subframe is to allow the UEs to decode the scheduling assignments as early as possible [4]. Another advantage is that the UEs which are not scheduled in a subframe may power down their receiver circuit to save power. The downlink L1/L2 control signaling in LTE consists of three different physical-channel types:[1]

- **Physical Control Format Indicator Channel (PCFICH)**: This channel is used for informing the UE about the size of the control region, hence the PCFICH information is always sent on the first OFDM symbol in a subframe. If the PCFICH is wrongly decoded by UE, it can neither know how to process the control channels nor where the data region starts in a subframe. The two bit PCFICH information is encoded using rate 1/16 block code for error protection. The 32 coded bits are modulated using QPSK to obtain 16 modulation symbols. These 16 QPSK symbols are divided into four groups and sent on four resource elements each (called *resource-element group*). The four groups are well separated in frequency to provide diversity for the PCFICH information [4].
- **Physical Downlink Control Channel (PDCCH):** This control channel is used to transmit downlink control information (DCI). The DCI typically consists of downlink scheduling assignments (including downlink resource indication, transport block format, HARQ acknowledgements and information related to spatial multiplexing), uplink scheduling grants and power control commands for UEs. The PDCCH information for each user is appended with a user specific 16 bit CRC and coded using a rate 1/3 tail-biting convolutional code. The coded output bits are transmitted using 1, 2, 4 or 8 control channel elements (CCE's), where each CCE consists of 9 resource-element groups [4]. The number of coded bits transmitted per CCE is 72.
- **Physical HARQ Indicator Channel (PHICH):** This channel is used to transmit the HARQ acknowledgements for the packets received in the uplink. Each PHICH carries the acknowledgment message (one information bit) of one uplink data session. For transmission, several PHICHs are code multiplexed on to a set of resource elements. Each PHICH bit is repeated three times, followed by a BPSK modulation on either the in-phase or quadrature-phase branch and then followed by spreading with a length-four orthogonal sequence. Several PHICHs are transmitted together on the same resource elements, and this set is called a PHICH group. Each PHICH group typically consists of eight PHICHs for normal cyclic prefix configuration. After the spreading operation, the symbols in each PHICH group are added and transmitted using three resource-elements groups [4].

[1] In the latest LTE releases, a new downlink control channel called Relay-Physical Downlink Control Channel (R-PDCCH) has been added [4].

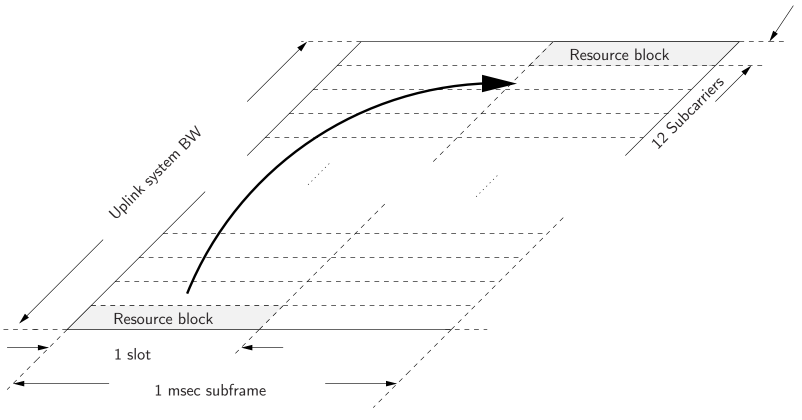


Figure 3.1: Uplink L1/L2 control signaling transmission on PUCCH (reproduced from [4, p. 228])

3.2 Uplink L1/L2 Control Signaling

The uplink L1/L2 control signaling carries the information about the HARQ acknowledgements for the packets received in the downlink, channel state reports to assist the channel-dependent scheduling in the downlink, and uplink scheduling requests. The uplink L1/L2 control signaling in LTE uses two different methods to send the uplink control data, depending on whether or not the UE has been assigned an uplink resource for uplink shared channel (UL-SCH) transmission:

- **Simultaneous transmission of UL-SCH:** In case the UE has a valid scheduling grant, the uplink L1/L2 control signaling is time-multiplexed with the coded UL-SCH onto the so-called physical uplink shared channel (PUSCH) prior to modulation.

- **No simultaneous transmission of UL-SCH:** In case the UE does not have a valid scheduling grant, a separate physical channel, the physical uplink control channel (PUCCH) is used for the uplink L1/L2 control signaling. The location of PUCCH resources on which control signaling information is transmitted is shown in Figure 3.1. As we can note, PUCCH resources are located at the edges of the available frequency spectrum to provide frequency diversity to the control signaling information. Each resource block consists of 12 subcarriers within each of the two slots of a subframe. Since the bandwidth of a resource block in one subframe is too large for transmitting control signaling information from a single UE, multiple UEs can share the same resource block. To minimize the interference among the UEs sharing the same PUCCH resources, different orthogonal phase-rotations of a cell-specific length-12 sequence are assigned to the UEs. This method uses two different formats for sending control signaling information:[2]

- **PUCCH format 1:** Scheduling requests and HARQ acknowledgments are sent using this format. In case of HARQ acknowledgments, the eNodeB uses three-state detection, ACK, NACK or DTX (nothing is transmitted on PUCCH if control signaling corresponding to downlink data is not detected on PDCCH). In case of NACK, additional parity bits are sent, whereas in case of DTX, systematic bits are transmitted again. This format can support a maximum of 2 bits of information per subframe and uses length-12 phase rotation sequences to spread a single BPSK or QPSK modulation symbol across the 12 subcarriers of each OFDM data symbol in the two resource blocks.[3]
- **PUCCH format 2:** Usually periodic CSI reports are sent using this format. These CSI reports consist of i) rank indicator (RI), informing the eNodeB of the number of layers preferably to be used for downlink transmission; ii) precoder matrix indication (PMI), informing the eNodeB about the index of precoding matrix to be used for downlink transmission; and iii) CQI information representing the highest MCS that should be used in the downlink. Sometimes simultaneous transmission of HARQ acknowledgments and CSI reports is also done using this format. This format can support a maximum of 13 information bits per subframe. For transmitting control signaling information using this format, a $(20, N_{\mathrm{PUCCH}})$-Reed-Muller code is specified in the standard [39], where N_{PUCCH} denotes the number of control signaling information bits.

3.3 Performance of Control Signaling Information

Even though the control signaling information transmission in wireless systems enables the use of advanced transmission techniques, it is seen as an overhead as it consumes valuable channel resources. Most wireless systems are optimized in terms of the amount of resources allocated for control signaling transmission and the improvements they provide in system performance.

To take advantage of gains provided by advanced transmission techniques, the feedback channel over which the control signaling information is transmitted should be adequately protected against the channel fading. For example, if the CSI reports

[2] A new control signaling format, namely PUCCH format 3 has been introduced in release 10 of LTE standard to support the transmission of more HARQ acknowledgements bits when using carrier aggregation [4].

[3] When using carrier aggregation, if the total number of bits for HARQ acknowledgments is four, then a resource selection mechanism is used [4]. For more than four bits, the new PUCCH format 3 introduced in release 10 is used.

are received in error, the eNodeB might use a higher order MCS than that reported by an UE and this might result in waste of resources (of course there are HARQ schemes to address such scenarios). If the eNodeB uses a lower MCS level than that reported by the UE, this will also lead to inefficient utilization of radio resources. Similarly, errors in HARQ feedback and scheduling grants could cause ineffective utilization of resources, longer delays, redundant retransmissions. As we have discussed in this chapter, the control signaling information typically consists of a small number of information bits. For encoding these small number of information bits, one cannot use the capacity achieving codes like LDPC codes which work well only when the block size of the code is very large [40]. Moreover, the decoding complexity associated with controlling signaling information should be minimized to reduce additional delays introduced by complex decoding algorithms.

In LTE systems, control signaling information is encoded using repetition codes (spreading across adjacent subcarriers), block codes and convolutional codes (or a combination of some of these codes). Even though the channel resources used for transmitting the control signaling information is spread across the available bandwidth to provide frequency diversity, in some cases, the specified codes with small block size may not extract all of the available frequency diversity.[4]

3.4 Overview of Research on LTE Control Signaling

Previous wor on LTE control signaling focused on different aspects. For example, different strategies for sending downlink scheduling information to the UEs was studied in [41]. To reduce the overhead associated with control signaling, a new mobile-assisted scheduling technique which consumes less resources for transmission of downlink control signaling was proposed in [42]. The effect of various control signaling information errors in terms of system performance was studied in [43]. A power boosting method was proposed in [44] for improving the radio resource control signaling reliability in the uplink. An efficient low complexity receiver for improving the performance of detection for PUCCH format 2a and 2b signaling was proposed in [45]. For PUCCH format 1, a multi-user receiver was proposed in [46], and for PUCCH format 2, robust multiuser channel estimator and detector were proposed in [47].

[4]Note that this limitation is not just related to transmission of control signaling information. In some application scenarios, weaker channel codes should be used to transmit data because of the encoding and decoding complexities associated with good channel codes.

3.5 Contributions Related to Control Signaling Transmission

In this dissertation, we specifically focus on the PUCCH format 2 control signaling transmission for LTE uplink. In Paper E, we propose a new transmission method based on complex-field coding [60] to improve the error rate performance of PUCCH format 2 transmission. In Paper F, we propose another method based on repetition across the two frequency bands used for transmitting PUCCH format 2 control signaling information (see Figure 3.1). Performance of the method in Paper F is better than the method suggested in Paper E.

Based on the idea of Paper E, we propose a new constant envelope (CE) signal space diversity (SSD) technique in Paper G. The new CE-SSD technique is more power efficient than the existing SSD schemes. Moreover, the proposed CE-SSD technique can be useful for application scenarios involving transmission of a small number of information bits, such as in the case of control signaling information transmission.

Chapter 4

Superposition Coding

In the final part of this dissertation, we use the concept of superposition coding (SPC) [7, 8] in the context of HARQ systems. One of the advantages of using superposition coding in wireless systems is better utilization of channel resources. In its simplest form, SPC can be viewed as a multiple level modulation (MLM) technique or a multiplexing technique in which multiple superimposed layers are simultaneously transmitted. Note that there are many ways in which one can superimpose multiple data streams, for example in the Euclidean space as in [48, 51] or in the GF (2) domain as in [55, 56]. In the following, we consider only the superposition in the Euclidean space.

4.1 Capacity of Downlink Broadcast Channel

Consider a K-user downlink broadcast channel model as shown in Figure 4.1. The received signal at each user can be written as:

$$y_k(n) = h_k x(n) + w_k(n), \quad k = 1, 2, \ldots, K \text{ and } n = 1, 2, ..., \tag{4.1}$$

where $w_k(n) \sim \mathcal{CN}(0, N_0)$ is the i.i.d. complex Gaussian noise and $y_k(n)$ is the received signal for user k at time n. The symbol h_k denotes the fixed channel gain from the base station to user k and $x(n)$ is the transmitted signal from the base station. If h_k is known to both the base station and the user k, the optimal transmission strategy is to encode the information of each user using an i.i.d. Gaussian code spread over the entire bandwidth. The total available transmit power P at the base station is split between the users' streams such that

$$x(n) = \sum_{k=1}^{K} x_k(n), \quad n = 1, 2, ... \tag{4.2}$$

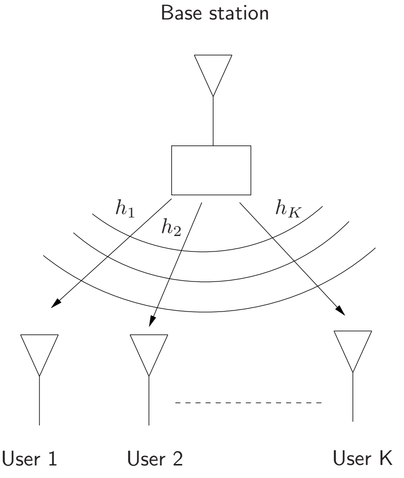


Figure 4.1: Downlink broadcast system model.

with $\mathbb{E}\left(|x_k(n)|^2\right) = P_k$ and $\sum_{k=1}^{K} P_k = P$. Assuming that each users data stream is formed using a capacity achieving code, the boundary of the capacity region is characterized by the parametrized rate tuples [8]:

$$R_k = \log_2\left(1 + \frac{P_k |h_k|^2}{N_0 + \left(\sum_{j=k+1}^{K} P_j\right)|h_k|^2}\right), \quad k = 1, 2, \ldots, K$$

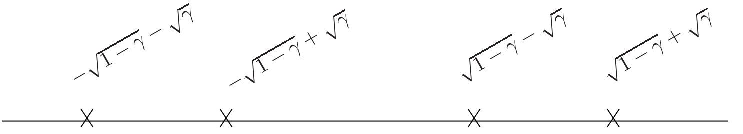
for all possible power splits $\sum_{k=1}^{K} P_k = P$. The boundary of the capacity region is achieved by the superposition coding operation in (4.2) at the transmitter and successive interference cancellation (SIC) at the receivers. In SIC, the users with stronger channel gains first decode the data of the users with weaker channel gains and subtract it before decoding their own data.

4.2 SPC for Finite Input Symbol Alphabets

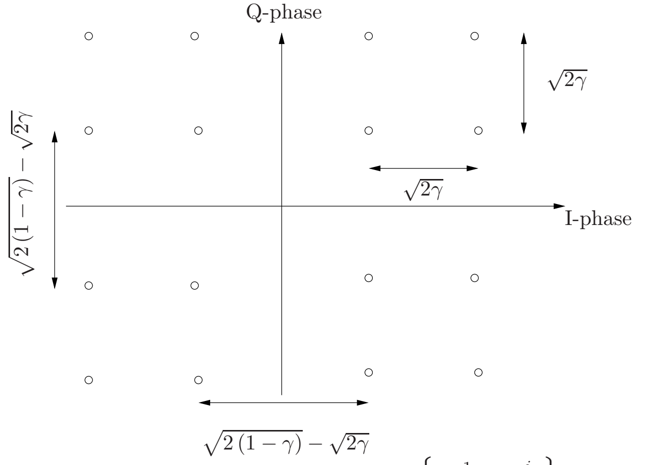
In practical systems, the modulation symbols $x_k(n)$ in (4.2) come from a finite input alphabet. For example if $x_k \in \mathcal{A}$, $\forall k$, where $\mathcal{A}$ corresponds to a finite dimensional constellation such as PAM or QAM with unit average energy, the superimposed modulation symbols in general can be written as [57][1]:

$$x = \sum_{k=1}^{K} \rho_k e^{j\theta_k} x_k. \tag{4.3}$$

[1]We drop the index m for notational convenience.



(a) Constellation for x when $x_1, x_2 \in \{\pm 1\}$.



(b) Constellation for x when $x_1, x_2 \in \left\{\pm\frac{1}{\sqrt{2}} \pm \frac{j}{\sqrt{2}}\right\}$.

Figure 4.2: Constellation for the super-symbol x for a two user case when x_1, x_2 belong to BPSK and QPSK constellations with $\rho_1 = \sqrt{\gamma}, \rho_2 = \sqrt{1-\gamma}$ and $\theta_1 = \theta_2 = 0$ deg. The parameter γ denotes the fraction of the total power allocated to one of the users.

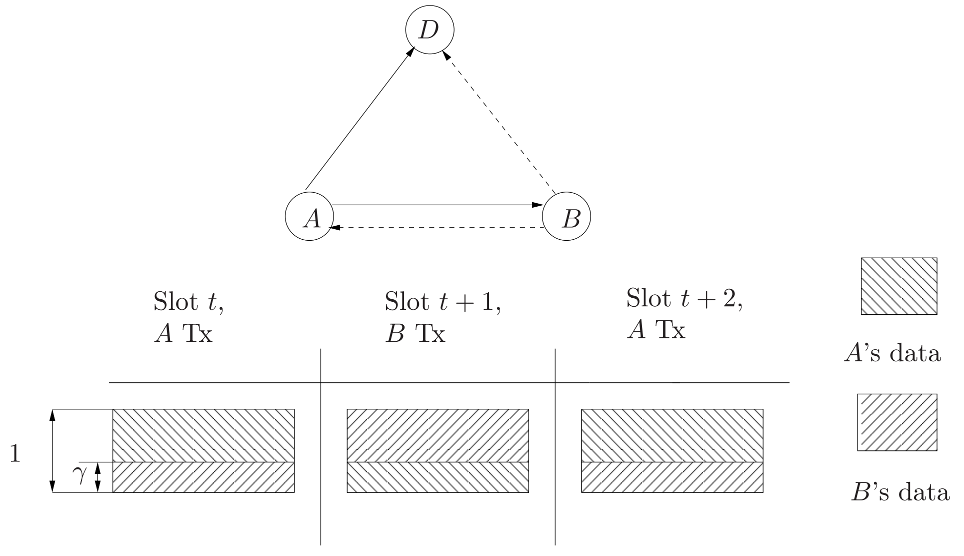


Figure 4.3: Symmetric relaying scenario using SPC. The amount of power allocated for partner's data is denoted by γ.

where ρ_k denotes the amplitude scaling factor and θ_k denotes the phase rotation parameter (in case of complex modulation symbols) for user k's data. Note that when $\rho_k = \frac{1}{K}$ and $\theta_k = 0, \forall k$, then the signal points corresponding to the super-symbol $x \in \mathcal{B}$ exhibit a non-uniform nature. Example constellations of x for a two user superposition case when x_1, x_2 belong to BPSK and QPSK constellations are shown in Figure 4.2. In Rayleigh fading channels, one can optimize θ_k to maximize the product distance between the constellation points for the super-symbol x to obtain performance improvements as in [58].

4.3 Applications and Overview of Research Related to SPC

The concept of SPC has found many applications in modern communication system designs. The dirty paper coding (DPC) technique [49] which was proposed in the literature as an SIC mechanism at the transmitter can also be seen as a reminiscent of the SPC principle. The linear dispersion codes (LDC) proposed in [50] for MIMO transmission are also based on the SPC principle.

Another application of SPC is found in relaying systems, for example, in the symmetric relaying scenario [51] shown in Figure 4.3. In a symmetric relaying scenario using SPC, two or more users can convey their information to a common destination. For a two user case, as shown in the figure, at time slot t, user A superimposes

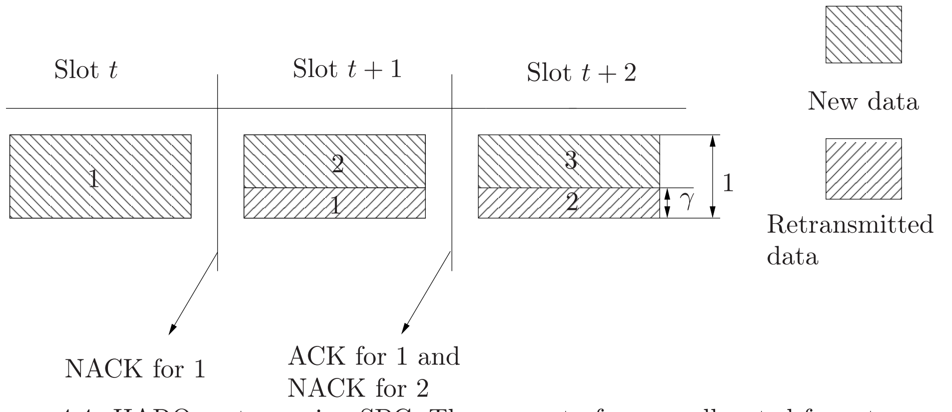


Figure 4.4: HARQ system using SPC. The amount of power allocated for retransmitted data packet is denoted as γ.

his own data on top of user B's data decoded during the previous time slot. During time slot t, user B tries to decode user A's data after subtracting his own data transmitted by user A using superposition operation. If user B successfully decodes user A's data in time slot t, in the next time slot user B sends his own data as well as the user A's data using superposition operation. The destination node D then decodes user A's packet using the data it received during the two time slots t and $t+1$. In [52, 53], similar cooperative multiple access (CMA) or multiple source cooperation (MSC) techniques based on SPC were proposed.

Recently, an SPC based HARQ system was proposed in [54] for efficient utilization of channel resources. An example of an SPC-HARQ system with one additional retransmission for each packet is shown in Figure 4.4. During time slot t, packet 1 is transmitted. After receiving a NACK message for packet 1, during the retransmission phase in time slot $t+1$, the source sends information of a new data packet 2 as well as the data corresponding to the erroneous packet 1 using superposition coding as shown in Figure 4.4. The receiver then combines the information it received about packet 1 in two time slots t and $t+1$ to decode it. An in-depth discussion about the CMA relaying systems using SPC and the SPC-HARQ systems is available in [57].

There are also other forms of SPC that have been suggested in the literature. For example, the SSD concept introduced in [59] can also be interpreted as a variation of SPC.In a linear SSD scheme, the modulation symbols are precoded with an orthonormal (unitary for the complex case) matrix and transmitted over the channel to extract the diversity available in the channel resources. For example, suppose that two real uncoded modulation symbols x_1 and x_2 are sent to the destination in two channel uses with fading gains h_1 and h_2 respectively. If any of these channel fades are deep, then the receiver cannot detect the symbols correctly. In an SSD system, instead of sending x_1 and x_2 on the channel, the precoded modulation symbols s_1 and s_2 obtained by

$$\begin{bmatrix} s_1 \\ s_2 \end{bmatrix} = \underbrace{\begin{bmatrix} \psi_{11} & \psi_{12} \\ \psi_{21} & \psi_{22} \end{bmatrix}}_{\triangleq \Psi} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \tag{4.4}$$

are transmitted on the channel. The matrix Ψ in (4.4) is an orthonormal matrix. As we can see from (4.4), the precoded modulation symbols s_1 and s_2 in (4.4) are also linear combinations of x_1 and x_2, similar to the operation shown in (4.3). The SSD concept was later generalized to complex modulation symbols with complex valued matrix Ψ and evolved as complex-field coding (CFC) [60]. CFC has also found its application in space-time coded systems [61] and relay systems [62].

4.4 Contributions Related to SPC-HARQ Systems

The conventional way of superimposing data packets as done in [54] results in an inherent natural mappings of bits-to-superimposed data symbols. This, however, may not be optimal for a given performance metric of interest. In Paper H, we look at different bits-to-symbol mappings for SPC based HARQ systems in terms of maximizing the mutual information.

Chapter 5

Summary of Specific Contributions of the Dissertation

The dissertation is comprised of eight publications related to various aspects of HARQ systems. In Papers A-D, we consider the resource allocation problem for different HARQ systems. Papers A-B specifically address the resource allocation for IR-HARQ systems, whereas Papers C-D consider the CC-HARQ systems. In Papers E-F, we focus on improving the error rate performance of control signaling in LTE systems. Specifically, we consider the PUCCH format 2 control signaling in LTE uplink and propose two new methods which improve the performance relative the current transmission methods suggested in the standard. In Paper G, we propose a new power efficient CE-SSD scheme, which can be useful for applications involving the transmission of small amounts of information such as in the case of control signaling information in practical wireless systems. Finally, in Paper H, we consider the problem of optimal bits-to-symbol mappings for SPC-HARQ systems.

5.1 Included Papers

Brief summaries of the papers included in this dissertation are as follows:

Paper A: Outage-Optimal Power Allocation for Hybrid ARQ with Incremental Redundancy

Authored by T. V. K. Chaitanya and E. G. Larsson

Published in the IEEE Transactions on Wireless Communications, 2011.

We consider the optimization of power in incremental redundancy (IR) based hybrid automatic repeat request (HARQ) schemes when the maximum number of (re)transmissions is fixed. We formulate two optimization problems: (i) minimizing the packet drop probability (PDP) under a total average transmit power constraint, and (ii) minimizing the average transmit power under a fixed PDP constraint. We consider in detail the special case of only two allowed transmissions, and we prove that the two optimization problems are equivalent. For this special case, we also provide a sub-optimal root-finding solution and compare its performance with the optimal solution obtained through an exhaustive search. The results show that the optimal power allocation can provide significant gains over the equal power solution in terms of average transmit power spent. The performance of the proposed root-finding solution is practically the same as that of the optimal solution.

Paper B: Optimal Resource Allocation for IR-HARQ

Authored by T. V. K. Chaitanya and E. G. Larsson.

Published in the proceedings of the IEEE Swedish Communication Technologies Workshop, 2011.

This paper is an extension of the work in Paper A.

In this work, we first provide an exact closed-form expression for the packet drop probability (PDP) in incremental redundancy (IR) based hybrid automatic repeat request (HARQ) schemes with a limit on the maximum number of transmissions. In the later part, we extend our work in Paper A, and consider the optimal resource allocation problem of minimizing the PDP under the constraints of an average transmit power and total number of channel uses. We provide two approaches to solve this optimization problem and compare their performance with the solution given in Paper A.

Paper C: Optimal Power Allocation for Hybrid ARQ with Chase Combining in i.i.d. Rayleigh Fading Channels

Authored by T. V. K. Chaitanya and E. G. Larsson.

Published in the IEEE Transactions on Communications, 2013.

We consider the optimization of Chase combining (CC)-based hybrid-automatic repeat request (HARQ) schemes with a limit on the maximum number of retransmissions. We formulate two optimization problems: (i) minimizing the packet drop probability (PDP) under a total average transmit power constraint, and (ii) minimizing the average transmit power under a fixed PDP constraint. Towards solving these equivalent optimization problems, we provide a closed-form expression for the outage probability of a CC-HARQ scheme. We then show that solving the optimization problems using an exact expression of the outage probability becomes complex with an increase in the maximum number of retransmissions. We propose an alternative approach in which we approximate the optimization problems by using an approximate outage probability expression and formulate the two optimization problems as two equivalent geometric programming problems (GPPs), which can be solved efficiently even for a large limit on the maximum number of retransmissions. The results show that the optimal power allocation solution provides significant gains over the equal power allocation solution. For PDP values below 10^{-3} , the optimal solution provided by the GPP approach has a performance close to that of the solution provided by solving the optimization problem exactly using nonlinear optimization techniques.

Paper D: Adaptive Power Allocation for HARQ with Chase Combining in Correlated Rayleigh Fading Channels

Authored by T. V. K. Chaitanya and E. G. Larsson.

Submitted to the IEEE Wireless Communications Letters, 2013.

This paper is an extension of the work in Paper C.

We consider the problem of minimizing the packet drop probability (PDP) under an average transmit power constraint for Chase combining (CC)-based hybrid-automatic repeat request (HARQ) schemes in correlated Rayleigh fading channels. We propose a method to find a solution to the non-convex optimization problem using an exact expression of the outage probability. However, the complexity of this method is high. Later, we propose an alternative approach in which we use an asymptotically equivalent expression for the outage probability and reformulate it as a geometric programming problem (GPP), which can be efficiently solved using convex optimization algorithms. The results show that the proposed power allocation methods provide significant gains over equal power allocation (EPA).

Paper E: Improving 3GPP-LTE Uplink Control Signaling Performance Using Complex-Field Coding

Authored by T. V. K. Chaitanya and E. G. Larsson.

Published in the IEEE Transactions on Vehicular Technology, 2013.

We study the uplink control signaling in 3GPP Long Term Evolution (LTE) systems. Specifically, we propose a precoding method that uses complex-field coding (CFC) to improve the performance of the physical uplink control channel (PUCCH) format 2 control signaling. We derive optimal detectors for both the conventional method and the proposed precoding method for different cases of channel state information (CSI) and noise variance information at the receiver. With a single receive antenna, the proposed method offers significant gains compared to the coding currently used in 3GPP-LTE for all the different scenarios considered in this work. However, the gains are relatively less with two receive antennas.

Paper F: Improving 3GPP-LTE Uplink Control Signaling by Repetition Across Frequency Bands

Authored by T. V. K. Chaitanya and E. G. Larsson.

Published in the proceedings of IEEE International Communications Conference Workshop, 2013

We propose improvements for the physical uplink control channel (PUCCH) format 2 control signaling in 3GPP-LTE systems. These improvements can be useful for low-cost UE design and optimization planned for the future LTE releases. In the proposed method, instead of repeating a single QPSK symbol across the 12 subcarriers in each OFDM symbol of a resource block as done in the current release of the standard, we pick two QPSK symbols from two independent resource blocks and repeat them across 6 subcarriers each. The proposed method has a performance gain of about 5.5 dB and 1.85 dB over the conventional method with one and two receiving antennas at the base station, respectively. These gains can be achieved without the use of any additional transmission power, time-frequency resources or receiver complexity.

The cell-specific QPSK sequences specified in the standard for PUCCH transmission are chosen according to the conventional repetition across the 12 subcarriers, hence we suggest new cell-specific QPSK sequences which minimize the peak-to-average-power ratio (PAPR) of the PUCCH signal with the proposed method.

Paper G: Constant Envelope Signal Space Diversity

Authored by T. V. K. Chaitanya, D. Danev and E. G. Larsson.

To be submitted to IEEE International Conference on Communications, 2014.

We propose a nonlinear signal space diversity (SSD) precoding technique that produces transmit signals that have constant envelope (CE) in discrete time, resulting in low peak-to-average power ratio (PAPR) waveforms after pulse-shape filtering. We propose two methods for construction of CE signal set. While the proposed CE-SSD scheme is inferior to the conventional SSD designs in terms of coding gain performance, it performs better in terms of overall power efficiency because of the reduced back-off requirement of the power amplifier (PA).

Paper H: Bits-to-Symbol Mappings for Superposition Coding Based HARQ Systems

Authored by T. V. K. Chaitanya and E. G. Larsson.

Published in the proceedings of IEEE Wireless Communications and Networking Conference, 2013.

We added an appendix containing additional results at the end of the paper. This appendix was written more recently and was not included in the conference paper.

We consider the mapping of bits-to-superimposed constellation symbols in terms of the achievable rate on the channel for the HARQ system using superposition coding. We show that using a Gray mapping of bits-to-superimposed constellation symbols has better performance than the conventional natural mapping that results from superposition in the signal space, for all values of the superposition ratio. We also show through link-level simulations that the predicted gains in terms of achievable rate can be realized in practice using LDPC codes. Furthermore, we show that the optimal superposition ratio for the Gray mapping case results in conventional higher order constellation symbols after the superposition operation.

5.2 Not Included Papers

The following publications by the author are not included in the dissertation either because they do not fit within the main scope of the dissertation, or they were earlier versions of the journal publications included in the dissertation.

- T. V. K. Chaitanya, E. G. Larsson, and N. Wiberg, "Improved Error Protection for Uplink Control Signaling in 3GPP-LTE via Complex-Field Coding", in *Proceedings of the IEEE Vehicular Technology Conference (VTC)*, 2010.
- T. V. K. Chaitanya and E. G. Larsson, "Superposition Modulation Based Symmetric Relaying with Hybrid ARQ: Analysis and Optimization", *IEEE Transactions on Vehicular Technology*, vol. 60, no. 8, pp. 3667-3683, Oct. 2011.
- T. V. K. Chaitanya and E. G. Larsson, "Retransmission Strategies for Symmetric Relaying Using Superposition Modulation", in *Proceedings of the IEEE Vehicular Technology Conference (VTC)*, 2010.

Chapter 6

Future Research Directions

There are many open research problems in HARQ systems that need to be addressed. Here we list some of the directions in which the results and insights from this dissertation can be taken forward.

- The resource allocation for HARQ systems problem studied in this work only considered minimization of outage probability under an average transmit power constraint. There are also many application scenarios in which other performance metrics like delay minimization and throughput maximization are important. One needs to study how much gains the optimal resource allocation provides when other performance metrics are considered. Moreover, we assumed Gaussian codes and an ideal feedback channel for ACK/NACK feedback signaling in our work. Ideally the resource allocation problems should be considered with finite dimensional signaling and feedback channel errors so that the results can give a more accurate picture of the predicted gains in practice.
- In this dissertation, we used SISO transmission when considering resource allocation for HARQ systems. It might be interesting to extend the results to MIMO systems and relaying systems. It is also challenging to study resource allocation problems in cognitive radio and femtocell systems in which interference from a secondary network and a small cell site, respectively, plays a significant role in overall system performance.
- Even though we specifically focused on control signaling transmission in LTE uplink in this dissertation, there are other application scenarios like communication in wireless sensor networks and smart grids, which consist of transmission of a small number of information bits. We believe that it is a very challenging problem to come up with efficient (in terms of using channel resources and providing reliability) transmission methods for these application scenarios.

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