MIMO MULTI-HOP RELAY SYSTEMS

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Abstract

Multiple Input Multiple Output (MIMO) systems use multiple transmit and receive antennas to achieve higher data rates by transmitting multiple independent data systems. Transmission errors can be reduced by using Hybrid Automatic Repeat request (HARQ) combining techniques with MIMO systems. In this thesis, the use of HARQ for MIMO multi-hop communication is studied. We propose two MIMO HARQ combining methods which are based on using pre-combining only and a joint pre and post combining techniques. In addition to conventional single-hop transmission, HARQ schemes for MIMO multi-hop relay systems are also investigated. A novel approach is proposed to deal with the parallel HARQ processes in MIMO relay scenario. An information theoretic throughput analysis is performed to evaluate the performance of the relay system by employing various transmission techniques for relay-destination link. Evaluation is carried out on the delay involved while employing the relay systems as compared to single-hop systems. Simulation results show that the proposed system can enhance the overall throughput performance of MIMO single-hop and multi-hop relay systems. Considering the recent research interest in green radio and requirements of reduced energy consumption by the wireless networks, we evaluated the energy efficiency of existing and proposed MIMO HARQ techniques for sensor and cellular networks. The results show that the proposed scheme is more energy efficient compared to other schemes in single-hop as well as multi-hop scenarios.

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Dedication

To my lovely parents, my wife, kids and my teachers.

List of Abbreviations

ADC	Analog-to-digital converter
ANF	Amplify-and-forward
ARQ	Automatic repeat-request
AWGN	Additive white Gaussian noise
BER	Bit error rate
CDMA	Code division multiple access
CP	Cyclic prefix
CRC	Cyclic redundancy check
CSI	Channel state information
DAC	Digital-to-analog converter
D-BLAST	Diagonal-Bell Laboratories Layered Space-Time
DFE	Decision feedback equalizer
DFT	Discrete Fourier transform
DNF	Decode-and-forward
ECR	Energy consumption ratio
ECG	Energy consumption gain
EGC	Equal gain combiner
EMT	Electro magnetic transmission
ERG	Energy reduction gain
FBF	Feedback filter
FFF	Feed forward filter
FIR	Finite impulse response
HARQ	Hybrid Automatic-Repeat-reQuest
IDFT	Inverse discrete Fourier transform

ISI	Inter symbol interference
ITU	International Telecommunications Unions
LLR	Log-Likelihood Ratio
LOS	Line of sight
LTE	Long Term Evolution
MIMO	Multiple-input multiple-output
MISO	Multiple-input single-output
MLD	Maximum Likelihood Detection
MLSE	Maximum likelihood sequence estimation
MMARQ	MIMO Multiple-stream ARQ
MMSE	Minimum mean square error
MRC	Maximal ratio combiner
MSARQ	MIMO Single-stream ARQ
MSE	Mean squared error
OSIC	Ordered Successive interference cancellation
pdf	Probability density function
PSD	Power spectral density
QPSK	Quadratic phase shift keying
RF	Radio frequency
RMS	Root mean square
SC	Selection combiner
SER	Symbol error rate
SIMO	Single-input multiple-output
SISO	Single-input single-output
SNR	Signal to noise ratio
STBC	Space-time block code
STC	Space-time code
STTC	Space-time trellis code
V-BLAST	Vertical-Bell Laboratories Layered Space-Time
ZF	Zero forcing

List of Variables

A	Peak amplitude of LOS
a	Amplitude of a multipath component
B_C	Coherence bandwidth
B_D	Measure of spectral broadening
B_S	Bandwidth of transmitted signal
C	Channel Capacity
d	Distance for path loss
d_o	Reference distance for path loss
E^s	Transmitted signal energy
f_D	Doppler frequency
G_r	Receive antenna gain
G_t	Transmit antenna gain
$\mathbf{H}$	Channel matrix
$I\,(;)$	Mutual information
I_0	Modified Bessel function of the first kind and zero order
K	Ricean factor
K_{max}	Maximum Number of Retransmissions
L_p	Path loss
N_r	Number of receive antennas
N_t	Number of transmit antennas
$\mathbf{N}$	Noise matrix
N_0	Power spectral density of AWGN
$p(x)$	probability density function
P_r	Received power

P_t	Transmit power
T_C	Coherence time
T_S	Symbol period
T	Frame duration
$\mathbf{W}$	Filter matrix
$\mathbf{S}$	Transmitted data matrix
X_σ	Standard deviation of the log-normal shadowing effect
$\hat{\mathbf{s}}$	Estimated signal
$\mathbf{Y}$	Received data matrix
α	Path loss constant
δ	Kronecker delta function
γ	Signal-to-noise ratio
λ	Wavelength
η	Throughput rate
σ_T	RMS delay spread
θ	Phase
δ	Symbol delay
$\mathbf{V}$	Pre-detection nulling matrix

List of Mathematical Notations

$(\cdot)^H$	matrix Hermitian
$(\cdot)^\dagger$	matrix pseudo-inverse
$(\cdot)^*$	complex conjugate
$\det(\cdot)$	determinant of a matrix
$\mathbb{E}(\cdot)$	expectation operator of a random variable
$\mathrm{diag}(\cdot)$	a vector that contains all diagonal elements of a matrix
$\log_2(\cdot)$	base-2 logarithm
$\lvert\cdot\rvert$	amplitude of a scalar
$\lVert\cdot\rVert$	norm of a vector
$\lVert\cdot\rVert_F$	Frobenius norm of a matrix
$\otimes$	circular convolution
$\mathbf{I}_M$	$M \times M$ Identity matrix
$\approx$	approximately equal to
$\mathcal{R}$	Random Reward

Chapter 1

Introduction

1.1 History of Wireless Communication Systems

The history of wireless communication dates back to 1896, when first time telegraphic signals were sent and received across the Atlantic successfully [4]. Since then wireless communication has seen major developments as well as enormous popularity and usage across the globe. Inventions like radio, TV, satellite and mobile etc, all has been only possible because of the success in the wireless technology. The latest technical innovation in the telecommunication field is in the form of mobile communication. The latest developments have made the existing handset become smaller, stylish, and efficient and there is significant improvement in its battery life. The quality of voice and coverage has improved.

The first generation of mobile communication focused on voice whereas present attention has shifted and there are more requirements to improve it's data handling capability. The first generation mobile network 'Advance Mobile Phone System (AMPS)' was introduced in 1980 in USA and the second generation mobile communication systems which were based on digital technology were seen in 1990's in the form of Global System for Mobile Communication (GSM) and IS-95. Second generation systems came with dedicated data channels for the data

services which was lacking in their predecessor system. The maximum data rate that these systems could handle was 9.6 kbps. These new generation sytems were not compatible with each other and were area or country specific. In 1985, International Telecommunications Unions (ITU) planned to standardize the mobile communication systems and proposed 3rd generation (3G) mobile systems named it as International Mobile Telecommunication 2000 (IMT-2000). The IMT-2000 or 3G standard was set up so that a comprehensive personal mobile communication system could be developed which could not only be globally compatible but which could offer a higher data transmission rate. The target was to handle data rate from 64kbps to 2Mbps. However, with the development of internet and increase in multimedia applications, such demand was far beyond the capability of 3G communication systems. Therefore, 3rd Generation Partnership Project-Long Term Evolution (3GPP-LTE) was evolved and they set the targets and requirements to cover the data demands for mobile radio. The target was a data rate exceeding 100 Mbps for the downlink and 50 Mbps for the uplink [5]. In LTE the use of multiple antennas at both the transmitter and the receiver is the key to meeting higher data rate demands. LTE is a step towards the fourth generation (4G) systems that are projected to provide high spectral efficiency due to the use of multiple antennas also known as multiple-input multiple-output (MIMO). Use of four transmit and receive antennas can provide peak download rate of 326.4Mbps [6]. By using MIMO system, the receiver can be provided with multiple versions of an information bearing signal by exploiting multipath effects and get the advantage of diversity and/or multiplexing gain [7,8]. The main idea behind diversity is to transfer the same signal over essentially independent fading paths. These independent paths are combined in such a way that the fading of the resultant signal is reduced. Multi-transmit antenna environment is generated which facilitates the propagation of redundant signals over multi-path in the

network. This redundancy allows the receiver to mitigate the channel variation caused by shadowing, fading and other forms of interference.

Considering the existing architecture of the present day cellular networks and to maintain stringent requirements envisioned for future mobile systems, MIMO systems are likely to play a major role in the future mobile systems. In addition, the cooperative communication has recently emerged as a new communication paradigm for wireless networks such as wireless ad hoc networks, sensor networks, and cellular networks to exploit the spatial diversity gain inherent in multiuser wireless systems [7, 9–15]. The use of additional relay nodes is considered, where, use of relaying has been discussed for a long time in academia [16] and has been included in IEEE 802.16j standard [17, 18] as well. Relaying is also an integral part of the WINNER air interface, a beyond 3G system concept [19]. The main advantage of relaying is that coverage can be increased and the capacity can be extended to distant users. A better user experience can be achieved by managing the capacity with improved fairness of the system [20]. Fig. 1.1 shows a basic MIMO multi-hop relay arrangement. Relay technologies are also being actively considered in 3GPP LTE-Advanced and IEEE 802.16j [21].
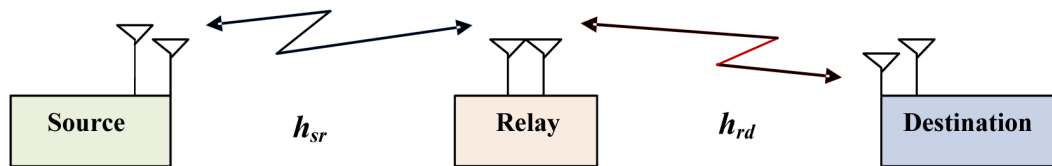
Figure 1.1: A basic MIMO multi-hop relay arrangement.

1.2 Motivations

In order to achieve nearly error free transmission, Automatic-Repeat-reQuest (ARQ) schemes are normally employed as a key component of the data link layer [22]. This is an ideal way to ensure that the information will eventually be

received correctly assuming perfect error detection and that an infinite number of retransmissions are allowed. Using Hybrid Automatic-Repeat-reQuest (HARQ) improves the throughput performance of ARQ by combining retransmitted packets with the soft values of previous erroneous transmission of same packet [4, 23]. The combining process can be performed before or after the equalization process at the MIMO receiver, where former is named as pre-combining and the later is known as post-combining. Combining schemes were initially proposed for Single Input Singe Output (SISO) systems and it was shown that pre-combinig technique performs better than post-combining technique [24]. HARQ combining schemes with post-combining have been investigated for MIMO Layered Space Time System (V-BLAST) while considering MIMO Single-stream ARQ (MSARQ) as well as MIMO Multiple-stream ARQ (MMARQ). MSARQ jointly encodes the data packet at the transmiter using a single CRC and convert the packet into smaller sub-packets called substreams. Unlike MSARQ, MMARQ encodes each substream with its own independent CRC. This scheme provides an advantage of better throughput because un-necessary re-transmissions of error free substreams is not carried out [3]. In [25] and [26], couple of new detection schemes have been proposed to improve the procedure of post-combining scheme, whereas [27] proposes an improvement in the detection ordering procedure of MMARQ. A bit-level post-combining scheme for Zero Forcing (ZF) V-BLAST based on log-likelihood ratio (LLR) is proposed in [28]. All the research works presented in [3, 25–28] focused on using post-combining whereas pre-combining was not considered for MMARQ systems. A detailed study is necessary to evaluate the use of pre-combining for MIMO systems specially considering the advantages of pre-combining against post-combining in terms of performance. It was considered that use of pre-combining technique for MSARQ and MMARQ systems may further increase the performance of these systems. Therefore, a detailed study

is required to utilize advantages of pre-combining technique in MIMO HARQ systems.

The conventional cellular architecture appears to be inefficient and is not expected to comply with the high user demands in terms of high data-rate, coverage and efficiency. The recent MIMO systems do promise significant improvement in terms of spectral efficiency, link reliability, increase in capacity and data rates. Applying relaying systems with MIMO techniques mimics the performance advantages of MIMO systems and can exploit the spatial diversity of relay systems. In addition, relays can also shorten the point to point transmission distance, which results in lower transmit power levels and better coverage. The inadequacy of the conventional cellular architecture requires a fundamental change in the way systems are designed and deployed in future.

With these motivations, a detailed study is carried out in this work to exploit the advantages of pre-combining technique in existing MIMO HARQ systems. Therefore, multi-hop relay strategies are discussed in conjunction with MIMO systems in such a way that diversity is maximized or advantages of spatial multiplexing can be exploited as well. To the best of our knowledge, existing research has not considered HARQ processes for MIMO relay systems. We also carried out energy efficiency analysis of MIMO HARQ schemes for single as well as multi-hop scenarios.

1.3   Contributions

In this study MMARQ based schemes have been investigated at the receiver to exploit the performance improvement over existing schemes. The contributions in this thesis can be summarized as follows:

1. Two novel schemes have been proposed for MMARQ based system by incorporating advantages of pre-combining at the receiver [29]. The existing

MMARQ systems only consider post-combining for HARQ processes. The proposed schemes show considerable throughput improvement as compared to existing techniques.

2. A throughput rate analysis is carried out regarding the proposed and existing MIMO HARQ schemes. The analysis is extended to V-BLAST based MSARQ and MMARQ systems. The analysis shows improvement in the overall throughput by using proposed scheme.

3. The existing and proposed schemes have been extended to MIMO multi-hop relay system. A relay-MMARQ protocol has been proposed for efficient management of the MIMO HARQ based relay system. A detailed link level implementation as well as throughput rate analysis results have been compiled to show the importance of MIMO multi-hop relay systems. Again the proposed scheme show better system performance for multi-hop systems as compared to post-combining based existing MSARQ and MMARQ methods.

4. A delay evaluation is carried out which shows that the proposed multi-hop relay MMARQ can reduce the latency comparing to single-hop MMARQ and MSARQ in a practical path loss condition.

5. A detailed energy efficiency analysis of MIMO HARQ protocols is carried out in both sensor and cellular networks. The results show that the proposed scheme is more energy efficient compared to other schemes.

1.4   Thesis Organization

This thesis consists of seven chapters. This first chapter begins with the overview of history and current trends in wireless communications. It also explains the

motivation of this research work and the contributions made.

In Chapter 2, an overview of the wireless communication channel and its characteristics are given. The chapter begins with an overview of different types of fading channels. Next, depending on the relationship between the signal parameters and channel parameters, different types of small-scale fading are discussed.

In Chapter 3, multi-antenna systems are reviewed. This chapter covers the underlying principles of spatial diversity and discusses on different diversity combining techniques at the receiver. We give an overview of MIMO channel model and study how multiple antennas can enhance channel capacity and in particular how MIMO systems can provide a linear increase in capacity making it attractive for practical systems. We also discuss how multiple antennas can offer diversity. The architectures of different MIMO transmission schemes such as Bell Laboratories Layered Space-Time (BLAST), and Space time coding (STC) are also provided.

Existing literature that contribute to Hybrid ARQ transmission schemes is presented in Chapter 4. The basic combining schemes have been discussed with a focus to existing multiple HARQ processes for MIMO systems. Two novel HARQ combining schemes are presented in this chapter for MIMO HARQ systems.

A detailed throughput rate analysis for the existing and proposed schemes is presented in Chapter 5. The evaluation criteria combines HARQ processing with MIMO data transmission and considers an upper bound on the throughput of MIMO-HARQ system by utilizing conditional cutoff rate of a MIMO transmission instead of employing the conditional mutual information.

In Chapter 6, basics of relay systems are discussed along with various MIMO multi-hop relay scenarios. The existing and proposed schemes have been extended to MIMO multi-hop relay system. A detailed system implementation as well as capacity analysis results have been compiled to show the importance of MIMO

multi-hop relay systems. A detailed delay analysis is carried out to show that the proposed multi-hop relay MMARQ can reduce the latency comparing to single-hop MMARQ and MSARQ in a practical path loss condition.

In Chapter 7, energy efficiency analysis is carried out for MIMO HARQ protocols in sensor as well as cellular networks. The energy efficiency metrics used are discussed in detail. The performance of proposed and existing schemes in single as well as multi-hop scenarios is evaluated and discussed.

Finally, chapter 7 concludes the thesis and discusses possible future work.

1.5   List of Publications

Journal Publications

1. Imran Rashid and Daniel K. C. So, Novel HARQ Schemes for MIMO Single-hop and Multi-hop Relay Systems, *IEEE Transaction on Wireless Communication (under submission)*

2. Imran Rashid, Warit Prawatmuang and Daniel K. C. So, Energy efficiency of MIMO HARQ Single-hop and Multi-hop Relay Systems, *IEEE Communication Letters (under submission)*

Conference Publications

1. Imran Rashid and Daniel K. C. So, Novel HARQ Schemes for MIMO Single-hop and Multi-hop Relay Systems, in *IEEE 21st International Symposium on Personal, Indoor and Mobile Radio Communications(PIMRC)*. 2010

2. Imran Rashid and Daniel K. C. So, HARQ Schemes for MIMO Single-hop and Multi-hop Relay Systems, in *EEE PGR Conference, The University of Manchester, UK*. 2009

Chapter 2

Wireless Channel Characteristics

2.1 Introduction

Once the information signal is passed from one place to the other, the medium through which this signal travels is known as the channel. There are mainly two types of channels: guided and unguided channels. Wired mediums like coaxial cable are considered as guided channels, whereas wireless mediums like radio channel comes under the unguided category.

Ideally, the received signal should follow a single path; however, it does not happen this way. In practice, the received signal is distorted by the randomness of propagation channel and noise. It could reach after reflection, refraction, diffraction and attenuation of the original copy of the signal. Therefore, performance of any wireless system mainly depends upon the channel characteristics through which it travels.

2.2 Wireless Channel Fading Models

The wireless signal can travel through a path which has a clear line of sight (LOS) or a path severely obstructed by structures such as mountains, and buildings. Due to this uncertainty, the receiver receives signal through different paths with different arrival times and different phases. These signals are combined either constructively or destructively at the receiver resulting in rapid fluctuation in the received signal strength. Propagation models traditionally focus on predicting the average received signal strength at a given distance from the transmitter, as well as variability of the signal strength in close proximity to a particular location. These models predict the mean signal strength for an arbitrary transmitter-receiver separation distance. Phenomenon like attenuation or path loss affects the strength of the signal and are considered long term, whereas rapid fluctuations of the received signal strength over short distances or short durations are called short-term fading models. On the basis of transmitter-receiver (T-R) separation, fading models can be broadly categorized as

- Long-Term Fading

- Short-Term Fading

2.3 Long-Term Fading Model

During the propagation of a signal through the channel from one place to the other, the power density of the signal reduces due to the phenomenon known as attenuation or path loss. The power drop in the signal can vary due to certain factors like transmission distance, and obstructions in the transmission path. Due to the presence of obstructions in between the transmitter and the receiver's direct line of sight path, the signal power is reduced as the signal follows indirect path to reach the destination and this process is known as shadowing.

Obstruction can be caused due to walls, buildings in urban areas and mountains in the rural areas. Shadowing is severe in urban areas where there are more multistory buildings. The transmission signal has the property of diffraction off the boundaries of obstructions, thus total shadowing of the signals is prevented. The diffraction always dependent on the frequency of the signal, it is more at lower frequencies than higher frequencies. Thus signals on higher frequencies are more directional like in microwave or satellites and require line of sight for sufficient signal strength [30]. Long-term fading can be characterized by path loss and general propagation model can be given by [31]

$$\frac{P_r}{P_t} = \frac{L_{p0}}{d^\gamma} \tag{2.1}$$

where γ is the path loss exponent that typically ranges from 2 to 5 depending upon the propagation environment, P_r and P_t are the received and transmitted powers respectively. L_{p0} is the path loss at a reference distance d_0 that is related to the frequency, antenna gains, and other factors by

$$L_{p0} = \frac{(4\pi)^2}{\lambda^2 G_t G_r} \tag{2.2}$$

where λ is the wavelength, G_t and G_r are the transmitter and receiver antenna gains respectively.

As shadowing is caused by the variation of terrain and presence of obstacles, it is modeled as log-normal distribution. It demonstrates the variation of the received signal power in different locations at a fixed distance. The effect of shadowing can be mathematically expressed as

$$L_p(d) = L_{p0} + 10\gamma \log_{10}\left(\frac{d}{d_0}\right) + X_\sigma \tag{2.3}$$

where the first two terms account for the path loss at distance d, and X_σ represents log-normal shadowing effect and is a zero mean Gaussian distributed random variable in logarithm scale.

2.4   Short-Term Fading

In wireless communication, the variations in amplitude or phase of received signal over a short period of time or distance is called short-term fading or microscopic fading. Illustration of this variation of the signal is for a very short period of time (in the order of seconds). This is due to the constructive or destructive interference of multipaths, speed of the mobile and surrounding objects, and the transmission bandwidth of the signal. Fig. 2.1 illustrates long-term and short-term fading. The short-term curve is the combined effect of long-term and short-term fading.

2.4.1   Multipath Fading

Multipath fading is the phenomenon which occurs when a signal arriving at receiver contains large number of reflected paths. The reflected waves possess different phase and amplitude and interfere with direct signal resulting in fluctuations in the amplitude. It may or may not have direct line of sight signal. Mathematically, it can be modeled as [31]

$$h(t,\tau) = \sum_{i=0}^{N-1} a_i\left(t,\tau\right) e^{j\theta_i(t,\tau)} \delta\left(\tau - \tau_i\left(t\right)\right) \tag{2.4}$$

where $a_i(t,\tau), \tau_i\left(t\right)$ and $\theta_i\left(t,\tau\right)$ are the amplitude, excess delay, and phase of the i-th multipath component at time t respectively. Excess delay is the relative delay of the i-th component compared to the first arriving component. There are N number of multipath components, each with respective phase, amplitude and
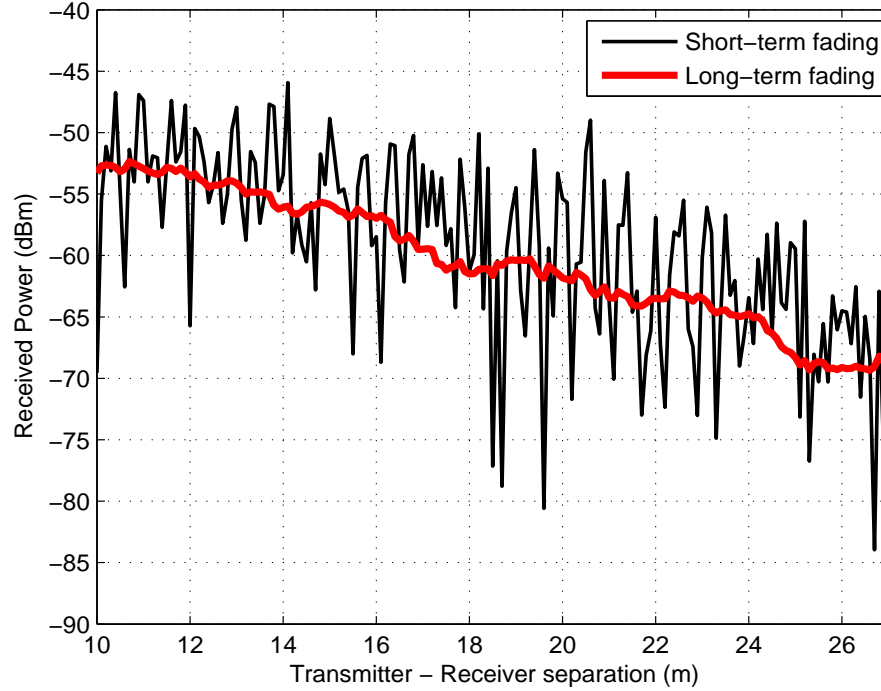
Figure 2.1: Long-term and short-term fading.

excess delay.

2.4.2   Doppler Shift

The motion of the transmitting or receiving antenna produces doppler shifts to the received signal waves at the receiver. The received signal frequency shifts due to this motion. The amount of frequency shift depends on the mobile velocity and the spatial angle between the direction of motion and the direction of signal arrival. The shift f_D can be expressed as [32]

$$f_D = \frac{v}{\lambda} \cos \psi \tag{2.5}$$

where v is the speed of movement, λ is the wavelength and ψ is the angle between the direction of motion and wave propagation. From (2.5), it is observed that the

Doppler shift is positive if the receiver is moving towards the transmitter i.e. the apparent received frequency is increased. On the other hand, the Doppler shift is negative if the receiver is moving away from the transmitter i.e. the apparent received frequency decreases [32].

2.5   Types of Short-term Fading

Fading is a type of the attenuation that a radio signal experiences over certain propagation medium. Fading may vary with time, geographical position and/or radio frequency, and is often modelled as a random process. A fading channel is a communication channel that experiences fading. Frequency and time dispersion leads to four types of fading that are explained in the following subsections.

2.5.1   Fading Effects Due to Multipath Time Delay Spread

Time dispersion due to multipath causes the transmitted signal to undergo either flat or frequency selective fading.

Flat Fading

Coherence bandwidth is maximum bandwidth over which two frequencies of a signal undergo comparable or correlated amplitude fading. In other words, the range of frequencies over which the channel can be considered "flat". In case of flat fading, the coherence bandwidth of the channel is larger than the bandwidth of the signal therefore, all frequency components of the signal will experience the same magnitude of fading. The channel as seen by the system possesses a constant gain and linear phase response. The spectral characteristics of the transmitted signal are preserved at the receiver. However, the strength of the received signal changes with time due to fluctuations in the channel gain caused

by multipath. Flat fading channels are also called amplitude varying channels and sometimes referred as narrowband channels, as bandwidth of the applied signal is narrower than the coherence bandwidth [32]. Flat fading can be mathematically summarized as [32]

$$B_S \ll B_C \tag{2.6}$$

and

$$T_S \gg \sigma_\tau \tag{2.7}$$

where B_S is the bandwidth of the transmitted signal, T_S is the symbol period, and B_C and σ_τ are the coherence bandwidth and the root mean square(rms) delay spread of the channel respectively. The radio signal travelling on shorter paths reach the receiver earlier than those on longer paths, due to this phenomenon these unsimultaneous arrivals of signal causes the spread of the original signal in time domain, known as delay spread. Commonly, the rms delay spread is used which is the standard deviation for all excess delays [32].

Frequency Selective Fading

If the coherence bandwidth of the channel is smaller than the bandwidth of the signal then different frequency components of the signal experience decorrelated fading. In terms of time domain, the symbol period is much smaller than the delay spread. After one symbol is transmitted, the delayed component of this signal will remain in the channel along with the subsequent transmitted signal, thereby, creating a distortion. This distortion is called inter symbol interference (ISI) in which the received signal is distorted due to interference from delayed symbol. In this type of fading the received signal consists of the attenuated transmitted waveforms that are delayed in time, and hence frequency selective fading can be

mathematically summarized as [32]

$$B_S > B_C \tag{2.8}$$

and

$$T_S < \sigma_\tau. \tag{2.9}$$

Equalization techniques are needed to retrieve the original transmitted signal in frequency selective channel.

2.5.2 Fading Effects Due to Doppler Spread

Fading occured due to the motion of transmitter or receiver is considered in this section. Comparing the rate of change of channel to that of the transmitted baseband signal, a channel can be classified as either fast fading or slow fading.

Fast Fading

Fast fading occurs when the coherence time of the channel is relatively smaller than the symbol duration. The channel's amplitude and phase changes occur rapidly over the period of use. This type of fading causes frequency dispersion due to Doppler spreading, that leads to the signal distortion and is also called time selective fading [32]. Mathematically, we can summarize it as

$$T_S > T_C \tag{2.10}$$

and

$$B_S < B_D \tag{2.11}$$

where, T_C is the coherence time and B_D is a measure of the spectral broadening caused by the time variation of the channel. It is defined as the range of frequencies over which the received Doppler spectrum is essentially non-zero. Coherence time is a statistical measure of the period over which channel fading process is correlated.

Slow Fading

This type of fading occurs when the coherence time of the channel is large relative to the symbol duration of the signal. The channel impulse response changes at a slower rate than the transmitted signal [33]. The amplitude and phase changes occur slowly and can be considered roughly constant over the period of use. In frequency domain, this implies that the Doppler spread of the channel is much less than the bandwidth of the baseband signal. Mathematically, we can summarize it as

$$T_S \ll T_C \tag{2.12}$$

$$B_S \gg B_D. \tag{2.13}$$

2.6   Types of Multipath Fading

In this section we present two types of multipath fading - Rayleigh and Ricean fading.

2.6.1   Rayleigh Fading

Rayleigh fading is a statistical model which assumes that the magnitude of a signal varies randomly once passed through a communication channel as per Rayleigh distribution. The receiver receives a large number of independent scattered components with similar power. The in-phase and quadratic components

of the received signal can be modelled as uncorrelated zero mean complex valued Gaussian process [34]. The envelope of the received signal has a Rayleigh distribution with the probability density function (pdf) given by

$$p(s) = \frac{s}{\sigma_s^2} \, e^{-s^2/2\sigma_s^2} \, u(s), \tag{2.14}$$

where $\mathbb{E}\left[s^2\right] = 2\sigma_s^2$, and $u(s)$ is the unit step function given by

$$u(s) = \begin{cases} 1 & \text{if } s \geq 0, \ s \in \mathcal{R} \\ 0 & \text{if } s < 0, \ s \in \mathcal{R}. \end{cases} \tag{2.15}$$

The Rayleigh fading model is commonly used when there is no LOS between the transmitter and the receiver, such as a congested urban area.

2.6.2 Ricean Fading

In case there is a LOS component present between the transmitter and receiver, the envelope of the received signal can be modeled by Ricean distribution with pdf given by

$$p(s) = \frac{s}{\sigma_s^2} \, e^{-\frac{(s^2+A^2)}{2\sigma_s^2}} \, I_o\left(\frac{As}{\sigma_s^2}\right) \, u(s) \tag{2.16}$$

where A is the peak amplitude of the dominant signal (LOS) and $I_o(s)$ is the modified Bessel function of the first kind and zero order defined as

$$I_o(s) = \frac{1}{2\pi} \int_0^{2\pi} e^{-s \cos \theta} d\theta. \tag{2.17}$$

It is similar to Rayleigh fading but it has a strong dominant component present (typically a LOS component). The random multipath components arriving at different angles are superimposed on a stationary dominant signal. At the output of an envelope detector, this has the effect of adding a DC component to the
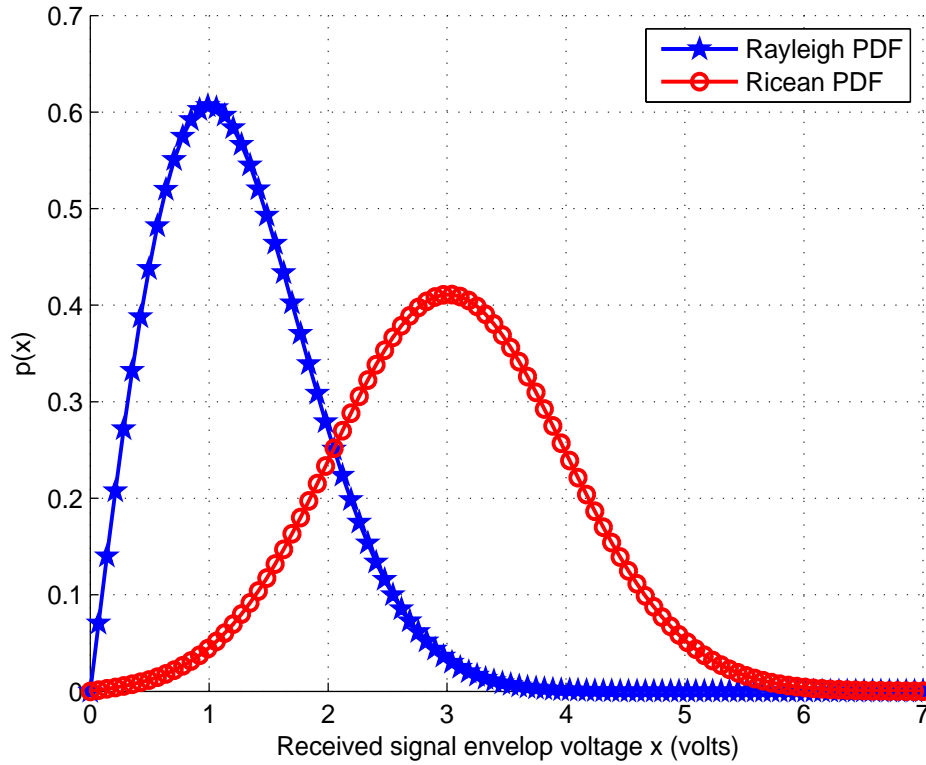
Figure 2.2: Probability density function of Ricean distribution: $K = -\infty$ dB (Rayleigh distribution) and $K = 6$dB.

random multipath [32].

The Ricean distribution is normally defined in terms of factor K called *Ricean Factor*, which is the power ratio between LOS component and the scattered components i.e.

$$K = \frac{A^2}{2\sigma_s^2}. \tag{2.18}$$

As $A \to 0, K \to -\infty$ dB, and as the dominant path decreases in amplitude, the Ricean distribution degenerates to a Rayleigh distribution as can be seen from Fig. 2.2.

2.7 Diversity Techniques

Diversity is a method with which effects of multipath fading are reduced and the reliability is improved by using two or more communication channels with different characteristics. As individual channels experience independent fading, multiple versions of the same signal will fade in an uncorrelated manner and it provides a receiver with several observations of the same signal. There are more chances that one of the versions of the signal transmitted through multiple antennas may be above the given threshold level as compared to signal transmitted through one transmit antenna. These multiple versions of the signals are combined at the receiver, and correspondingly, improve reliability of transmission. A key characteristic of multi-antenna systems is their ability to turn multipath propagation into a benefit for the user through diversity [35].

In wireless communication, the most common diversity techniques are classified as following:

- Time Diversity

- Frequency Diversity

- Spatial Diversity

Time Diversity

In this type of diversity, multiple versions of the same signal are transmitted at different time slots separated at least by the coherence time of the channel. One of the approach is that the message is spread in time by means of bit-interleaving before it is transmitted to obtain the independent or nearly independent fading gains at the input of the decoder. As the time interleaving results in decoding delays, this technique is more effective for fast fading environments where the coherence time of the channel is small. For slow fading channels, a large interleaver

is required which can lead to a significant delay which might not be acceptable for delay sensitive applications such as voice transmission [36]. Considering these aspects, time diversity is not suitable for mobile radio communication. Another disadvantage of this scheme is the loss of bandwidth efficiency due to the redundancy introduced in the time domain.

Frequency Diversity

Frequency diversity can be achieved by transmitting the signal using several frequency channels or spread over a wide spectrum. The frequencies need to be separated by more than the coherence bandwidth of the channel. Due to this separation frequencies are not correlated and will not experience the same fade during transmission. Like time diversity the frequency diversity has a disadvantage of loss in bandwidth efficiency as redundancy is introduced in the frequency domain.

Spatial Diversity

The signal is transmitted over several different propagation paths using multiple transmitter antennas (transmit diversity) and/or multiple receiving antennas (receive diversity). This type of diversity is also referred as antenna diversity because multiple antennas are used for transmission and/or reception. The transmit and receive antennas are separated such a way that the fading associated with the different antennas is uncorrelated i.e. antenna spacing is larger than the coherence distance, where coherence distance is the minimum spatial separation of antennas for independent fading [36]. Spatial diversity technique is bandwidth efficient and is an attractive diversity option for high data rate wireless communications. Spatial diversity can be subdivided into following three types.

- *Receive Diversity*: In this diversity technique, multiple antennas are used

at the receiver. Received signals from the antennas are combined using different combining techniques, thus mitigating multipath fading and improve the received signal quality. Use of multi-antennas at the receiver adds the cost and the complexity of the receiver which is the reason that transmit diversity is preferred over the receive diversity in the mobile handset.

- *Transmit Diversity*: In this diversity technique, multiple antennas are used at the transmitter, which can then be exploited by appropriate signal processing techniques at the receiver. This technique usually needs complete channel state information (CSI) at the transmitter but in space time coding techniques like Alamouti's scheme [37], it is possible to implement transmit diversity without channel knowledge at the transmitter [38].

- *Polarization Diversity*: In this diversity technique, multiple versions of a signal are transmitted and received via antennas with different polarization (horizontal and vertical polarization). A diversity combining technique is applied on the receiver side. As two signals are uncorrelated by different polarization, the two antennas do not have to be installed far apart.

2.8   Simulation Parameters and Assumptions

All the simulations in this thesis are carried out in MATLAB. We developed all the codes without using any standard MATLAB functions and our own custom made basic and advanced functions. A complete communication link is made while evaluating SISO and MIMO systems. As our work is based on existing schemes therefore, we extended same assumptions which were being used by existing literature [24] [39] [40] [3]. This was done to obtain the same published results first so that there is no error in the simulation model. Then we deveoped our results on the same model for an accurate comparison for performance

measures. The major assumptions are

- A Rayleigh channel is assumed which is is reasonable for an environment where there are large number of reflectors like urban environment.

- The channel is flat fading meaning that the multipath channel has only one tap. So, the convolution operation reduces to a simple multiplication.

- In HARQ systems, as there are retransmissions involved therefore, we assume a qausi static Rayleigh channel is assumed. In this assumption, channel remains constant for entire block of data transmission, whereas channel changes with every new transmission.

- The channel experience by each transmit antenna is independent from the channel experienced by other transmit antennas.

- The channel experienced between each transmit to the receive antenna is independent and randomly varying in time.

- It is assumed that the channel is known at the receiver.

- Monte-Carlo simulations are carried out for BER and throughput results.

- The simulation of all basic and published techniques discussed in this thesis are carried out by writing our own simulation codes in MATLAB and the results were verified by comparing to the actual published results.

2.9 Summary

In this chapter basic concepts on wireless channel have been discussed which are important for understanding the digital wireless communication system. Effects of long-term fading and short-term fading are discussed in detail. Various basic diversity techniques are also discussed.

Chapter 3

Multi-antenna Wireless Communications

3.1 Introduction

In wireless communication, multiple antennas at both the transmitter and receiver are used to improve the performance. In this chapter, basics of multi-antenna systems are discussed. Then various receiver combining techniques are presented. Techniques like spatial diversity and spatial multiplexing are also discussed for MIMO systems with their BER performances presented.

3.2 Multi-antenna Systems

Wireless communication with multiple antennas is one of the major breakthroughs in modern communications which promises significant improvement in terms of both spectral efficiency and link reliability. In multiple antenna systems, the signals at transmit and receive antennas are exploited in such a way that both the quality and data rate of the communication is improved.

Fig. 3.1 shows different antenna configurations where the most well know
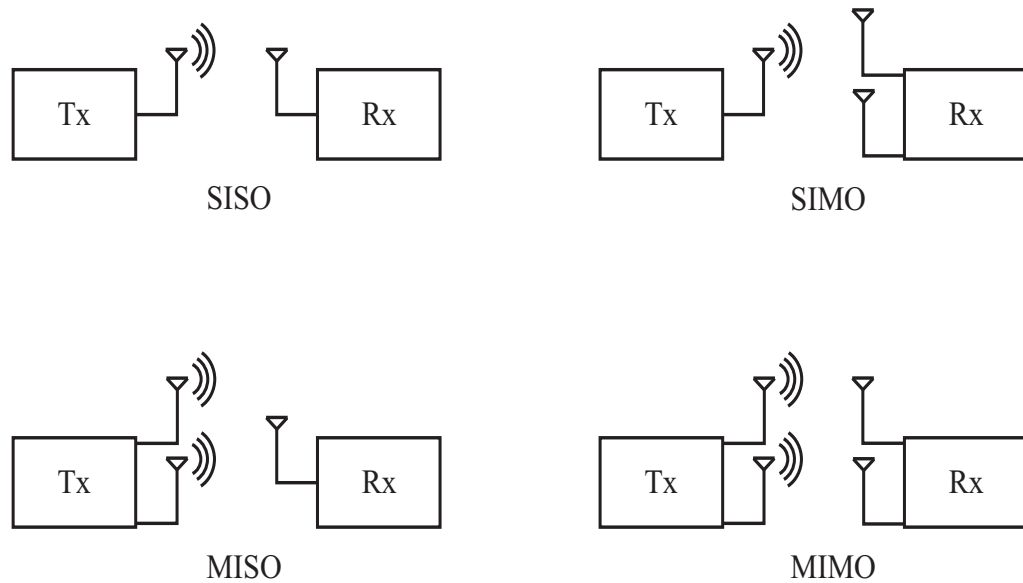
Figure 3.1: Different antenna configurations in space-time systems.

configuration is single-input single-output (SISO) that consists of a single antenna at both the transmitter and receiver. Single-input multiple-output (SIMO) uses a single transmit antenna and multiple receive antennas; multiple-input single-output (MISO) has multiple transmitting antennas and a single receiving antenna whereas, multiple-input multiple-output (MIMO) has multiple transmit antennas and multiple receive antennas. The configuration that comprises a base station with multiple antennas interacting with multiple users, each with one or more antennas is called Multiuser MIMO (MIMO-MU) [38].

3.3 Diversity Combining Techniques

In the previous chapter, basic diversity techniques are discussed. By use of these diversity techniques, a corresponding set of fading channels is created that is essentially independent. To achieve improved receiver performance, the outputs of these statistically independent fading channels need to be combined in accordance with some criterion. This section discusses major diversity combining techniques
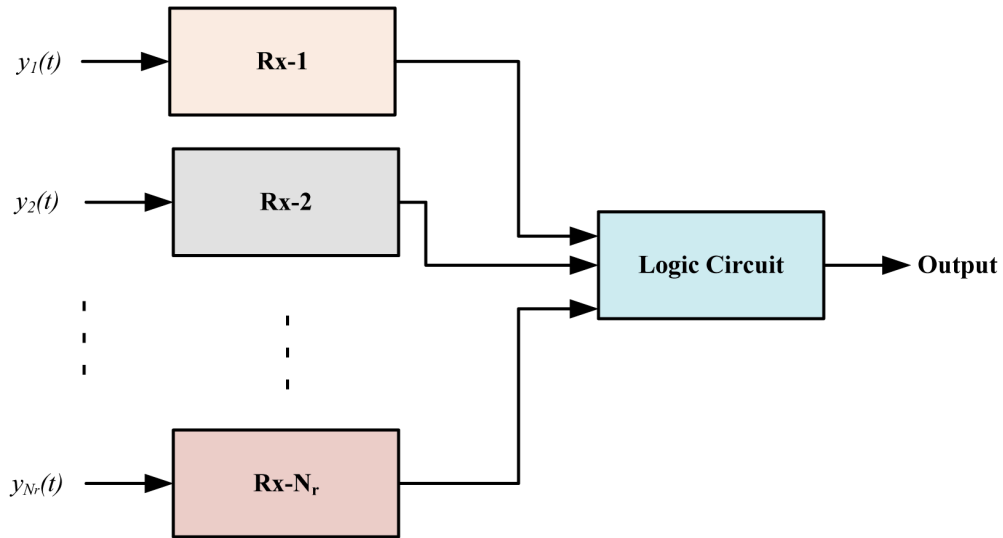
Figure 3.2: Block diagram of selection combining.

based on receive diversity [41].

3.3.1 Selection Combining (SC)

The simplest combining method is SC which involves N_r linear receivers and a logic circuit. Fig. 3.2 illustrates the structure of SC technique. In this scheme, the received signal with the highest instantaneous SNR is selected by the logic circuit ignoring the observations from other antennas. Let $s(t)$ defines the complex envelop of the modulated signal, then the complex envelop at the k-th diversity branch of the received signal is defined by

$$y_k(t) = h_j s(t) + n_j(t), \qquad j = 1, 2, \ldots, N_r \qquad (3.1)$$

where $n_j(t)$ is the Additive white Gaussian noise (AWGN) and h_j is the slow varying fading channel at the j-th branch. AWGN is a channel model in which white noise is the only impairment to communication. It has a constant spectral density (watts per hertz of bandwidth) and a Gaussian distribution of amplitude.

The average SNR at the output of the j-th branch is defined by

$$(SNR)_j = \left(\frac{\mathbb{E}\left[|h_j s(t)|^2\right]}{\mathbb{E}\left[|n_j(t)|^2\right]}\right) = \frac{\mathbb{E}\left[|s(t)|^2\right]}{\mathbb{E}\left[|n_j(t)|^2\right]}\mathbb{E}\left[|h_j|^2\right] \tag{3.2}$$

$$= \frac{E_s}{N_0}\mathbb{E}\left[|h_j|^2\right], \qquad j = 1, 2, \ldots, N_r \tag{3.3}$$

where N_0 is the noise spectral density and E_s is the transmitted symbol energy. Now, the instantaneous output SNR of the j-th branch is given by

$$\gamma_j = \frac{E_s}{N_0}|h_j|^2, \qquad j = 1, 2, \ldots, N_r. \tag{3.4}$$

The instantaneous SNR of SC is given by

$$\gamma_{sc} = \max\left\{\gamma_1, \gamma_2, \ldots, \gamma_{N_r}\right\}. \tag{3.5}$$

this method ignores the information from all diversity branches except the one with the largest SNR therefore, it is not the optimal method to use [31].

3.3.2 Equal Gain Combining (EGC)

In this receive combining technique, all the received signals are co-phased and then summed together with equal gain. The received signal is equalized by dividing the received symbol with the channel phase. EGC is suboptimal method but it does simple linear combining. In polar form, the channel is represented as $h_j = |h_j| e^{i\theta_j}$. The output of the EGC can be expressed as

$$y_{EGC} = \sum_{j=1}^{N_r} y_k e^{-i\theta_j}$$

$$= \sum_{j=1}^{N_r} |h_j| \ s + n_j e^{-i\theta_j} = \sum_{j=1}^{N_r} |h_j| \ s + \bar{n}_j \tag{3.6}$$

where $\bar{n}_j$ is the AWGN scaled by the phase of the channel coefficient.

3.3.3 Maximal-Ratio Combining (MRC)

In this diversity combining technique, linear receivers are used where the signals from all N_r branches are scaled according to their individual SNR. The received signals from N_r branches are summed. Fig. 3.3 shows the block diagram of MRC.
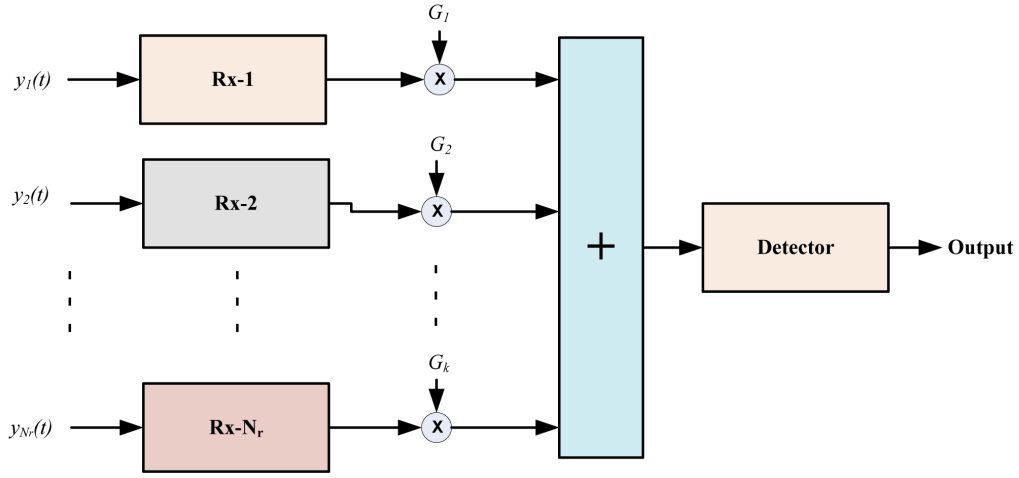
Figure 3.3: Block diagram of MRC.

The output signal is a linear combination of a weighted replica of all the received signals. It is given by

$$y_{MRC}(t) = \sum_{j=1}^{N_r} G_j y_j(t) \tag{3.7}$$

where y_j is the received signal at the receive antenna j, and G_j is the weighting factor for receive antenna j. Substituting (3.1) into (3.7), we obtain

$$y_{MRC}(t) = s(t) \sum_{j=1}^{N_r} G_j h_j + \sum_{j=1}^{N_r} G_j n_j(t). \tag{3.8}$$

Assuming that noise $n_j(t)$ from all branches $(j = 1, 2, \ldots, N_r)$ to be statistically

independent, the output SNR is given by

$$SNR = \frac{\mathbb{E}\left[\left|s(t)\sum_{j=1}^{N_r} G_j h_j\right|^2\right]}{\mathbb{E}\left[\left|\sum_{j=1}^{N_r} G_j n_j(t)\right|^2\right]} \tag{3.9}$$

$$= \frac{\mathbb{E}\left[|s(t)|^2\right]}{\mathbb{E}\left[|n_j(t)|^2\right]} \frac{\mathbb{E}\left[\left|\sum_{j=1}^{N_r} G_j h_j\right|^2\right]}{\mathbb{E}\left[\sum_{j=1}^{N_r} |G_j|^2\right]} \tag{3.10}$$

$$= \frac{E_s}{N_0} \frac{\mathbb{E}\left[\left|\sum_{j=1}^{N_r} G_j h_j\right|^2\right]}{\mathbb{E}\left[\sum_{j=1}^{N_r} |G_j|^2\right]}. \tag{3.11}$$

Let γ_{MRC} be the instantaneous output SNR of the linear combiner, (3.11) becomes

$$\gamma_{MRC} = \frac{E_s}{N_0} \frac{\left|\sum_{j=1}^{N_r} G_j h_j\right|^2}{\sum_{j=1}^{N_r} |G_j|^2}. \tag{3.12}$$

From Cauchy-Schwartz inequality for complex numbers [31], we have

$$\left|\sum_{j=1}^{N_r} G_j h_j\right|^2 \leq \sum_{j=1}^{N_r} |G_j|^2 \sum_{j=1}^{N_r} |h_j|^2 \tag{3.13}$$

where the equality holds when $G_j = h_j^*$, and leads to

$$\gamma_{MRC} = \frac{E_s}{N_0} \sum_{j=1}^{N_r} |h_j|^2. \tag{3.14}$$

This method performs optimal combining as it can maximize the output SNR. As can be seen from (3.14), the maximum output SNR equals to sum of the instantaneous SNRs of the individual signals [31].

Fig. 3.4 shows the BER performance comparison of combining schemes. Single transmit and two receive antennas are used for SC, MRC and EGC. QPSK is used as the modulation scheme. Channel is taken to be Rayleigh flat faded

and AWGN is assumed. We can see that the EGC offers approximately a 1dB improvement over SC. In addition, MRC outperforms both SC and EGC as it uses signals from both branches.
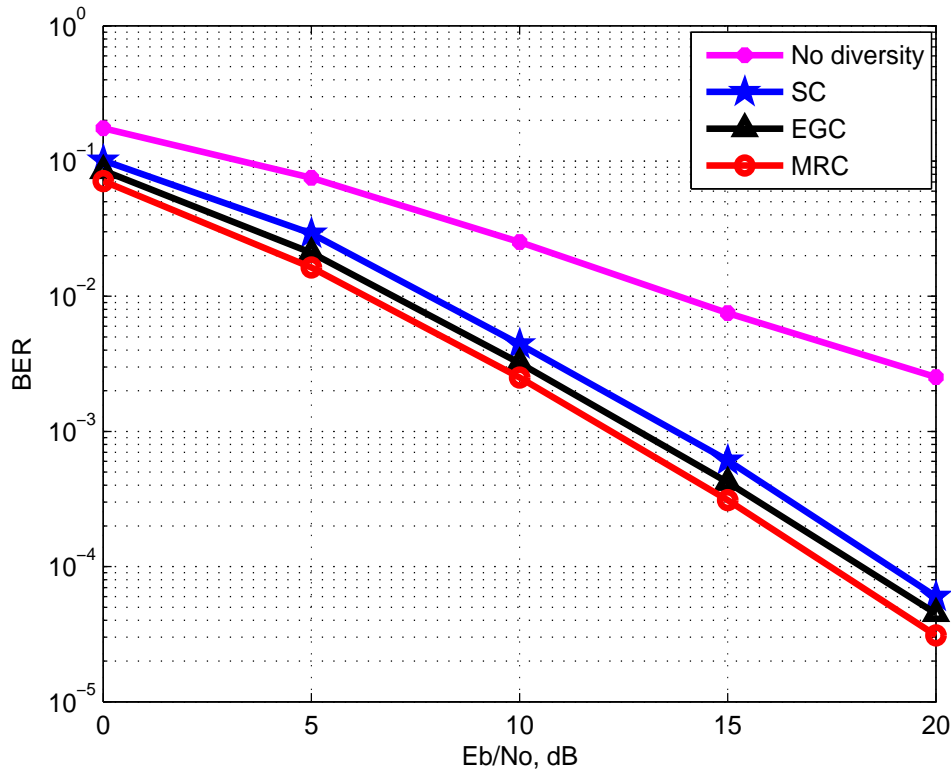
Figure 3.4: BER performance comparison among SC, MRC and EGC.

3.4 MIMO System Models

MIMO systems use multiple antennas at the transmitter and the receiver to improve communication performance. They offer improvement in data throughput and link range without additional transmit power or bandwidth. This is due to diversity and higher spectral efficiency. In this section, a MIMO system model is presented. Consider a general MIMO system with N_t transmit antennas and N_r receive antennas. The system block diagram is illustrated in Fig. 3.5.
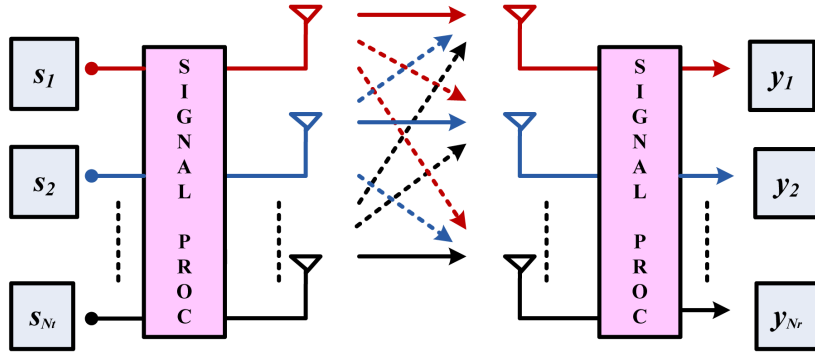
Figure 3.5: Block diagram of a MIMO system.

For a flat fading, and therefore memory-less channel, the MIMO channel is given by $N_r \times N_t$ matrix $\mathbf{H}(t)$ with

$$\mathbf{H}(t) = \begin{bmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,N_t} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,N_t} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_r,1} & h_{N_r,2} & \cdots & h_{N_r,N_t} \end{bmatrix}. \tag{3.15}$$

There are numerous multipaths between the transmitter and receiver in a rich scattering environment. The channel coefficient h_{ij} are assumed to be independent and identically distributed (i.i.d.). It is assumed that there is no dominant propagation path and $\mathbf{H}$ is a complex Gaussian distributed matrix with each entry h_{ij} be a complex Gaussian random variable with zero mean and $1/2$ variance in each complex dimension. This assumption is considered throughout this thesis.

Assuming signal s_j is launched from the j-th transmit antenna, the signal received at the i-th receive antenna, $y_i(t)$, is given by

$$y_i(t) = \sum_{j=1}^{N_t} h_{i,j}(t)\, s_j(t) + n_i(t), \qquad i = 1, 2, \ldots, N_r \tag{3.16}$$

where $n_i(t)$ is the AWGN. The input-output relationship for MIMO in (3.16) can

be rewritten in the compact matrix form as

$$\mathbf{y}(t) = \mathbf{H}(t)\,\mathbf{s}(t) + \mathbf{n}(t) \tag{3.17}$$

where $\mathbf{s}(t) = [s_1(t)\ s_2(t)\ \ldots\ s_{N_t}(t)]^T$ is a symbol vector of dimension $N_t \times 1$ at time t with $\mathbb{E}\left[\mathbf{s}(t)\mathbf{s}(t)^H\right] = \mathbf{I}_{N_t}E_s$, $\mathbf{y}(t) = [y_1(t)\ y_2(t)\ \ldots\ y_{N_r}(t)]^T$ is an $N_r \times 1$ vector and $\mathbf{n}(t) = [n_1(t)\ n_2(t)\ \ldots\ n_{N_r}(t)]^T$ describes a noise vector of dimension $N_r \times 1$ vector with zero mean and variance matrix $N_0\mathbf{I}_{N_r}$.

3.5 Space-Time Coding (Spatial Diversity)

Coding techniques designed for multiple antennas transmission are called space-time coding (STC) [42]. In STC the signal design extends over both space (via multiple antennas) and time (via multiple symbol times). Due to the joint design, STC can achieve transmit diversity as well as a coding gain without any additional bandwidth requirement [43]. A MIMO channel with N_t and N_r transmit and receive antennas respectively can achieve the maximum diversity order of N_tN_r. Fig. 3.6 shows the block diagram of STC system with N_t transmit antennas and N_r receive antennas.
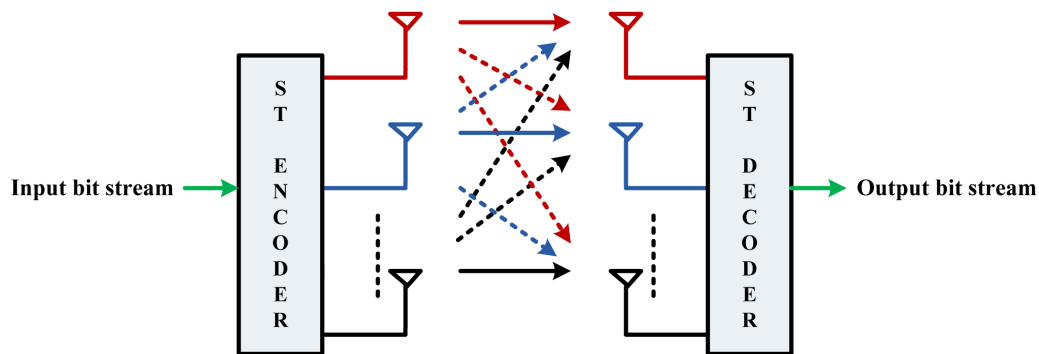
Figure 3.6: Block diagram of STC

STC can be divided into following two types [31].

- Space-Time Trellis Codes (STTC)

- Space-Time Block Codes (STBC)

3.5.1   Space-Time Trellis Codes

In this sub-section, simple form of STTC - delay diversity [42] is discussed. In this scheme, versions of the same symbol are transmitted through multiple antennas in different times as illustrated in Fig. 3.7. At the receiver, the delays of the second up to the N_t-th transmit antennas introduce a multipath-like distortion for the signal transmitted from the first antenna and creates frequency selective fading at a single receiver. The multipath distortion can be resolved at the receiver by using a MMSE or a MLSE equalizer to obtain diversity gain.
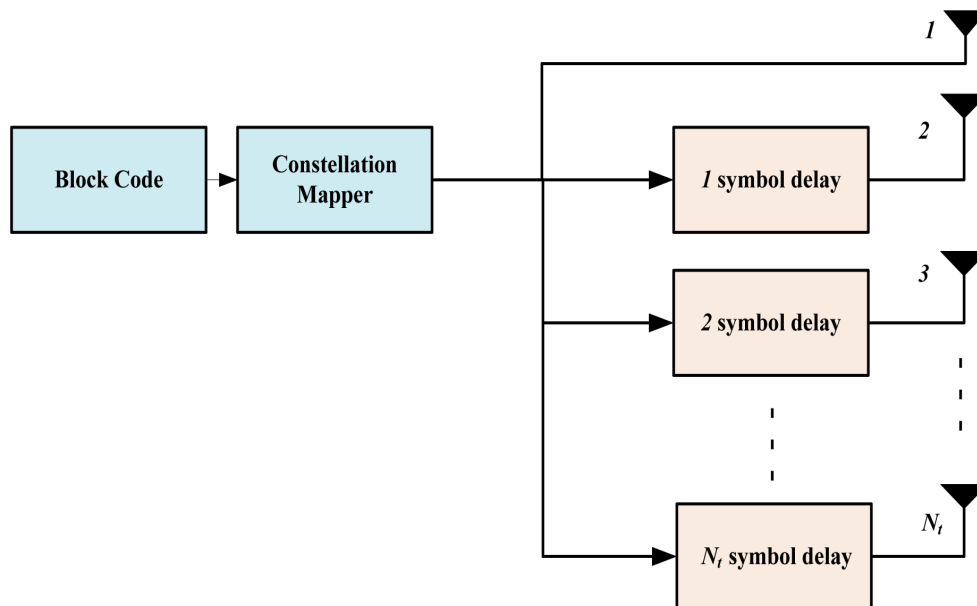
Figure 3.7: Delay Diversity Scheme for N_t transmit antennas.

3.5.2   Space-Time Block Codes

STBC is a simple transmit diversity technique in MIMO systems that was introduced by Alamouti [37]. He proposed a simple scheme for 2 transmit antennas
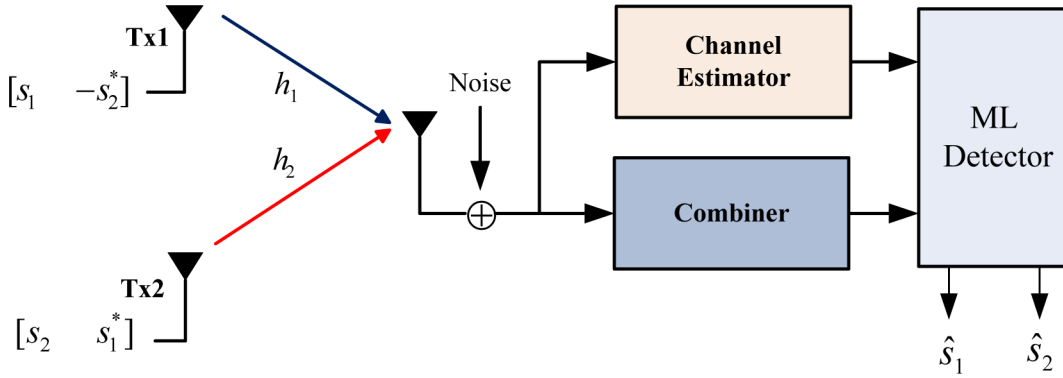
Figure 3.8: Block diagram of the Alamouti space-time receiver.

system that achieves full diversity gain. Let s_1 and s_2 denote the complex symbols which are to be transmitted over the wireless channel. At the first symbol period t, antenna one will transmit s_1, and simultaneously, antenna two will transmit s_2. In the next symbol period $t + T$, antenna one will transmit $-s_2^*$ and antenna two will transmit s_1^*, where T is the symbol period. The two by two space time block code can be written in matrix from as

$$\mathbf{S} = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix}. \tag{3.18}$$

The block diagram of the receiver for the Alamouti scheme is shown in Fig. 3.8. The channel at time t may be modeled as complex multiplicative distortion $h_1(t)$ for transmit antenna one and $h_2(t)$ for the transmit antenna two. Assuming the channel is flat fading and is constant over two consecutive symbols, we can write

$$h_1(t) = h_1(t + T) = h_1 \tag{3.19}$$

and

$$h_2(t) = h_2(t + T) = h_2. \tag{3.20}$$

The received signals can then be given by

$$y(t) = y_1 = h_1 s_1 + h_2 s_2 + n_1 \tag{3.21}$$

$$y(t + T) = y_2 = -h_1 s_2^* + h_2 s_1^* + n_2 \tag{3.22}$$

where y_1 and y_2 are the symbols received at time t and $t + T$, and n_1 and n_2 are complex channel noise. Now, the received signal is multiplied with the Hermitian transpose of the channel matrix $\mathbf{H}$ to obtain Eq.(3.23),

$$r_j = \left(|h_1|^2 + |h_2|^2\right) s_j + n_j. \qquad j = 1, 2. \tag{3.23}$$

These combined signals are then sent to the maximum likelihood (ML) decoder. Assuming that all the signals in the modulation constellation are equiprobable, a ML decoder chooses a pair of signals $(\hat{s}_1, \hat{s}_2)$ from the signal modulation constellation to minimize the distance metric over all possible values of $\hat{s}_1$ and $\hat{s}_2$. Mathematically, ML decoder can be represented as

$$\hat{s}_1 = \arg \min_{\hat{s}_1 \in \mathbf{S}} \left\| r_1(t) - \left(|h_1|^2 + |h_2|^2\right) \hat{s}_1 \right\|^2 \tag{3.24}$$

and

$$\hat{s}_2 = \arg \min_{\hat{s}_2 \in \mathbf{S}} \left\| r_2(t) - \left(|h_1|^2 + |h_2|^2\right) \hat{s}_2 \right\|^2 \tag{3.25}$$

where $\mathbf{S}$ is a set of all possible modulated symbols. Monte-Carlo simulation is carried out to illustrate the BER performance of Alamouti's scheme as a function of SNR in Fig. 3.9. Circular-symmetric complex Gaussian noise with zero mean and N_0 spectral density is considered. The total transmit power of system is kept constant for a fair comparison between SISO and Alamouti's STBC scheme. The channel is assumed to be quasi-static Rayleigh flat faded. Furthermore, we assume that the receiver has perfect knowledge of the channel. At BER of 10^{-3}, a gain of 8dB to SISO is observed by employing Alamouti scheme with single receive antenna. This is due to the diversity achieved by STBC. The addition of

another antenna at the receiver further improves the performance.
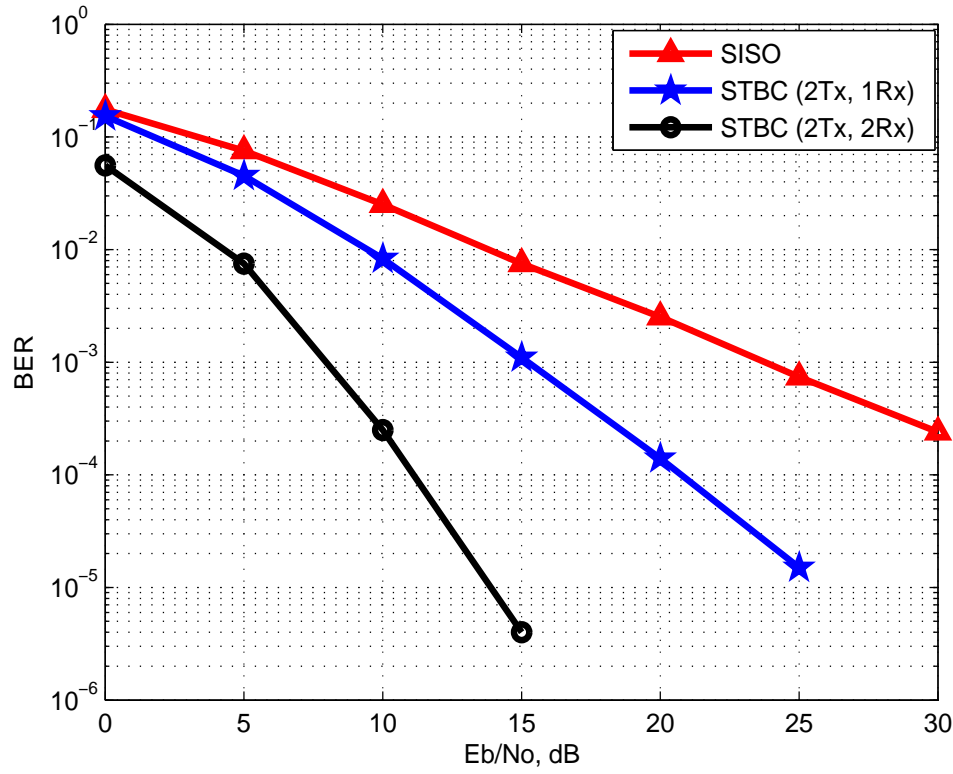
Figure 3.9: BER performance of Alamouti scheme as a function of SNR.

3.6 Spatial Multiplexing

In rich-scattering environments, if multiple antenna systems are used instead of single antenna systems, the spectral efficiency will increase enormously, and the capacity of the radio channel can be improved by using antenna arrays at both the transmitter and the receiver [44,45]. Spatial multiplexing (SM) is a transmission technique in MIMO wireless communication where multiple antennas at the transmitter and receiver are employed to increase the channel spectral efficiency with no additional bandwidth and power consumption [46]. Fig. 3.10 illustrates

the basic principle of spatial multiplexing with three transmit and receive anten-
nas. The concept can be extended to more general MIMO channels. The high
rate data stream is spatially multiplexed into three independent bit sequences
which are then transmitted simultaneously using multiple antennas. Considering
that the receiver knows the channel, it can differentiate between the co-channel
signals and can extract the desired data stream. Thus SM increases the data rate
proportionally with the number of transmit-receive antenna pairs.
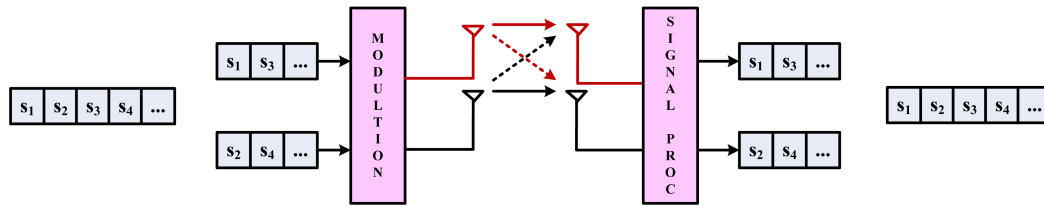
Figure 3.10: Spatial multiplexing system.

Bit streams are transmitted over all N_t transmit antennas to obtain diversity
advantage. This can be achieved using serial encoding, shown in Fig. 3.11. The
bit stream is passed through temporal encoder with block length L to form the
codeword $[s_1, s_2, \ldots, s_L]$. The codeword is then interleaved, mapped to a signal
constellation point and de-multiplexed onto the different antennas. The first N_t
symbols are transmitted by N_t antennas in first symbol time, the next N_t symbols
are transmitted over the next symbol time and this process continues until the
entire codeword is transmitted. When the codeword is sufficiently long, it is
transmitted over all N_t antennas and received by all N_r receive antennas, resulting
in full diversity gain i.e. $N_r N_t$. However, the complexity grows exponentially
with the codeword length. This increase in complexity makes serial encoding
impractical [47].

Wolniansky *et. al* [48] proposed a simpler method to achieve spatial multi-
plexing using parallel encoder as illustrated in Fig. 3.12. Their architecture for
MIMO channel is known as Vertical Bell Labs Layered Space Time (V-BLAST).
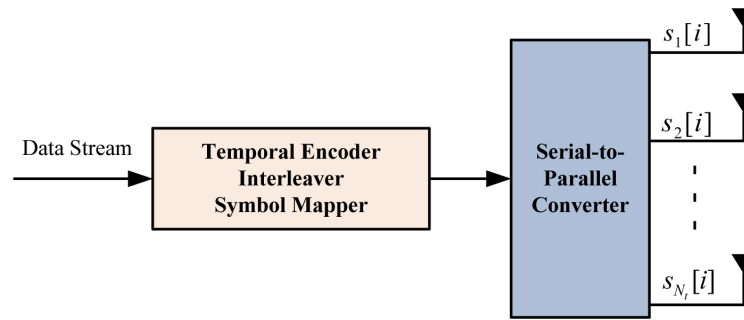
Figure 3.11: Spatial multiplexing with serial encoding.

In this scheme data stream is de-multiplexed into N_t independent substreams. Each substream is passed through a SISO temporal encoder with block length L. The codeword is interleaved and mapped to a constellation point and transmitted over its corresponding transmit antenna. The j-th SISO encoder generates the codeword $s_j[k], k = 1, \ldots, L$, which is transmitted sequentially over the j-th antenna. Since the codeword in V-BLAST is transmitted from one antenna and received by N_r antennas, it can achieve at most a diversity order of N_r. The system encoding complexity is linear in the number of antennas and is far less than the serial encoder.
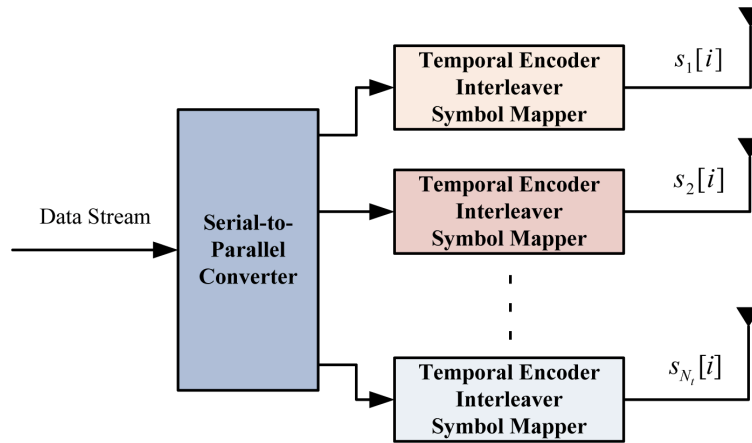
Figure 3.12: Spatial multiplexing with parallel encoding.

It is shown in [49] that the receiver complexity reduces significantly by the use of Ordered successive interference cancellation (OSIC) as illustrated in Fig.

3.13. The OSIC detector processes the substreams using a sequence of nulling and cancellation steps. The strongest transmitted signal is obtained by nulling out all the weaker transmit signals using the zero forcing (ZF) criterion. Then this detected signal is subtracted from the received signal, proceeding to detect the strongest signal of the remaining transmitted signals, and so on. ZF criterion applies the inverse of the channel to the received signal, to restore the signal before the channel. The name Zero Forcing corresponds to bringing down the ISI to zero in a noise free case. The disadvantage with the ZF filter is that channel inversion may excessively amplify the noise [32]. Consider a (N_t, N_r) V-BLAST system with N_t transmit antennas and N_r receive antennas. Defining transmit symbol matrix $\mathbf{S}$ with L number of symbols per substream,

$$\mathbf{S} = \begin{bmatrix} s_{1,1} & s_{1,2} & \cdots & s_{1,L} \\ s_{2,1} & s_{2,2} & \cdots & s_{2,L} \\ \vdots & \vdots & \ddots & \vdots \\ s_{N_t,1} & s_{N_t,2} & \cdots & s_{N_t,L} \end{bmatrix}. \tag{3.26}$$

The received signal vector at the k-th retransmission of $\mathbf{S}$ is

$$\mathbf{r}(k) = \mathbf{H}(k)\mathbf{S} + \mathbf{n}(k), \tag{3.27}$$

where $\mathbf{H}(k)$ is the $N_r \times N_t$ channel matrix containing un-correlated complex Gaussian fading gains at the k-th retransmission. The channel is assumed to be quasi-static flat fading, and is known perfectly at the receiver only. $\mathbf{n}(k)$ represents the i.i.d complex Gaussian noise vector with zero mean and the co-variance matrix $N_0\mathbf{I}_{N_r}$.

At the receiver, ZF detection method can be used to compute the nulling

vector $\mathbf{w}_j(k)$,

$$\mathbf{W}(k) = \mathbf{H}^\dagger(k) = \left[\mathbf{w}_1(k)\,\mathbf{w}_2(k)\cdots\mathbf{w}_{N_t}(k)\right]^T \tag{3.28}$$

where $\mathbf{H}^\dagger$ is the pseudo-inverse matrix of $\mathbf{H}$, and $\mathbf{w}_j$ is a $N_r \times 1$ nulling vector for the j-th transmit antenna. Therefore,

$$\mathbf{y}_j(k) = \mathbf{w}_j^T(k)\,\mathbf{r}(k) = \mathbf{s}_j + \mathbf{w}_j^T(k)\,\mathbf{n}(k)\,;\, j = 1, 2, ..., N_t \tag{3.29}$$

where $\mathbf{y}_j$ is the decision statistic for the j-th transmitted substream. Therefore, SNR for this j-th substream is

$$SNR_j = E_s/\left\|(\mathbf{w}_j)\right\|_F^2 N_0 \tag{3.30}$$

where $\left\|\mathbf{w}_j\right\|_F$ is the Frobenius norm of $\mathbf{w}_j$ and E_s is the symbol energy. It is been proved that selecting the substream with the smallest $\left\|\mathbf{w}_j\right\|_F$ at each stage provides optimum detection ordering [48]. Once a selected substream is detected, its contribution to the received signal is removed to form the modified received signal for subsequent stages. Figure 3.13 shows a V-BLAST system with OSIC. Simulation results of V-BLAST with 2 transmitter and 2 receiver antennas is
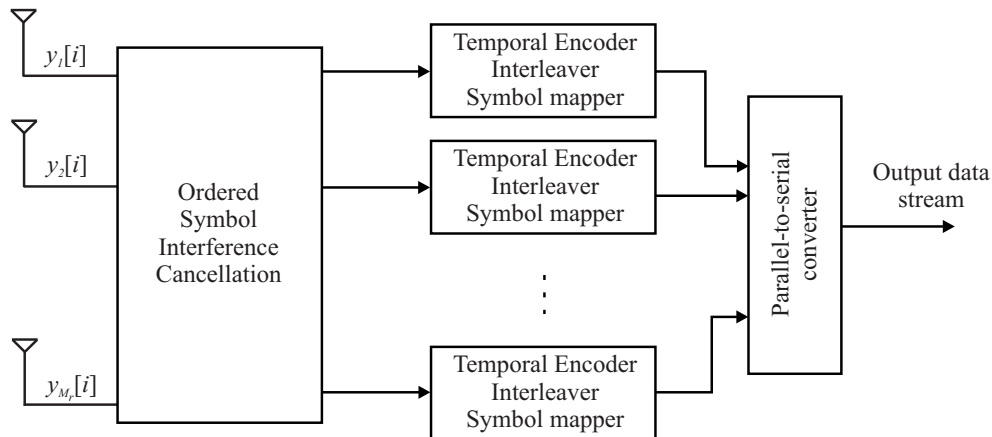
Figure 3.13: V-BLAST receiver with Ordered Successive Interference Cancellation.

shown in Fig. 3.14. QPSK is used as a modulation scheme with Rayleigh flat faded channel and AWGN. Performance is measured in terms of symbol error rate (SER). V-BLAST with ZF performs better than SISO case when the SNR is more than 4dB, whereas the performance of V-BLAST improves with MMSE.
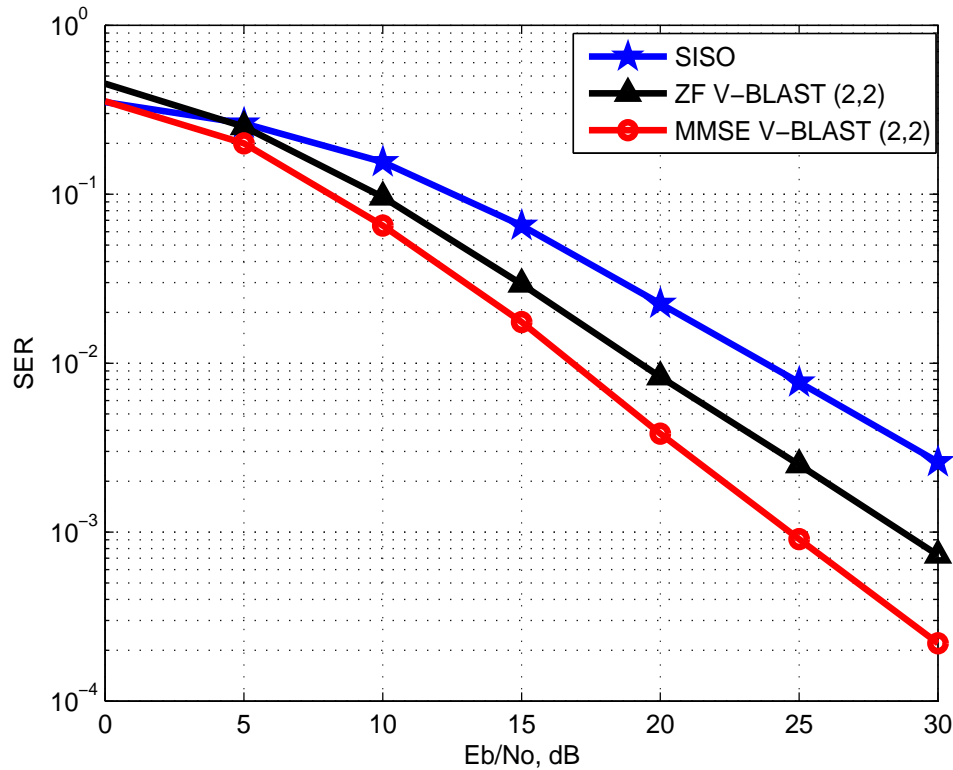
Figure 3.14: Symbol error rate performance analysis of V-BLAST.

3.7 Summary

In this chapter basic concepts related to Multi-antenna systems have been discussed. Various diversity combining techniques are highlighted. Techniques like Spatial diversity and spatial multiplexing are discussed in detail for MIMO systems with their BER performances.

Chapter 4

Hybrid ARQ Transmission and Combining

4.1 Introduction

This chapter begins with the basics fo Hybrid ARQ systems, then we discuss various HARQ combining schemes. We also discuss various aspects of Multiple HARQ processes for MIMO system. We presented two novel HARQ combining schemes which utilize better performance advantages of pre-combining method and contribute to improving the performance of existing MMARQ techniques. At the end, simulation are presented to demonstrate the throughput performance improvement of the proposed schemes over existing post combining based MMARQ scheme.

4.2 Hybrid ARQ System

The design of a communication network traditionally is divided into seven parts each corresponding to a layer in the open systems interconnection (OSI) reference model. Lowest two layers (physical layer and the data link layer) are considered

for MIMO wireless communication in this thesis. The information bits to be sent are organized into frames. A frame contains information bits and some control information. The frames are often formed at the data link layer or network layer. The physical layer design normally consists of several components like coding, modulation and channel estimation etc. It deals with the transmission of information frames from source to destination. The main difference between a wireless and a fixed network is the communication channel [47]. Fixed communication networks are connected by fixed communication cables or optical fibres in which the physical characteristics of the medium are almost constant. On the other hand, the physical characteristics of wireless radio channels may vary significantly during a transmission. Therefore, wireless channels are often described using statistical rather than a deterministic channel model [47]. In order to overcome the channel impairments, a lot of research has been done to improve the design of the physical layer and the data link layer. In order to achieve nearly error free transmission, ARQ schemes are normally employed as a key component of the data link layer [50]. This is a practical way to ensure that the information will eventually be received correctly assuming perfect error detection and that infinite number of retransmissions are allowed. The ARQ scheme defines how to retransmit information that was received incorrectly and how to use the received information from the multiple transmissions in the receiver. One of the major disadvantages of using ARQ from communication point of view is that it incurs a delay due to retransmissions. Real time applications cannot afford this delay unless a sufficiently long buffer is included. Traditional ARQ schemes work well with non-real time applications but can be used for other applications as well. In case of an ARQ scheme, the performance is normally measured by several parameters including packet or frame error rate and data throughput to the end user. In practical systems, it is not possible to send infinite number of retransmissions,
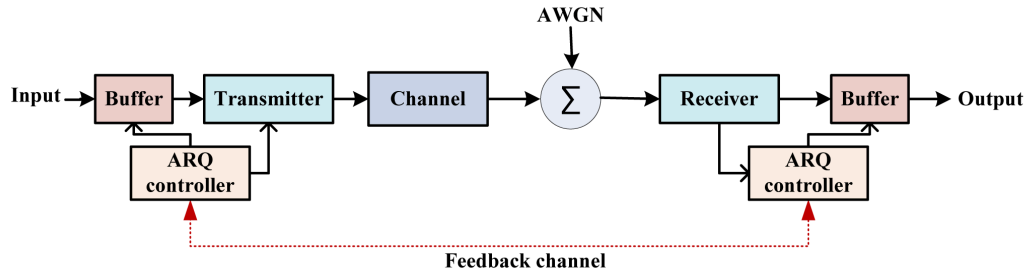
Figure 4.1: An ARQ based system

therefore a packet is declared as "Dropped Packet" once it reaches maximum allowed value. The dropped packet rate can be defined as the ratio of the number of dropped packets to the total number of transmitted packets (including the dropped packets and the packets received correctly).

4.2.1 Pure ARQ Schemes

The ARQ schemes are part of the data link layer and normally deal with packets rather than individual bits. The earliest ARQ schemes which only defined the retransmission strategy are called pure ARQ schemes [51]. These schemes used a high rate cyclic redundancy check (CRC) to encode a block of bits to form a packet. The decoder checks the validity of the received packets by decoding the error detection code. In case of a success an ACK is sent to the transmitter whereas in case of a failure a NACK is sent accordingly. The same packet is resent from the transmitter if the corresponding NACK is received. There are three basic types of pure ARQ schemes, namely stop-and-wait, go-back-N and selective repeat. These schemes differ in the retransmission strategy used when a NACK is received at the transmitter. The three pure ARQ schemes are described briefly as follows:

- **Stop-and-Wait**: After transmitting one packet, the transmitter stops transmitting new packets until an ACK/NACK is received. Then, a new

packet or the same packet is sent according to the feedback received.

- **Go-back-N**: The delay once a codeword is transmitted and an acknowledgment arrives back at the transmitter is defined as the time interval. Let us assume that, during this interval, the transmitter sends N distinct packets. If a NACK is received, this packet and the following $N-1$ packets are retransmitted again regardless of whether any of the following $N-1$ packets were received correctly or not [51].

- **Selective-Repeat**: The transmitter is continuously transmitting packets. When a NACK is received, only the packet corresponding to this NACK gets retransmitted.

Out of the three pure ARQ schemes above, the stop-and-wait scheme is the most inefficient due to the idle time used to wait for the arrival of an acknowledgment. The efficiency is improved by using the go-back-N scheme, but deteriorates for a communication system with high data rate and a long time interval [51]. The efficiency of the selective-repeat scheme is the highest. However, the efficiency is obtained at the cost of requiring extra memory. For the stop-and-wait scheme, no memory is required at the transmitter or receiver. It can be used for communication systems which do not have duplex links, which means the information is only allowed to flow in one direction at a time. For the go-back-N scheme, a memory buffer, which is big enough to store $N-1$ codewords is required at the transmitter. The selective-repeat scheme has the highest memory requirements. It requires a memory buffer at both the transmitter and the receiver. A transmitted packet has to be stored in the transmitter until it has been acknowledged. The receiver memory is required because a correctly received packet has to be stored in the receiver until all packets which were transmitted before this packet are received correctly. The size of the required memory must be chosen carefully to prevent overflow [52]. Because most practical systems can only tolerate limited delays,

the selective-repeat scheme with a specified maximum number of retransmissions is typically used for practical systems. The transmission is truncated after the maximum number of retransmissions is reached and this packet is declared as a dropped packet. This is called truncated selective-repeat ARQ (TS-ARQ). Some modified selective-repeat schemes were proposed in [53] and [54].

4.2.2 HARQ Schemes for SISO Systems

The performance of an ARQ scheme not only depends upon the selection of a retransmission strategy but it is also affected by the probability of generating a retransmission request. HARQ is a technique that enables faster recovery from errors by storing erroneous packets in the receiving device rather than discarding them. Inspite of errors in the retransmitted packets, a good packet can be derived from the combination of bad ones. HARQ schemes use error detection and correction processes to improve error performance. Following are HARQ schemes for SISO communication channels are [4, 23, 47]

- **HARQ Type-I**: A FEC code is used so that the receiver attempts error correction on receipt of a packet containing errors. If the decoding is not successful, then a retransmission request is generated. The same packet will be retransmitted until an ACK is received. Compared with pure ARQ schemes, the type-I HARQ schemes decrease the probability of retransmissions due to the use of an error control code with error correction capability.

- **HARQ Type-II**: In this HARQ scheme, the first transmission contains only information bits and error detection capability using CRC (no FEC is sent for first transmission). If data is received in error, the second transmission will contain FEC parities and error detection. In case of error, FEC attempts error correction combining the information received from both transmissions. Type-II HARQ schemes were proposed to act like an

adaptive system. When the channel is quite good, they act like pure ARQ schemes. The error correction capability is added only when it is needed. The previous erroneously received packets need to be stored in memory for combining purpose instead of being discarded.

- **Chase Combining**: On every retransmission request, same packet is sent to the receiver (same data and parity bits). The receiver combines the current received packets with the erroneous packet from previous transmission using maximum-ratio combining. Every retransmission adds effectively extra energy by increasing the received energy at the receiver.

- **Incremental Redundancy**: Every retransmission contains different coding information than the previous one. For the same set of information bits, multiple sets of coded bits are generated for the retransmissions. The retransmission have different redundancy versions generated by puncturing the decoder output. The receiver gains extra knowledge at every retransmission.

4.2.3 HARQ Schemes for MIMO Systems

The fundamental concept behind the ARQ schemes designed for MIMO systems is to explore the time diversity provided by the ARQ schemes to enhance the overall diversity of MIMO system at the cost of spectral efficiency (multiplexing gain) [22]. All the basic ARQ schemes, stop-and-wait, go-back-N, selective-repeat [52] can be used for MIMO systems directly without any modification. The HARQ schemes designed for SISO systems using hard algebraic decoders can be easily modified for MIMO systems by being concatenated with an STC. But the research conducted in existing literature [55] [56] show that if ARQ schemes are designed jointly with MIMO systems and STCs, then the performance can be improved significantly. A MIMO ARQ system is shown in Fig. 4.2. Most of the
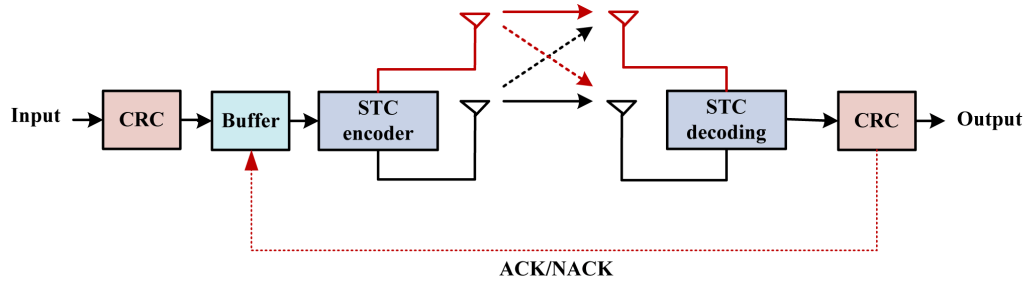
Figure 4.2: A MIMO ARQ system model

proposed HARQ schemes, so far, are designed for MIMO systems with orthogonal space-time block codes (OSTBCs) [39], space-time trellis codes (STTCs) [57], turbo codes [58] [40] and layered space-time (LST) systems [3]. Normally for an ARQ scheme, it is assumed that CSI is not available at the transmitter. If the error detection and correction capabilities are provided by different error control codes, the information bits should be encoded using an error detection code first, for instance a CRC code. The information bit and CRC together are then coded by using an error correction code. If the CRC check fails, a retransmission is requested. Various error detection codes exist, which have better error detection capability than that of CRC codes, including extended Hamming codes and extended binary Golay codes [59]. However they are not convenient to be used with ARQ schemes for the following reasons. Firstly, these codes place constraints on packet length. Secondly, these codes have much lower rate than a CRC code. Thirdly, a well chosen CRC code can offer an error detection capability close to these optimal ones. Therefore, in most of the existing literatures and this thesis, CRC code is used for error detection purpose. It is also assumed that this CRC check is perfect in most of the existing literature.

The HARQ combining scheme used in [39] works in such a way that a packet is retransmitted $N - 1$ times once the CRC check for each transmission fails. If the N-th received packet is still in error, soft values of the current and previously received symbols are combined. Another way of HARQ scheme Layered Space

Time (LST) systems [3] uses CRC code for each substream. In this scheme, each input packet is split into several substreams and each substream is encoded using a CRC code. These CRC coded substreams are then encoded using other error control codes to provide coding gain. Each encoded substream is interleaved separately before it is transmitted from a single transmit antenna or a group of antennas. All substreams are transmitted simultaneously. The receiver decodes the received information substream by substream. It uses the CRC code attached to each substream to validate the contents of the substream. If the CRC check for a particular substream fails, a NACK for this substream is sent back and the corresponding substream is retransmitted. This scheme is more efficient and reliable compared to using the traditional ARQ schemes for LST systems, in which the CRC encodes the entire packet. This is because, in the scheme of [3], substreams rather than packets get retransmitted and each substream is checked based on its CRC parity bits which results in a more reliable interference cancellation for this substream.

In the system simulation of HARQ schemes a concept of "Actual CRC" is used. Actual CRC means that as we know the actual contents of the transmitted packet while carrying out detection procedure in simulations, therefore it is more appropriate to compare the actual transmitted packet with the received packet instead of CRC check. Using actual comparison of sent and received packets produce more realistic result as compared to CRC check beacuse CRC may ignore few errors. In this thesis, we use actual CRC for all the link level simulation results. In some of the research literature a term "Perfect CRC" is also used for this procedure [1, 60].

4.3 HARQ Combining Schemes

There are two HARQ combining schemes for MIMO systems which are briefly discussed below.

4.3.1 Post-Combining Scheme

In this HARQ combining scheme [24], after the nulling process in the OSIC, the decision statistics of the data streams are stored in the receiver buffer. In case the data packet is found to be erroneous through CRC in the first transmission, the receiver asks for a re-transmission. If the second transmission also fails the CRC, the previously stored decision statistics are combined with that of the retransmitted data packets and detection procedure is performed again. Fig. 4.3 shows a block diagram where the combiner combines the current erroneous packet with the previously stored erroneous packet in the buffer. This is a soft combining process based on Chase combining procedure in [23]. In nulling process in which interference of one sub-stream is removed from the received signal to detect the other substream. Post combining is performed after the nulling process where the interference of the other substream has already been removed. Detection procedure is performed after the combining of soft values related to a particular substream
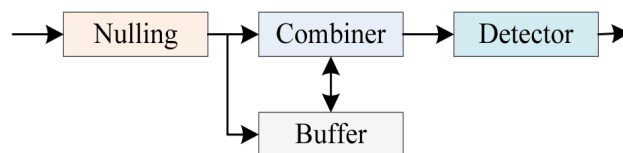
Figure 4.3: HARQ Post-combining in MIMO systems

Once the post-combining is performed for number of retransmissions due to continous decoding faliures at the receiver, the combined soft statistics of the data received in retransmissions is termed as cumulative soft statistics. Therefore,

cumulative soft statistics vector for the received signal (including all substreams) in one expression can be denoted as $\mathbf{Y}^{post}(K)$. Here k is the index which counts the number of retransmissions carried out and K represents the current counted value of index k. Therefore, index k can have a range between 1 to K. The cumulative soft statistics of all substreams is represented by

$$\mathbf{Y}^{post}(K) = \sum_{k=1}^{K} \mathbf{H}^{\dagger}(k)\, \mathbf{r}(k).$$

(4.1)

To calculated individual substream decision statistics we have,

$$\mathbf{y}_j^{post}(K) = \sum_{k=1}^{K} \mathbf{w}_j^{T}(k)\, \mathbf{r}(k) = \mathbf{s}_j + \sum_{k=1}^{K} \mathbf{w}_j^{T}(k)\, \mathbf{n}(k).$$

(4.2)

where $\mathbf{y}_j^{post}(K)$ is the decision statistic and $\mathbf{w}_j^{T}$ represents the weighting vector for j-th substream. This procedure continues till the packet is detected correctly or the maximum allowed re-transmissions are reached. In the latter case, the packet is discarded. Fig. 4.5 presents BER performance of post combining based MIMO HARQ system with MMSE based (4, 4) V-BLAST system. These simulation are carried out in MATLAB and modified for a (4, 4) V-BLAST system based on already published work in [24] which uses a (2,2) V-BLAST system.

4.3.2 Pre-Combining Scheme

In the pre-combining scheme [24], instead of storing the decision statistics, the receiver stores the channel matrix and the received signal in the buffer. The combining process of the received signal is performed prior to the nulling process and the Hermitian form of the channel matrix is multiplied to its corresponding received signal. Hence, it is effectively performing a maximal ratio combining before the OSIC procedure. Fig. 4.4 shows a block diagram where the combiner combines the current channel and received signal with the previously stored channel

and received signal of previous transmission.
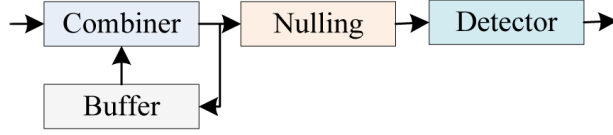
Figure 4.4: HARQ Pre-combining in MIMO systems

Once the current channel and received signal is combined with previously stored channel and received signal using pre-combining procedure, the combined soft statistics are termed as cumulative soft values. The cumulative soft values vector of the received signal (including all substreams) after K retransmissions is denoted as $\mathbf{Y}^{pre}(K)$. The pre-combining procedure can be represented as

$$\mathbf{Y}^{pre}(K) = \left(\sum_{\acute{k}=1}^{K} \mathbf{H}^{H}\left(\acute{k}\right) \mathbf{H}\left(\acute{k}\right) \right)^{\dagger} \sum_{k=1}^{K} \mathbf{H}^{H}(k)\,\mathbf{r}(k), \tag{4.3}$$

where Hermitian form of the current and previous channels is combined and a pseduo-inverse of the matrix is taken as per [24]. In addition, the current received signal is also combined with previously received signals to get a cummulative soft values for detection. This procedure has better performance than post-comining due to the contribution of channel statistics of current and previous transmissions [24]. Again here k is the index which counts the number of retransmissions carried out and K represents the current counted value of index k. Therefore, index k can have a range between 1 to K. To calculated individual substream decision statistics we have,

$$\mathbf{y}_{j}^{pre}(K) = \mathbf{V}_{j}(K) \sum_{k=1}^{K} \mathbf{H}^{H}(k)\,\mathbf{r}(k) = \mathbf{s}_{j} + \mathbf{V}_{j}(K) \sum_{k=1}^{K} \mathbf{H}^{H}(k)\,\mathbf{n}(k) \tag{4.4}$$

whereas $\mathbf{y}_{j}^{pre}(K)$ is the decision statistic for the j-th substream. $\mathbf{V}_{j}(K)$ represents the j-th row of the pre-detection nulling matrix at the K-th retransmission.
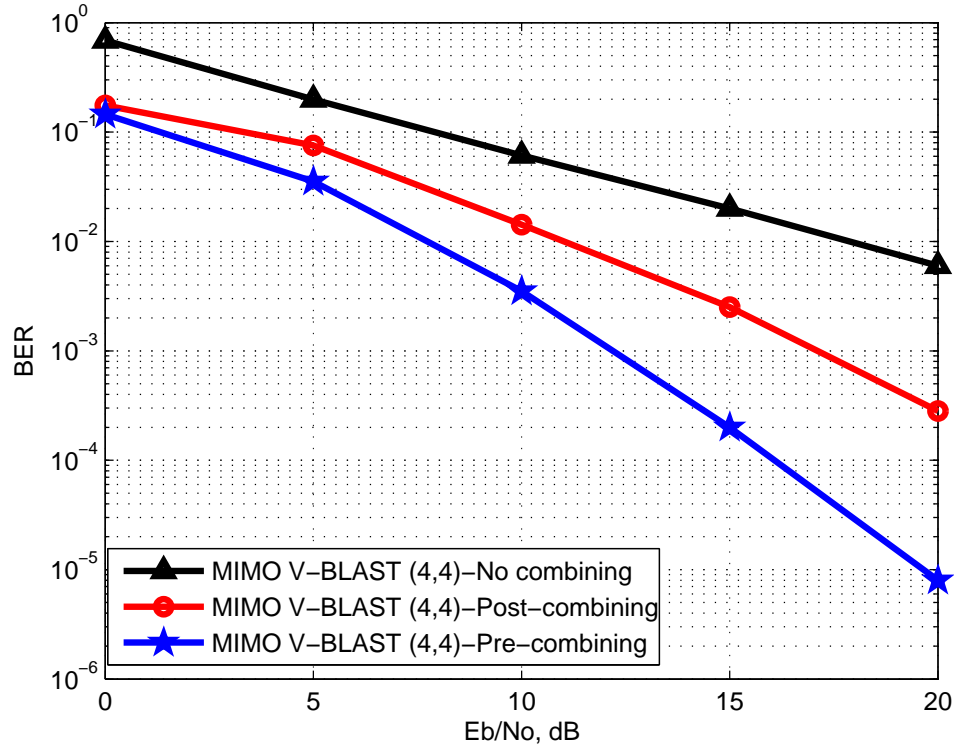
Figure 4.5: BER performance comparison of MMSE based V-BLAST (4Tx-4Rx) system with Pre-combining and Post-combining HARQ at the receiver. A max of 4 retransmissions are allowed.

$$\mathbf{V}(K) = \left(\sum_{\acute{k}=1}^{K} \mathbf{H}^{H}\left(\acute{k}\right) \mathbf{H}\left(\acute{k}\right) \right)^{\dagger} \qquad (4.5)$$

The simulation results in Fig. 4.5 show the use of post combining and pre-combining techniques using MMSE based (4, 4) V-BLAST system. A maximum of 4 transmissions are allowed for HARQ process. The results indicate that pre-combining technique performs better than post-combining technique. Here we use value of 4 for maximum retransmissions because use of higher values can introduce increased delay due to high number of retransmissions, whereas lower value than this does not provide much advantage of HARQ. Existing literature also uses same value as in [61–63].

4.4 Single and Multiple HARQ Processes for MIMO Systems

4.4.1 MIMO Single ARQ (MSARQ)

The use of multiple transmit and receive antennas can enable the implementation of a number of MIMO technologies which can help to improve diversity and increase throughput without any need of additional power or bandwidth [3]. In this technique multiple transmitter and receiver antennas are used with Layered Space time architecture. Fig. 4.7 shows a block diagram of MSARQ system where the information bits are jointly encoded to share a single CRC. Then the frame is multiplexed into smaller substreams, where each transmit antenna transmits one substream which is different from the other substreams.
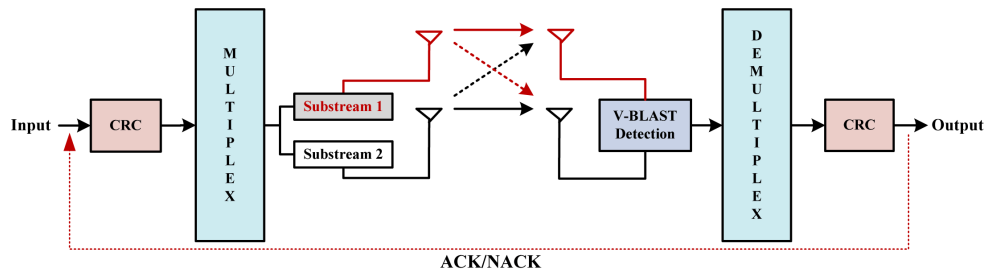
Figure 4.6: An MSARQ System Model

At the receiver, OSIC is performed and then the substreams are de-multiplexed into a frame. A CRC check is performed on the frame to find out if there is any error. In case of a success, an ACK is sent to the transmitter, on the other hand in case of a failure, a NACK is sent. The transmitter then retransmit all the substreams again. During the detection process, the soft values of erroneous transmission are stored in a buffer for subsequent combining process. Once the next retransmission is completed, a similar detection procedure is carried out. In case of a CRC failure again, the stored soft values are combined with the current

values and CRC check is performed again. In case it fails again, more retransmissions are carried out till the packet is decoded correctly. In other case, the packet is discarded once the maximum number of allowed retransmissions are reached.

The maximum number of allowed transmissions is not kept infinite but to a finite number as considered feasible in a particular system. The flow chart in Fig. 4.7 explains each step in detail. The receiver sends the acknowledgement information to the sender through the reverse channel, which is assumed to be error free. MSARQ process is inefficient in a way that if a small error occurs in only one substream, all the other substreams have to be retransmitted again as they all share a single CRC.

4.4.2   MIMO Multiple ARQ (MMARQ)

MMARQ technique removes the inefficiency of MSARQ, in which all the substreams are retransmitted even if only one substream becomes erroneous at the receiver. MMARQ scheme also uses multiple transmitters and receivers antennas with Layered Space time architecture but instead of jointly encoding all the substreams with one single CRC, all the substreams carry their own independent CRC. As each transmit antenna has to transmit one substream which is different from the substreams of other antennas, therefore a CRC is attached with each substream. Fig. 4.9 shows a block diagram of a 2×2 MMARQ system. The MMARQ system has to cater for parallel ARQ processes per each transmit and receive antenna pair. At the receiver, each substream goes through the process of interference cancellation (nulling) first, then detection procedure is done. After this its CRC is checked independently than the other substreams [3]. In this scenario, only erroneous substreams are considered for a retransmission whereas those substreams which pass the CRC are acknowledged. During the process of detection, the soft values of each erroneous substream are saved in their respective
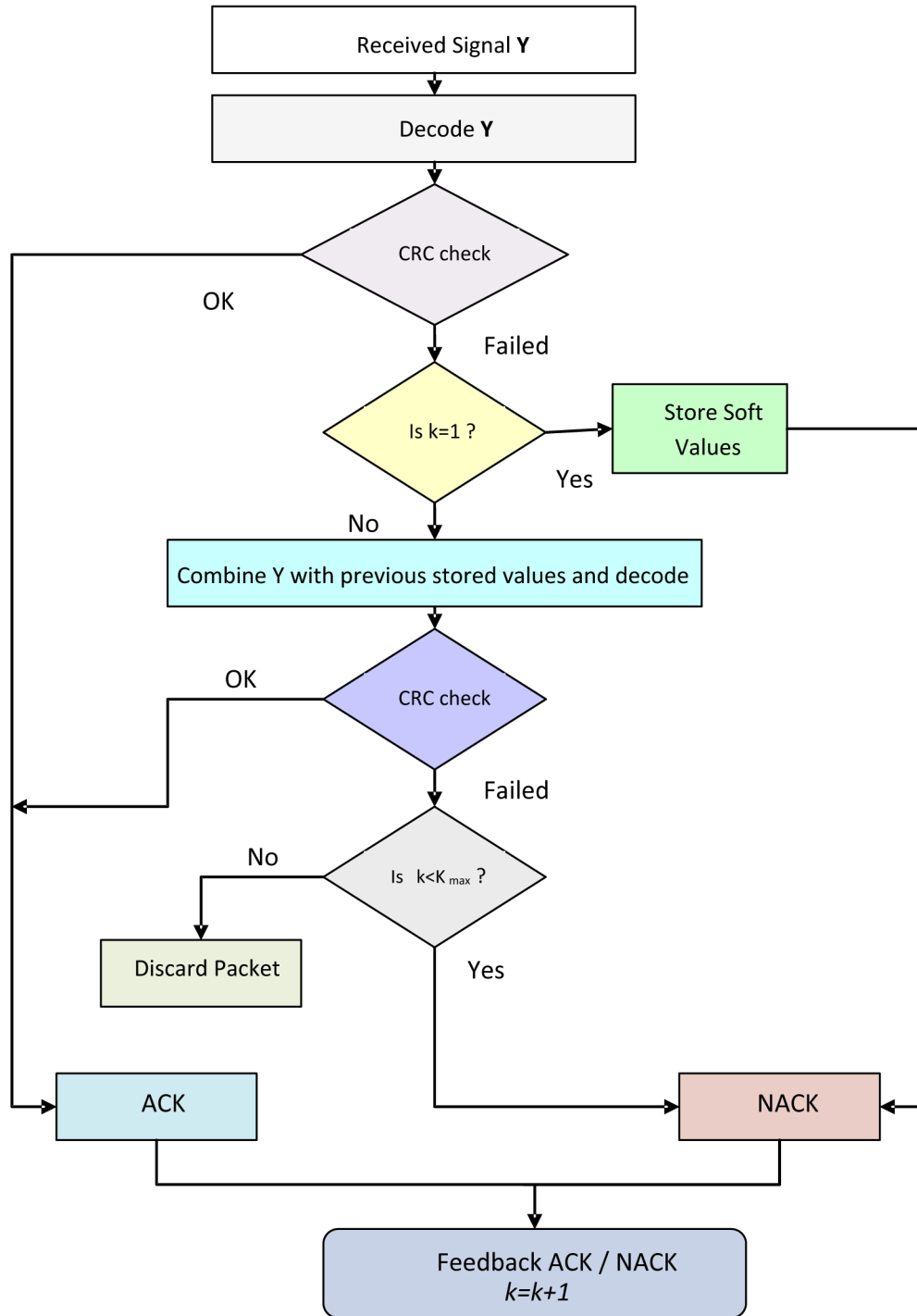
Figure 4.7: A MSARQ system flow chart (post combining) [3]
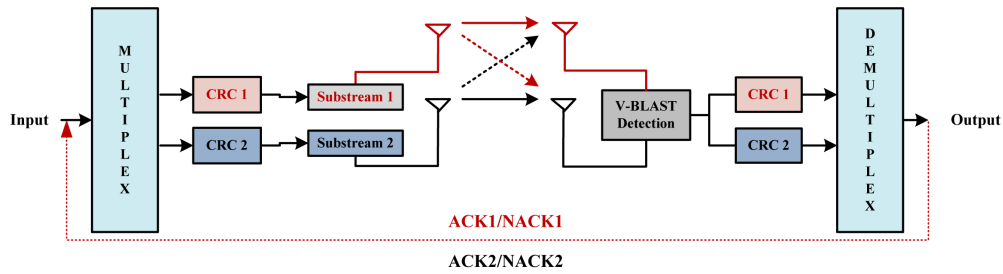
Figure 4.8: A 2×2 MMARQ System Model

buffer for using them in a subsequent retransmission for combining process. In MMARQ, if one substream fails a CRC test, then a re-transmission for only that substream is requested. The soft values of first detection procedure are stored for combining process in the subsequent retransmissions. The substream is discarded once the maximum number of allowed retransmissions is reached. This scheme provides an advantage of better throughput because unlike MSARQ, unnecessary re-transmission of error free substreams is not carried out. However, it comes with an expense in terms of increased complexity of the ARQ algorithm as multiple ARQ processes are required to be controlled by the system. In addition, management of separate buffer space is required to be carried out for each substream and more control information is required on the reverse channel. The flow chart in Fig 4.9 explains the process of MMARQ where it is assumed that there are 2 transmit antennas and 2 receive antennas for simplicity of understanding the process involved. There are two parallel substreams, one for each transmit antenna and there are independent ARQ processes involved for each substream. Fig. 4.10 presents BER performance of V-BLAST based MSARQ and MMARQ post combined schemes. The results are for $K_{max} = 2$ and $K_{max} = 4$. MMARQ scheme performs better than MSARQ scheme for both values of K_{max}. Fig. 4.11 presents throughput performance of V-BLAST based MSARQ and MMARQ post
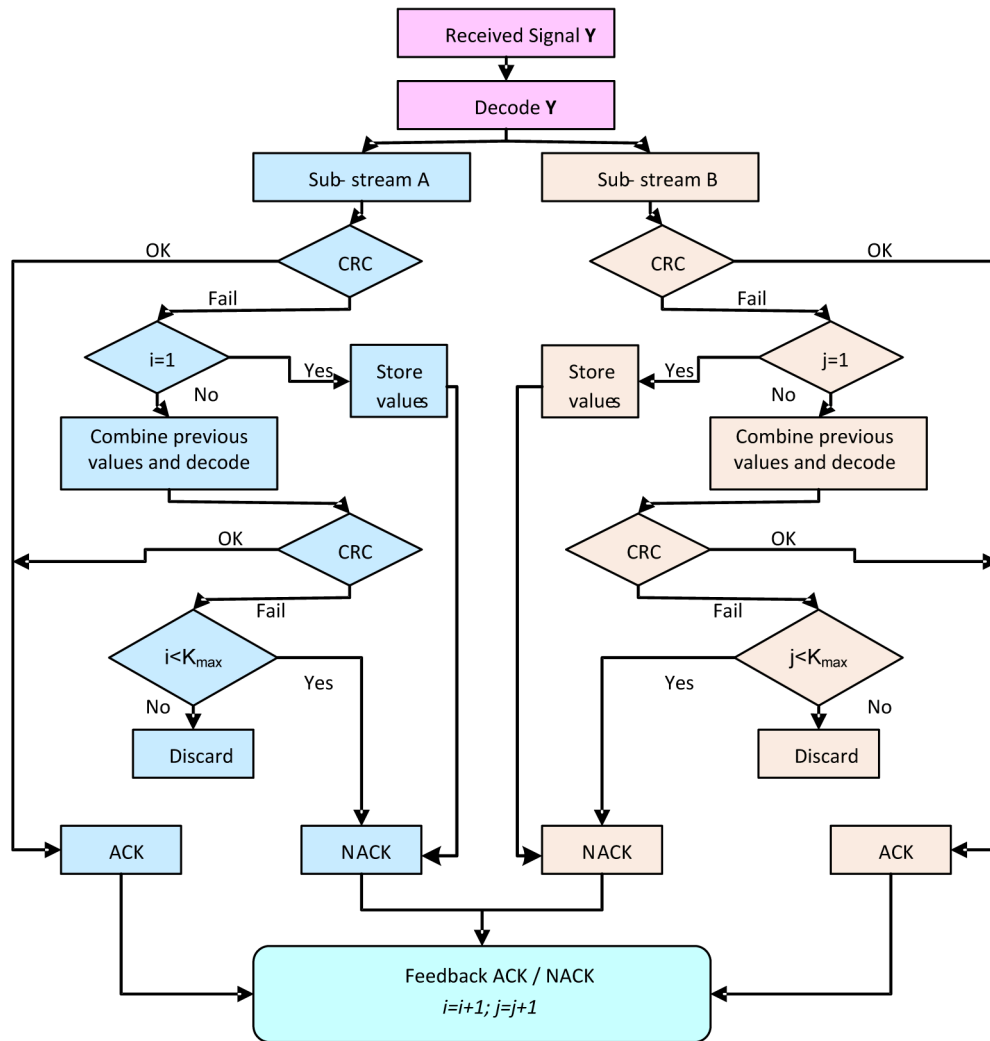
Figure 4.9: A MIMO Multiple-stream ARQ system flow chart(post combining) [3]
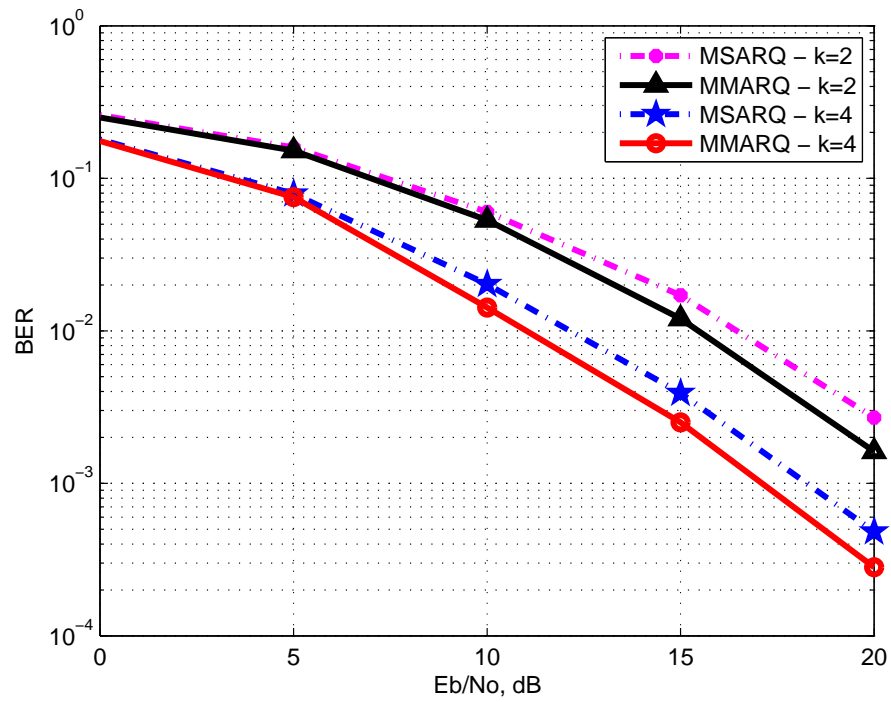
Figure 4.10: BER results of Post-combining based MSARQ and MMARQ V-BLAST(4,4) systems with maximum transmissions of 2 and 4 for HARQ process.
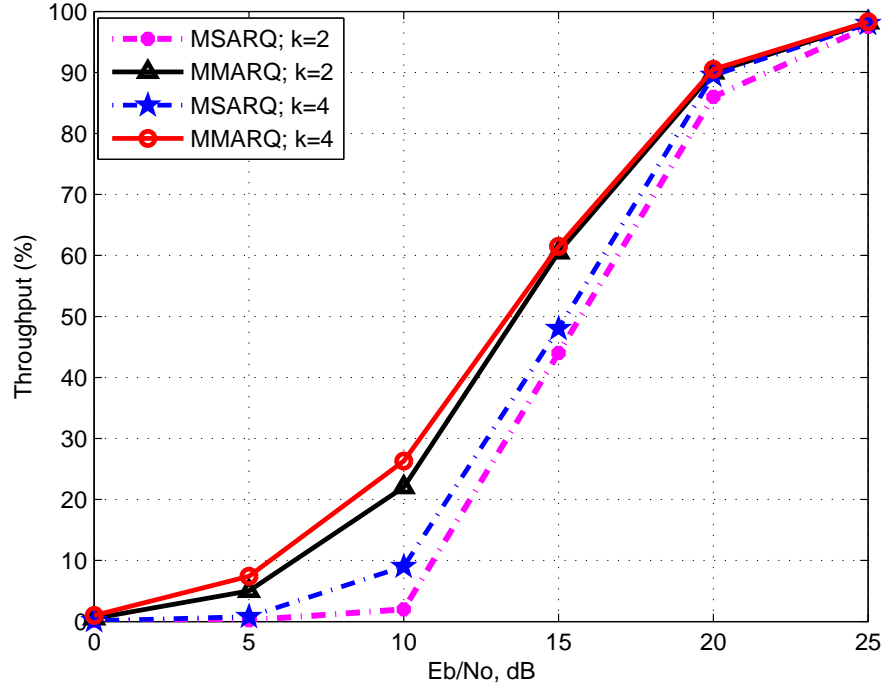
Figure 4.11: Throughput results of Post-combining based MSARQ and MMARQ V-BLAST(4,4) systems with maximum transmissions of 2 and 4 for HARQ process.

combined schemes. The throughput is calculated as

$$\text{Throughput}(\%) = \frac{\text{correct frames}}{\text{Total Tx frames (incl retrans)}} \times 100 \qquad (4.6)$$

The performance of HARQ systems is normally calculated in terms of throughput as in [3] instead of BER. Therefore, rest of the thesis only considers throughput performance of the existing and proposed schemes. The main reason for choosing the same performance criteria was that it is easy to compare the proposed system results with the already published results. The simulation results are for $K_{max} = 2$ and $K_{max} = 4$. MMARQ scheme outperforms MSARQ scheme in terms of throughput for both values of K_{max}.

4.5 Novel MMARQ Combining Schemes

The MMARQ has an increased throughput comparing to the MSARQ as the retransmission of correct substreams are avoided [3]. Various improvements have been proposed for the MMARQ process in terms of detection ordering and combining criteria [64] [65] [66] [67]. However, all these schemes consider post-combining for the HARQ process. The prior published pre-combining procedure is only for SISO systems and MSARQ based systems [61]. Due to the inherent drawbacks of MSARQ systems, pre-combining procedure cannot contribute significant performance advantage in those systems compared to MIMO system. However, no one considered using pre-combining for MMARQ systems. In this thesis, we make use of pre-combining scheme for MMARQ systems which was never been used before for such systems. Two novel methods of combining are proposed: 1) MMARQ with pre-combining and 2) MMARQ with joint pre and post-combining.

4.5.1 MMARQ with Pre-combining

The pre-combining procedure is efficient than post-combining as it combines channel as well as received signal values. Similarly, MMARQ scheme is more efficient than MSARQ becasuse it does not retransmit the correctly received substreams again unlike MSARQ. We considered to use both the efficient systems i.e, MMARQ and pre-combining for improvement of the existing MIMO HARQ systems. In MMARQ, if all the substreams are incorrect, the retransmission and combining procedure will be identical to MSARQ. Hence, applying pre-combining in this scenario is a simple extension to [3]. In MMARQ case, if one of the substream is in error, then sending the erroneous substream only in the following transmission will make the system highly inefficient and the throughput will be very low. A more practical approach is sending a newer substream with the

retransmitted substream in the following retransmission. In such a case, if we apply pre-combining directly on both new and retransmitted substreams this will result in a wrong procedure and thus will not work. Instead we propose a pre-combining scheme in which interference contribution of newly sent substream is removed from the received by nulling process first. Then the remaining soft values of the received signal (the retransmitted substream) is combined with the previous channel and the stored soft values from the buffer. Therefore, system is required to store channel and soft values in every transmission by removing the contribution of the correctly detected substreams from the received signal. These stored statistics are used in preceeding retransmissions for pre-combining. Without loss of generality, assume that the first N_t^C substreams are correctly detected, while the remaining $N_t^E = N_t - N_t^C$ substreams are erroneous. The interference cancelled received signal for the erroneous substreams is

$$\mathbf{r}^E(k) = \mathbf{r}(k) - \bar{\mathbf{H}}(k)_{\left(1:N_t^C\right)} \mathbf{s} = \bar{\mathbf{H}}(k)_{\left(N_t^C+1:N_t\right)} \mathbf{s} + \mathbf{n}(k) \qquad (4.7)$$

where $\bar{\mathbf{H}}(k)_{\left(1:N_t^C\right)}$ denotes the modified channel matrix containing the first to N_t^C-th column of matrix $\mathbf{H}(k)$, while the other columns are zeroed. At the next transmission interval, $\mathbf{r}(k+1)$ will consist of N_t^C new and N_t^E retransmitted substreams. Directly combining it with $\mathbf{r}^E(k)$ will double the noise power for the new substreams, as $\mathbf{r}^E(k)$ still consists of N_r noise elements. Consider a 2×2 antenna system and two substreams to send, if we try to combine current channel and the previous modified channel with one column related to erroneous substream, we get

$$\begin{aligned} \mathbf{r}(k+1) = {} & \left(\mathbf{H}^H(k+1)\mathbf{H}(k+1) + \bar{\mathbf{H}}^H(k)_{(2:N_t)} \bar{\mathbf{H}}(k)_{(2:N_t)} \right) \mathbf{s} \\ & + \mathbf{H}^H(k+1)\mathbf{n}(k+1) + \bar{\mathbf{H}}^H(k)\mathbf{n}(k) \end{aligned} \qquad (4.8)$$

where $\bar{\mathbf{H}}(k)_{(2:N_t)}$ denotes previous channel matrix with second column related to erroneous substream and first column zeroed. Eq. (4.8) shows that the noise power becomes double for pre-combined substream as compared to the newly sent sub-stream making this impractical. In view of this, the proposed procedure will always detect all the N_t^C new substreams first, in the retransmission $r(k+1)$ using V-BLAST with this pre-defined ordering procedure. After these substreams are detected, the modified received signal (after cancelling the interference from the detected substreams) is combined with the previously stored $\mathbf{r}^E(k)$. The combined signal after K retransmission can be expressed as

$$
\begin{aligned}
\mathbf{r}_{comb}(k) = \sum_{k=1}^{K} (\bar{\mathbf{H}}^H(k)_{\left(N_t^C+1:N_t\right)} \bar{\mathbf{H}}(k)_{\left(N_t^C+1:N_t\right)} \mathbf{s} \\
+ \bar{\mathbf{H}}^H(k)_{\left(N_t^C+1:N_t\right)} \mathbf{n}(k)).
\end{aligned}
\tag{4.9}
$$

In Eq. (4.9) newer substream is detected first and then OSIC detection procedure is performed for combined substreams. If newer substreams are more than one then OSIC is performed within the newer substreams. The SNR for a correct substream will be

$$
SNR_j = E_s / \|(\mathbf{w}_j)\|^2 N_0 N_t
\tag{4.10}
$$

whereas, SNR for a substream that has been retransmitted K times, will be

$$
SNR_j(K) = E_s / \|\mathbf{V}_j(K)\|^2 \sum_{k=1}^{K} \left\| \bar{\mathbf{H}}^H(k)_{\left(N_t^C+1:N_t\right)} \right\|^2 N_0 N_t.
\tag{4.11}
$$

where

$$
\mathbf{V}(K) = \left(\sum_{\acute{k}=1}^{K} \bar{\mathbf{H}}^H(\acute{k})_{\left(N_t^C+1:N_t\right)} \bar{\mathbf{H}}(\acute{k})_{\left(N_t^C+1:N_t\right)} \right)^{\dagger}
\tag{4.12}
$$

Fig. 4.12 shows the process of MMARQ with pre-combining for a two substream case. The system is modelled to carry out the V-BLAST detection similar to

MMARQ procedure in [3]. Firstly, the system performs a basic V-BLAST detection and checks the integrity of substreams through CRC. This simple V-BLAST detection is carried out without any combining procedure and is important to check the intergrity of each substream before further processing. During this process system stores the channel information in the buffer for subsequent use. Counter i is used to count the number of transmissions of substream A, whereas counter j is used for substream B. In case of first transmission ($i = 1$ or $j = 1$), the system will perform OSIC procedure with standard SNR based ordering. If both substreams are found erroneous in the first transmission, a request for retransmission is sent to the transmitter through a NACK. It then undergoes standard pre-combining procedure in the next retransmission stage using the stored channel information from previous transmission. In case one of the substreams is found erroneous in the first transmission, it will be retransmitted again whereas for the other correct substream, new data will be sent. In this case, the newer substream will be processed first and will undergo nulling procedure. Once the interference of this newer stream is removed from the overall received signal, the remaining portion will be pre-combined with the stored channel and decision statistics of this retransmitted substream from previous transmission. In case a substream is retransmitted for maximum number of times and does not pass CRC, it is discarded. This scheme requires two parallel HARQ processes for flow control through feedback channel. Although the illustration is based on a two substreams case, it can be easily extended to arbitrary number of substreams.

This scheme does not have an ideal SNR based detection ordering for all substreams, as newer substreams are always detected first to avoid excessive noise power. Nevertheless, limited ordering is applied within the detection of several new substreams, as well as the detection of several retransmitted substreams.

4.5.2 MMARQ with Joint Pre and Post-combining

The proposed MMARQ with pre-combining exploits the advantages of pre-combining. However as the new substreams have to be detected first, it cannot have optimal detection ordering, which is important for OSIC. Hence, we propose a joint pre and post-combining MMARQ with optimal detection ordering. In first transmission, the receiver performs the standard OSIC procedure and store the soft decision statistics of all the substreams after the interference cancellation procedure (nulling). All the substreams are detected and their integrity is checked through CRC check. Those substreams which fail, a corresponding retransmission request is sent to the receiver and ACK is sent for correctly detected substreams. In the next transmission, the transmitter sends newer substreams in place of acknowledged substreams and retransmits the erroneous substreams.

In the proposed scheme, if all substreams fail the CRC check in the first transmission, the receiver will request retransmission of all the substreams. In such a case, the receiver will perform standard pre-combining procedure in the subsequent retransmission. As combining is performed for all substreams in such a case, the optimal detection ordering can be used for OSIC. On the other hand if at least one of the substreams is correct, then the retransmitted signal will have a newer substream along with the retransmitted ones. In such a case post-combining procedure will be employed for the erroneous substreams. The interference cancelled soft decision statistics of previous transmission are combined with the current interference cancelled soft decision statistics for the erroneous substreams. As post-combining only combines the decision statistics, optimal detection ordering can be performed in such a scenario. Fig. 4.13 shows the process of MMARQ with joint pre and post-combining for a two substream case. The system is modelled to carry out the V-BLAST detection similar to MMARQ procedure in [3]. Firstly, the system performs a standard V-BLAST detection

and checks the integrity of substreams through CRC. It also stores the channel information and post-detection decision statistics which can be used later in case the retransmission is needed. Counter i is used to count the number of transmissions of substream A, whereas counter j is used for substream B. In case of first transmission ($i = 1$ or $j = 1$), the system will perform OSIC procedure with standard SNR based ordering and no combining procedure will be done. If both substreams are found erroneous in the first transmission, a request for retransmission is sent to the transmitter through a NACK. In the subsequent transmission, the receiver undergoes a standard pre-combining procedure using the stored channel and soft value statistics from previous transmission.

In case one of the substreams is found erroneous in the first transmission, it will be retransmitted again whereas for the other correct substream, new data will be sent. In the subsequent transmission, the retransmitted substream will undergo standard post-combining procedure by using the stored interference cancelled decision statistics. The OSIC procedure for post-combining also uses the standard SNR based ordering procedure during detection. In case a substream is retransmitted for maximum number of times and does not pass CRC, it is discarded. This scheme requires two parallel HARQ processes for flow control through feedback channel. Although the illustration is based on a two substreams case, it can be easily extended to arbitrary number of substreams.

4.5.3 Simulation Results

Link level throughput results are presented here to demonstrate the performance of the proposed methods. In the simulations, we assume perfect channel knowledge and symbol-synchronization at the receiver, and an error free reverse channel for ACK/NACKs. The system is operated in quasi-static flat Rayleigh fading

channels and employs QPSK modulation. Each data packet contains 496 information bits. A 1/2 rate convolutional coding is used with constraint length $m = 3$ and perfect CRC is assumed for the simulations. The systems are compared based on throughput, which is calculated as

$$\text{Throughput}(\%) = \frac{\text{correct frames}}{\text{Total Tx frames (incl retrans)}} \times 100. \qquad (4.13)$$

The throughput results shown in Fig. 4.14 presents a (4, 4) V-BLAST single-hop system using various HARQ schemes. These simulation results are carried out while keeping the maximum number of transmissions K_{max}=4. The proposed MMARQ methods are simulated and compared with MSARQ and conventional MMARQ. The MMARQ with joint pre and post-combining method has the best throughput performance whereas MMARQ with pre-combining also performs better than conventional MMARQ with post-combining. MSARQ with post-combining scheme performs the worst as it retransmits all the substreams in case of an error. Both the proposed methods exploit the performance advantage of pre-combining scheme. Simulation results clearly demonstrate that the proposed methods can be employed to enhance system throughput of MIMO HARQ systems. Few important aspects about the proposed schemes are highlighted below:

1. The proposed MMARQ with pre-combining scheme is specific to V-BLAST system as the newly sent substream is processed first even if the SNR of retransmitted sub-stream is more. Due to this predefined ordering procedure its performance is slightly worse than MMARQ with joint pre and post-combining method.

2. The advantage of Joint pre and post combining scheme is that it is generic and can be used for V-BLAST as well as other MIMO systems like MLD,

STBC etc. It also performs better than MMARQ with pre-combining scheme.

3. As Joint pre and post combining scheme is generic, we extend our analysis of this proposed scheme to MIMO-MLD system for throughput rate analysis along with V-BLAST in chapter 5. We also use this scheme with STBC based system while evaluating relay-destination link in a multi-hop scenario in chapter 6.

4.6   Summary

In this chapter we have discussed the basics of HARQ systems and various HARQ combining schemes. We also discussed basic concept of Multiple HARQ processes for MIMO systems. Considering the advantages of Multiple HARQ scheme, we presented two novel HARQ combining schemes which utilize better performance advantages of pre-combining method to improve the performance of existing MMARQ techniques. Simulation results demonstrate the throughput performance improvement over the existing post combining based MMARQ scheme.
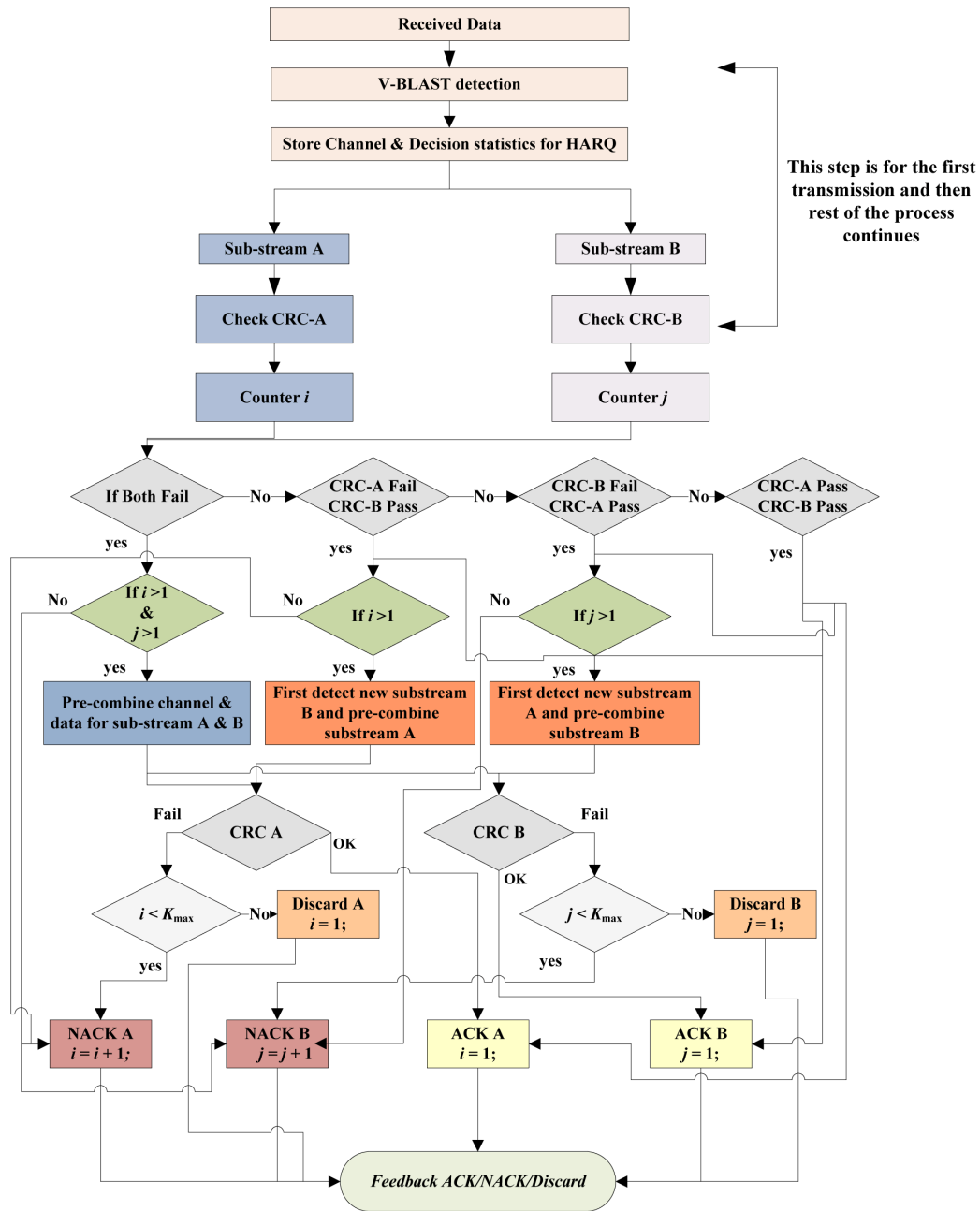
Figure 4.12: Flow Chart of the proposed MMARQ Scheme with pre-combining for 2 substream case.
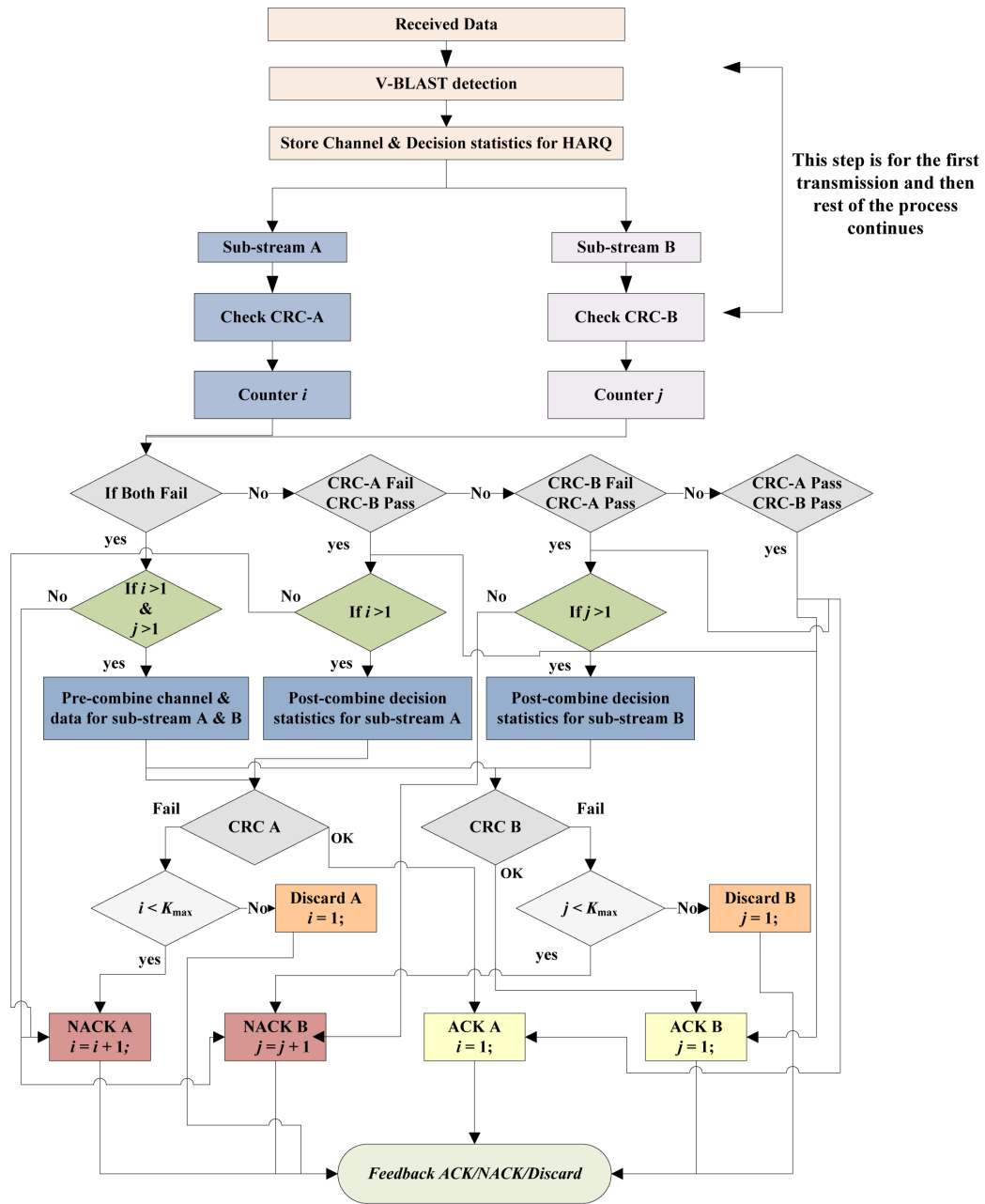
Figure 4.13: Flow Chart of the Proposed MMARQ Scheme for 2 substream case.
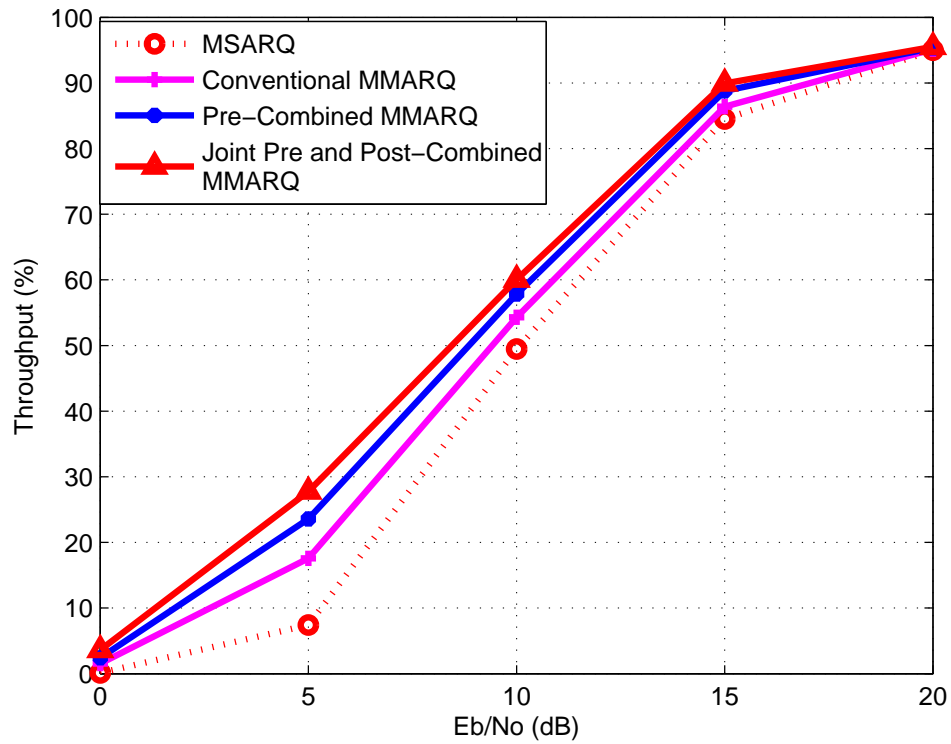
Figure 4.14: Throughput results of proposed MMARQ with Conventional MMARQ and MSARQ schemes for a (4,4) V-BLAST system with a maximum of 4 transmissions allowed for ARQ process.

Chapter 5

Throughput Rate Analysis of MIMO HARQ Systems

5.1   Introduction

In the last chapter, the novel MMARQ schemes are proposed and their throughput performances are evaluated. HARQ based systems are evaluted in terms of throughput of system instead of BER analysis, therefore for throughput capacity analysis of such schemes a detailed throughput rate analysis is performed. HARQ processes involve retransmission process and needs a stop criteria as retransmissions cannot be performed for ever. For information theoretic capacity analysis of a HARQ based MIMO system a throughput metric has been proposed in [62, 63] which is based on cutoff rate. With this method information theoretic capacity of HARQ system can be evaluted by taking care of retransmissions and related critera.

5.2 Throughput Rate Analysis

This section presents the analysis of MIMO HARQ schemes by means of a cutoff rate based throughput metric. An upper bound on the throughput rate of conventional post-combining MIMO-HARQ processing was proposed in [62, 63] by utilizing the conditional cutoff rate. The same approach is used to analyse our proposed schemes and highlight the advantages over conventional post combined methods. For comparison purposes, we also evaluate the throughput for Maximum Likelihood Detection (MLD) along with the V-BLAST based schemes. For brevity and completeness, some of the important expressions from [62, 63] are revisited here.

5.2.1 HARQ

To evaluate the Throughput of a HARQ based system the expression is developed on the basis of renewel-theory [68]. If average probability of each user accessing the channel is denoted by $\bar{p}$, meaning that each user is allowed to transmit a message with probability $\bar{p}$ in each transmission interval whereas doesnot transmit with probability $1 - \bar{p}$. Therefore, only one single user transmits in one transmission interval. In case of multiple users, single user MIMO channel signal model is extended to allow multiple access as per [69], [70]. Every user maintains its own HARQ process independently of the other users who are likely to transmit. This analysis is carried out under following assumptions.

1. We assume an delay free and error free feedback channel.

2. There is an infinite buffer space available to each user at receiver.

Throughput per user can written as

$$\eta = \lim_{l \to \infty} R\left(l\right)/l, \quad [b/s/Hz] \tag{5.1}$$

where $R(l)$ is the mutual information (bits per second per Hertz) successfully decoded up to slot l and is termed as throughput rate of the transmission. Stoppage of packet transmission is a recurrent random event and is denoted by $\mathbf{R}$. By using renewal-reward theorem [71], we get

$$\eta = E\{\mathbf{R}\}/E\{\mathbf{T}\}, \qquad (5.2)$$

where $\mathbf{R}$ is the random reward. In case transmission stops due to successful decoding then $\mathbf{R} = R$ b/s/Hz whereas in case of a failure $\mathbf{R} = 0$ b/s/Hz. The random variable $\mathbf{T}$ is called inter-renewal time and denotes the time taken between two consecutive recurrent events. There needs to be a stop criteria for maximum allowed transmissions in case a packet remains in error after repeated re-transmissions. If we denote maximum number of transmissions per packet by K_{max}, then transmission will stop if packet is successfully decoded at receiver at k-th transmission with $k < K_{max}$ or no successful decoding is possible till maximum number of allowed transmissions are reached i.e, $k = K_{max}$. If we consider A_k as an event of successful decoding of the packet within maximum allowed transmissions K_{max}, then $\bar{A}_k$ will be an event of unsucessful decoding at k-th transmission. In case of HARQ protocol, if decoding of a current packet fails in k-th attempt as well as all previous $k-1$ transmissions, then probability of unsuccessful decoding at k-th transmission will be written as

$$p(k) = P\{\bar{A}_1, \ldots, \bar{A}_k\}, \qquad (5.3)$$

Similarly, the probability of a successful decoding at the k-th transmission will be represented as

$$q(k) = P\{\bar{A}_1, \ldots, \bar{A}_{k-1}, A_k\} = p(k-1) - p(k), \qquad (5.4)$$

In HARQ the transmissions are restricted only to a maximum number of transmissions per packet ($k \leq K_{max}$) therefore, sometimes termed as truncated HARQ [71]. Therefore, expression in (5.2) can be simplified for per user throughput [62,63] by

$$\eta = \frac{R\left(1 - p\left(K_{max}\right)\right)}{\sum_{k=1}^{K_{max}} p\left(k\right)},$$
(5.5)

where $p\left(0\right) = 1$ as per definition [61]. Equation (5.5) represents cross-layer throughput metric for HARQ processes. $p\left(k\right)$ is the probability of unsuccessful decoding at physical layer.

5.2.2   MIMO MLD HARQ with Post Combining

An information theoretic method proposed in [62,63] evaluates the system performance of MIMO HARQ for post combining. Decoding in case of SISO channels is carried out after the receipt of k transmission in [72]. The probability of decoding failure is provided by information outage probability for large codeword lengths L [73] and the information message is conveyed in M blocks. The communication system uses L super symbols by joining together k symbols sending each in a different block. The fading channel is realized as a time-invariant memoryless channel. The reliability of transmissions is high if coding rates are close to conditional mutual information for very large L. The conditional mutual information is considered over k blocks with conditioning being on a block fading channel. If the trasmission rate is below the conditional mutual information over $k \leq K_{max}$ then there will be zero error codeword probabilty for each set encoder ($k \leq K_{max}$) with random codes with set decoding property [70]. This provides a guideline for the evaluation of coodeword analysis by investigation of information outage probability. In case statistically independent block fading is assumed then the conditional mutual information over $k \leq K$ transmissions can be found as

$$I^k_{|\{\mathbf{H}\}} = \sum_i I_{|\mathbf{H}_i}, \tag{5.6}$$

where $I_{|\mathbf{H}_i}$ is a conditional mutual information for i-th transmitted block and $\mathbf{H}_i$ as channel realization. Here i represents index for transmitted block in each transmission and k represents the number of retransmissions done for that particulr transmission block. The transmitted block is discarded once k approaches K_{max}. These expressions are based on the proposed cutoff rate metric in [62,63]. Index i ranges from 1 to k. Maximum value of index k can be equal to K_{max} where we use a moderate value, $K_{max} = 4$ in this thesis. Use of higher value of K_{max} than 4 can introduce increased delay due to high number of retransmissions, whereas lower value than this does not provide much advantage of HARQ. Existing literature also uses $K_{max} = 4$ as in [62,63]. For circularly symmetric Gaussian inputs, we can write

$$I_{|\mathbf{H}_i} = \log_2 \det \left(\mathbf{I} + \frac{P}{N_t N_0} \mathbf{H}_i \mathbf{H}_i^H \right) \tag{5.7}$$

Extending the above to MIMO transmissions, random space-time encoding is assumed with each space-time codeword having M set codewords with length L. The expression for the probability of unsuccessful decoding in k-th transmission block can be written as

$$P_{out} = P \left\{ I^k_{|\{\mathbf{H}\}} < R \right\}. \tag{5.8}$$

R represents the transmission rate in b/s/Hz. If we consider A as constellations size, then $R \leq N_t \log_2(A)$. The code symbols are drawn from a scalar constellation and throughput analysis $(R_{0|\mathbf{H}_i})$ are developed on the basis of cutoff rate instead of using mutual information of discrete modulations. The conditioning is on the fading channel and expression for an equally likely transmit vector $\mathbf{s}$ is

$$2^{-\mathbf{R}_{0|\mathbf{H}_i}} = \int_{\mathbf{y}} \left[\frac{1}{A^{N_t}} \sum_{\mathbf{s}} \sqrt{f_{\mathbf{y}}\left(\mathbf{y}|\mathbf{s}, \mathbf{H}_i\right)} \right]^2 d\mathbf{y}, \tag{5.9}$$

where $\sqrt{f_{\mathbf{y}}\left(\mathbf{y}|\mathbf{s}, \mathbf{H}_i\right)}$ is the channel pdf. Conditional cutoff rate can be written as [74]

$$R_{0|\mathbf{H}_i} = \log_2 \left(\frac{1}{A^{N_t}} + \frac{\sum_{\mathbf{s}} \sum_{\mathbf{s} \neq \mathbf{z}} \beta\left(\mathbf{s} \to \mathbf{z}|\mathbf{H}_i\right)}{A^{2N_t}} \right)^{-1} \tag{5.10}$$

Here,

$$\beta\left(\mathbf{s} \to \mathbf{y}|\mathbf{H}_i\right) = \exp\left(-\frac{P}{4N_t N_0} \|\mathbf{H}_i\left(\mathbf{s} - \mathbf{z}\right)\|_F^2 \right), \tag{5.11}$$

is the Chernoff upper-bound on the probability that the receiver decodes transmitted codeword $\mathbf{s}$ as codeword $\mathbf{z}$ assuming Maximum Likelihood Decoding (MLD). Therefore, the cutoff rate over $k \leq K_{max}$ transmissions is

$$R_{0|\{\mathbf{H}\}}^k = \sum_i^k R_{0|\mathbf{H}_i}. \tag{5.12}$$

$R_{0|\{\mathbf{H}\}}^k$ is the sum of k conditional cutoff rates reflecting the memory of HARQ process.

As for any channel realization $I_{|\mathbf{H}_i} \geq R_{0|\mathbf{H}_i}$, thus we can use (5.6) and (5.12) as upper bound for finding the codeword error probability at the k-th transmission by

$$P\left\{ I_{|\{\mathbf{H}\}}^k < R \right\} < P\left\{ R_{0|\{\mathbf{H}\}}^k < R \right\}. \tag{5.13}$$

As per the outage probability based on cutoff rate (upper bound) the event of unsuccessful decoding for k-th transmission block will be

$$\bar{A}_k = \left\{ R_{0|\{\mathbf{H}\}}^k < R \right\}. \tag{5.14}$$

In the information theoretic considerations the memory of HARQ-protocol

has been neglected. The probability of unsuccessful decoding at k-th transmission block for HARQ protocol was considered in (3.23). Also, we have $R_{0|\mathbf{H}_i} \geq 0$ for any specific $\mathbf{H}_i$. Therefore, the random sequence $R^1_{0|\{\mathbf{H}\}} \ldots R^k_{0|\{\mathbf{H}\}}$ is nondecreasing with probability 1. Then, $\bar{A}_k \subseteq \bar{A}_l$ for all $k \geq l$ and therefore,

$$p(k) = P\left\{\bar{A}_1, \ldots, \bar{A}_k\right\} = P\left\{\bar{A}_k\right\}. \tag{5.15}$$

Inserting (5.14) in (5.15), we get

$$p(k) = P\left\{R^k_{0|\{\mathbf{H}\}} < R\right\}, \tag{5.16}$$

where $R \leq N_t \log_2(A)$. To calculate the throughput of MIMO-HARQ, (5.16) is inserted in (5.5) which gives the following expression

$$\eta = \frac{R\left(1 - P\left\{R^{K_{max}}_{0|\{\mathbf{H}\}} < R\right\}\right)}{\sum_{k=1}^{K_{max}} P\left\{R^k_{0|\{\mathbf{H}\}} < R\right\}}. \tag{5.17}$$

Here cutoff rate is similar to the calculation of outage. The throughput rate of each transmission is calculated and then compared to the target cutoff rate for the decision of success or faliure. In case of a failure, throughput rate of the retransmission is combined to the previous transmission throughput rate and then compared to the target cutoff rate. This procedure continues till the combined throughput rate becomes greater than target rate or maximum number of retransmissions ($k = K_{max}$) is reached. In such a case the packet is discarded.

5.2.3 MIMO MLD HARQ with Joint Pre-Post Combining

We present the analysis of proposed joint pre-post combining scheme which is generic and can be used for MIMO MLD systems. MMARQ with pre-combining scheme uses predefined ordering procedure therefore, cannot be analyzed for

MIMO MLD. In joint pre-post scheme, if all substreams fail the CRC check, the receiver will request retransmission of all substreams and upon receiving the retransmitted substreams, the standard pre-combining procedure is followed. In such a case the channel statistics of current transmission are pre-combined with the channel of the previous transmission. Therefore, the combined channel for pre-combining cutoff rate will be

$$\mathbf{H}_{pre} = \sum_{i}^{k} \mathbf{H}_i^H \mathbf{H}_i. \tag{5.18}$$

The cutoff rate equation (5.10) will use the combined channel staistics and can be written as

$$R_{0|\mathbf{H}_{pre}} = \log_2 \left(\frac{1}{A^{N_t}} + \frac{\sum_{\mathbf{s}} \sum_{\mathbf{s} \neq \mathbf{z}} \beta\left(\mathbf{s} \to \mathbf{z} | \mathbf{H}_{pre}\right)}{A^{2N_t}} \right)^{-1}. \tag{5.19}$$

Here once all the substreams are in error then channel and cutoff rates are combined for all the retransmissions whereas in case one of the substream is in error then only cutoff rates are combined. The final cutoff rate for k retransmissions in case of all substreams in error will be calculated as

$$\eta = \frac{R\left(1 - P\left\{R_{0|\{\mathbf{H}_{pre}\}}^{K_{max}} < R\right\}\right)}{\sum_{k=1}^{K_{max}} P\left\{R_{0|\{\mathbf{H}_{pre}\}}^{k} < R\right\}}. \tag{5.20}$$

5.2.4 V-BLAST-MMSE for Post Combining

The cutoff metric is applied to V-BLAST scheme with MMSE detection [62, 63]. The data streams are seperately encoded and transmitted from various transmit antennas. Every antenna maintains an independent HARQ processing. The MMSE matrix is estimated by

$$\mathbf{W} = \sqrt{\frac{N_t}{P}} \left[\mathbf{H}_i \mathbf{H}_i^H + \left(\frac{N_t}{P}\right) N_0 \mathbf{I}_{N_t}\right]^{-1} \mathbf{H}_i, \tag{5.21}$$

while MMSE covariance matrix can be written as

$$\mathbf{Q}_i = \left(\mathbf{I}_{N_t} + \frac{P}{N_t N_0} \mathbf{H}_i \mathbf{H}_i^H \right)^{-1}. \tag{5.22}$$

The SINR for the post processed l-th substream is represented as

$$\gamma_{l,i} = \left([\mathbf{Q}_i]_{l,l} \right)^{-1} - 1. \tag{5.23}$$

where, $[\mathbf{A}_{l,l}]$ denotes the l-th diagonal element of a matrix $\mathbf{A}$. All substreams go through MMARQ dectection where each substream has its own independent HARQ process and a cutoff rate for each substream is calculated independently. Therefore, cutoff rate per substream for QPSK modulation can be calculated as

$$\mathbf{R}_{0,l,i} = -\log_2 \left(\frac{1}{q} \sum_{j=0}^{q-1} \exp \left(-\gamma_{l,i} \sin^2 \left(\pi j / q \right) \right) \right), \tag{5.24}$$

where $q = 2$ for BPSK and $q = 4$ for QPSK modulation, j is used as index for q whereas index i keeps track of transmitted block in each transmission. The codeword error probability per substream is expressed as

$$p_l(k) = P \left\{ R_{0|\{\mathbf{H}\}}^{k,l} < \frac{R}{N_t} \right\}, \tag{5.25}$$

with $R_{0|\{\mathbf{H}\}}^{k,l} = \sum_{i}^{k} \mathbf{R}_{0,l,i}$. R/N_t is the data rate per substream. By substituting (5.25) in (5.5) we can obtain per substream throughput η_l. Therefore, the total throughput of all substreams will be sum of all individual substream throughputs and can be written as $\eta = \sum_{l=1}^{N_t} \eta_l$.

5.2.5   V-BLAST-MMSE with Joint Pre-Post combining

Similar to MLD based cutoff metric for joint pre-post combining, if all substreams fail the CRC check, the standard pre-combining procedure is followed. The channel gains of previous transmissions are pre-combined with current retransmission as per (5.18). The MMSE covariance matrix can be written as

$$\mathbf{Q}_i = \left(\mathbf{I}_{N_t} + \frac{P}{N_t N_0} \mathbf{H}_{pre} \mathbf{H}_{pre}^{H} \right)^{-1}. \tag{5.26}$$

The SINR for the pre-combined l-th substream is represented as

$$\gamma_{l-pre,i} = \left(\left[\mathbf{Q}_{pre,i} \right]_{l,l} \right)^{-1} - 1. \tag{5.27}$$

where, $[\mathbf{A}_{l,l}]$ denotes the l-th diagonal element of a matrix $\mathbf{A}$. As joint pre-post combining scheme uses pre-combining when all the substreams are erroneous, therefore all substreams are detected and cutoff rate for each substream is calculated independently. While using individual cutoff rates, individual substream is calculated. The total throughput of all substreams will be sum of all individual substream throughputs and can be written as $\eta = \sum_{l=1}^{N_t} \eta_l$. In case one of the substreams is correct, conventional post-combining procedure is employed for the erroneous substreams.

5.3   Simulation Results and Analysis

The throughput rate versus cutoff rate R for MIMO-MLD and MIMO V-BLAST schemes are evaluated. QPSK modulation is assumed with SNR being set to $P/N_0 = 0$ dB. A $(4,4)$ MIMO configuration is considered and $K_{max} = 4$. For MIMO transmissions the cutoff rate is set at $R \leq 8$ b/s/Hz. Fig. 5.1 shows throughput results of MIMO-MLD with post-combining (conventional) and joint

pre-post combining (proposed). It also presents results of V-BLAST MMARQ post-combining (conventional) and joint pre-post combining (proposed). The details are as under:

- MIMO MLD result show that the proposed scheme provides throughput capacity gain once the cutoff rate is above 2.5 and this gain becomes very high at higher values of cutoff rate.

- MIMO V-BLAST result again shows throughput capacity gain from cutoff rate values of 2 to 8.

- Both the results highlight the importance of the proposed joint pre-post scheme, where it outperforms the conventional post combined scheme. This result indicates that the proposed scheme is generic and useful to be used for MIMO systems.

The results related to MSARQ post-combining, MMARQ post-combining schemes are compared with proposed joint pre-post combining scheme in Fig. 5.2. The details are as below:

- The result with no HARQ combining indicates the advantages of HARQ based MIMO schemes over no HARQ. All the schemes perform way better than no HARQ case.

- MSARQ is an inefficient scheme as compared to other MMARQ schemes and results do confirm this fact. MMARQ post-combining performs better than MSARQ.

- The proposed joint pre-post combining scheme outperforms all the MIMO HARQ schemes. The proposed scheme can be very useful for MIMO HARQ systems.
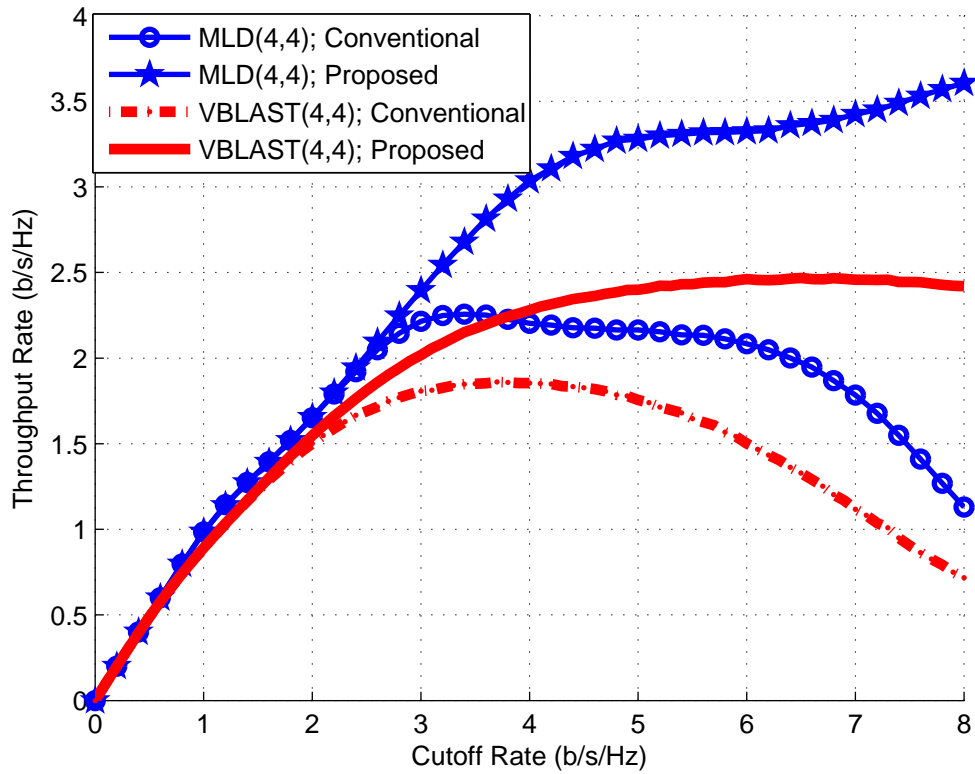
Figure 5.1: Throughput rate results of a (4,4) MIMO-MLD and MIMO V-BLAST systems with post-combined HARQ and Joint pre-post combining with $K_{max} = 4$.
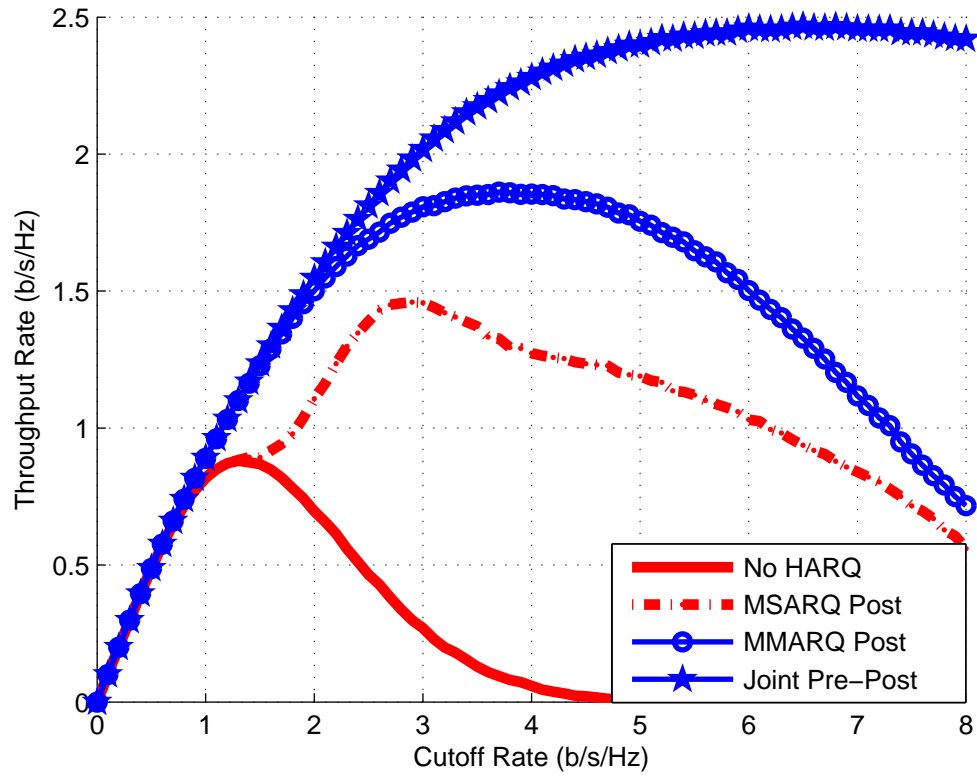
Figure 5.2: Throughput rate results of MIMO (4, 4) V-BLAST system with MSARQ Post-combining, MSARQ Pre-combining, MMARQ Post-combining and proposed MMARQ schemes with $K_{max} = 4$.

5.4 Summary

In this chapter we have presented a detailed throughput rate analysis of our proposed novel MMARQ scheme along with existing MSARQ and MMARQ schemes. The analysis is based on cutoff rate based throughput metric which is utilized to calculate the throughput rate of HARQ based systems. We compared the performance of our proposed HARQ combining scheme with existing MSARQ and MMARQ schemes and shown that the proposed scheme performs better than all the existing schemes for both MIMO MLD and MIMO V-BLAST based HARQ systems.

Chapter 6

MIMO HARQ Multi-hop Relay Systems

6.1 Introduction

In this chapter we present the basics of MIMO multi-hop relay systems. Then we extend the existing as well as proposed MIMO HARQ techniques into the multi-hop scenario. We present system implementation of all schemes as well as carry out capacity analysis of the proposed and existing schemes in detail. At the end, we present a delay analysis for all the schemes.

6.2 Multi-hop Relay Communication

Diversity techniques are used to improve the signal performance in a wireless channel. There has been a growing interest in the use of relay based techniques, where a relay station helps the source to extend the transmitted signal to a distant user. In this model the source (S) first transmits the data to the relay (R) and then relay forwards the data after processing to the destination. The model can be decomposed into two channels, i.e., source-relay channel (source transmits and

relay receives) and relay-destination channel (relay transmits and the destination receives).
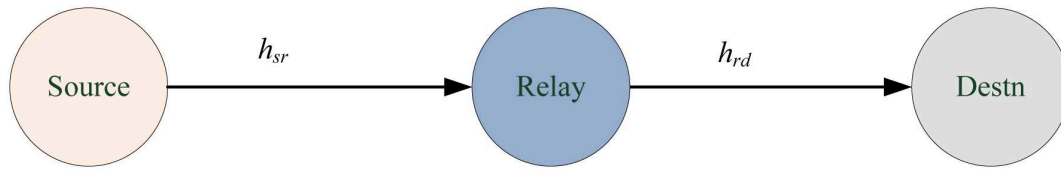
Figure 6.1: The single relay cooperative communication network.

Multi-hop techniques have received lot of attention, probably because of their inherent simplicity and direct application. Multi-hop techniques are being considered for cellular networks, where, in addition to enlarging the coverage area, they will help guaranteeing high data throughput even at the cell edge. Multi-hop techniques usually exploit two basic approaches, namely amplify-and-forward (ANF) [9] and decode-and forward (DNF) [11,75]. The relay station always assists the transmitter by forwarding the information from source to destination node. In the case of ANF, the relay amplifies the signal and retransmits it to the destination node. In DNF, the relay decodes, re-encodes and re-transmits the signals to the destination node. These multi-hop techniques are explained in the next subsection.

6.3   Classification of Relaying Techniques

Basic relay techniques ANF, DNF and coded relaying are discussed in the following subsections.

Amplify and Forward

This method was proposed by Laneman *et al.* [9,10] and is the most simple of relay signalling methods. In this method relay amplifies and retransmits the noisy

version of the signal. Source node signal travels lesser distance due to indroduction of relay and therefore, experiences lesser path loss. The overall transmit power of a relay based system is normalized to a corresponding single-hop link. The relay node helps in the extension of transmitted signal to larger distances without any increase in the overall transmit power. A three node cooperative network containing the source, relay and destination nodes is shown in the Fig. 6.2.
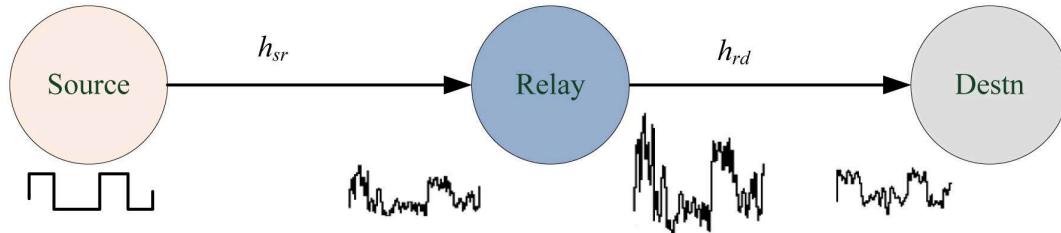
Figure 6.2: Amplify and forward cooperative scheme.

The downfall of this protocol is the noise amplification at the relay. But we save a lot of computing power and the complexity level is quite low. Considering this scheme with the relay node transmitting at the same frequency as the source node but in the next time slot. The signal received at the relay node from the source in the first time slot can be represented as

$$y_{sr}(t) = s(t) \sqrt{E^s} h_{sr} + n_r(t) \tag{6.1}$$

where $s(t)$ is the transmitted signal from the source node with unit energy at time t, E^s is the transmitted signal energy from the source node, h_{sr} is the normalized channel gain from the source to the relay node and is modeled as Rayleigh flat fading channel, and $n_r(t)$ captures the effect of AWGN at the relay node.

In the second time slot, the relay node amplifies the received signal from the

source node and forwards it to the destination node

$$y_{rd}(t + T) \quad = \quad \beta \; y_{sr}(t) \; h_{rd} + n_d(t + T) \tag{6.2}$$

where T is the time slot or frame duration, and β is the amplification factor at the relay, h_{rd} is the normalized channel gain from relay to the destination that is also modeled as Rayleigh flat fading channel, and $n_d(t+T)$ is the AWGN at the destination.

Decode and Forward

In this method the relay decodes the user data sent from the source. It then re-encodes and re-transmits it to the destination. This type of relay technique was first proposed by Sendonaris, Erkip and Aazhang as a cooperative signalling scheme in [11, 75]. The first phase of this scheme is similar to the ANF where the source node sends the information signal to the relay node as given by (6.1). In the second phase, assuming the decoded signal at the relay node is denoted by $\hat{s}(t)$, the transmitted signal from the relay to the destination is given by

$$y_{rd}(t + T) \quad = \quad \hat{s}(t) \; \sqrt{E^s} \; h_{rd} + n_d(t + T). \tag{6.3}$$

A three node relay network containing the source, relay and destination nodes is shown in the Fig. 6.3. The relay decodes the signal from source unlike ANF scheme.
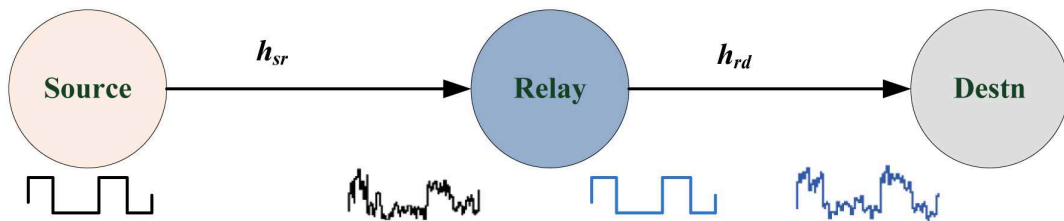
Figure 6.3: Decode and forward cooperative scheme.

6.3.1   Coded Relaying

In the relay based schemes discussed previously, a relay may either simply forward the analog signal received from the source or retransmit estimates of the received symbols, obtained via hard detection. The coded cooperation is different from previous schemes as it integrates user cooperation with channel coding [12]. Instead of repeating some form of the received signal, the relay decodes the source's transmission and transmits additional parity information according to overall coding scheme. The relay employs error checking such as cyclic redundancy check (CRC) code to avoid transmitting erroneous data. Fig. 6.4 illustrates the coded cooperative network.
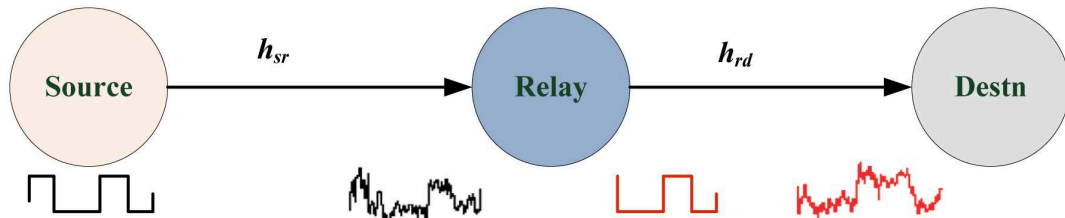
Figure 6.4: Coded cooperative scheme.

6.4   Multi-hop Relaying Implementation

Multi-hop relay system offers a relative path loss advantage compared to a direct link in specific conditions [76]. It is due to the shorter distances between the nodes as compared to direct link. To provide a fair comparison between single-hop and multi-hop, path loss is considered as

$$L_p \left(dB \right) = 10 \, \log \, \alpha \left(d/d_0 \right)^\gamma , \tag{6.4}$$

where d is the transmitter-receiver separation, d_0 is a close reference point and α is a constant of proportionality. The path loss exponent is denoted by γ. In

case of two-hop, the relay is placed at the mid-point. Thus, with the same total transmit power and source to destination distance, a two-hop link experiences less combined path loss compared to single-hop case. Therefore, this relative gain due to path loss can be termed as *relative pathloss advantage.* Use of relay systems provide a promising solution for extending the coverage of the classical cellular networks.

6.4.1 Scenario-I: SISO Multi-hop relay

A simple scenario is considered where a direct SISO link performance was compared with a relayed DNF SISO system considering the relative path loss advantage. In this scenario relative path loss advantage of 6 dB has been considered. The effect of direct signal in case of multi-hop relay is not considered and the distance is assumed to be 100 meters from source to destination. Fig. 6.5 shows the simulation results of QPSK SISO direct link and QPSK SISO with an intermediate relay node under multi-hop relay arrangement. The BER performance shows that two-hop link performs better than single-hop due to the relative path loss advantage.

6.4.2 Scenario-II:MIMO STBC Multi-hop relay

To investigate the effects of path loss and MIMO Multi-hop sytems, STBC based multi-hop system is considered. A (2,2) STBC system is simulated with and without relay node. Fig. 6.6 shows a MIMO multi-hop DF relay arrangement used for the simulations. The simulation results in Fig. 6.5 show that a relay based (2,2) STBC Multi-hop performs better than direct link STBC. The effect of relative path loss advantage was considered for the calculating the receive SNR of the two-hop link as compared to the direct link receive SNR as a reference. The analysis shows that multi-hop STBC link performs better than direct link
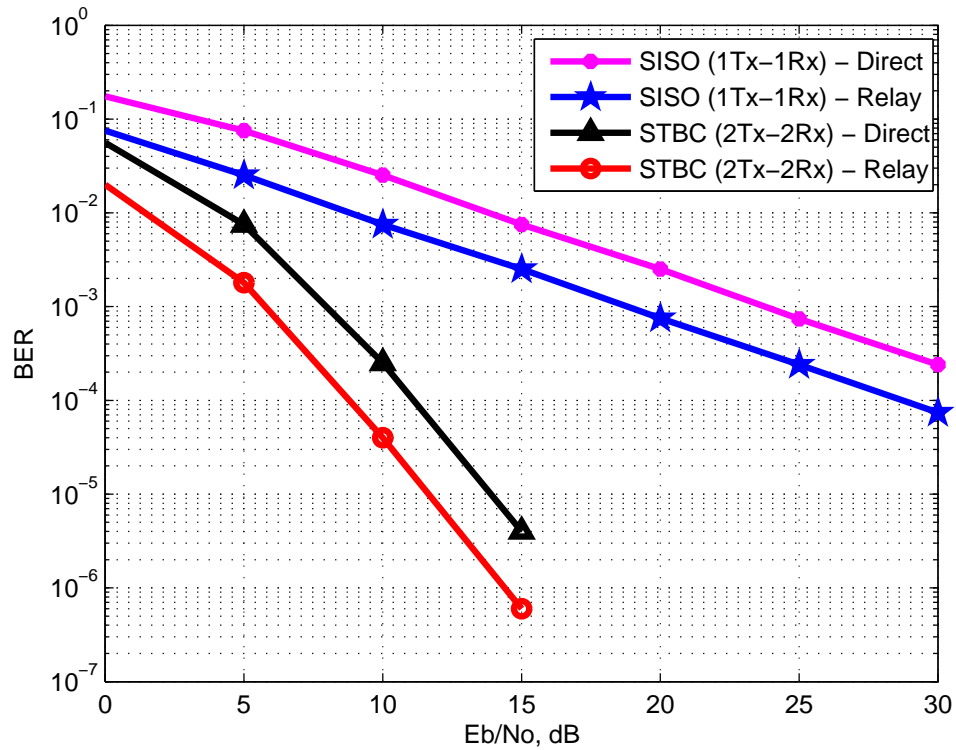
Figure 6.5: BER performance comparisons of SISO and STBC single and multi-hop relay arrangements. Effect of relative path loss advantage has been considered for the multi-hop systems as compared to single-hop.

due to the relative path loss advantage.
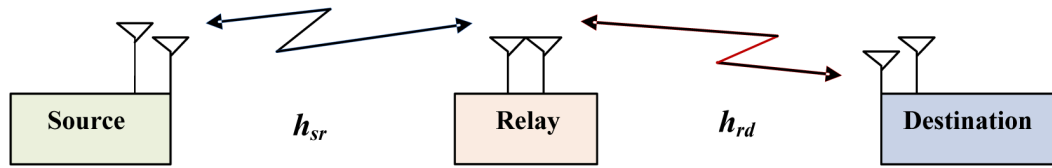
Figure 6.6: A MIMO multi-hop DF relay arrangement.

6.4.3 Scenario-III:MIMO Transmit Delay Diversity Multi-hop relay

STBC scheme is quite useful for DNF relay systems. However, to improve the performance of ANF relay systems a delay diversity scheme can be considered [77] in which delay of one symbol is introduced to artificially induce Inter-symbol interference at the intermediate node for exploiting diversity at the destination with use of a frequency domain equaliser. Fig. 6.7 shows a system model with relay node used for introducing delay diversity.
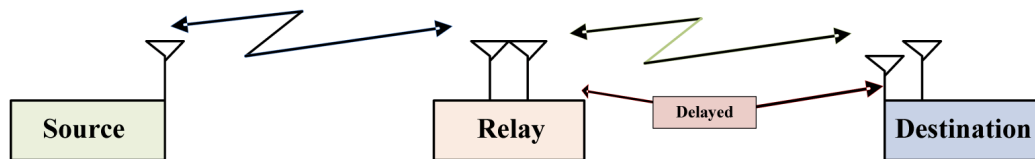
Figure 6.7: A MIMO multi-hop ANF relay arrangement where the relay introduces delay to one of the signals before transmitting it to destination.

Considering ANF system, concept of delay diversity is used at the intermediate node. The signal from the source is received at the intermediate node, which amplifies it and intentionally introduces delay to one of the signals. This delay creates intentional ISI at the receiver. The receiver can use an equalizer to detect the received signal and remove the ISI. Fig. 6.8 presents a BER comparison of
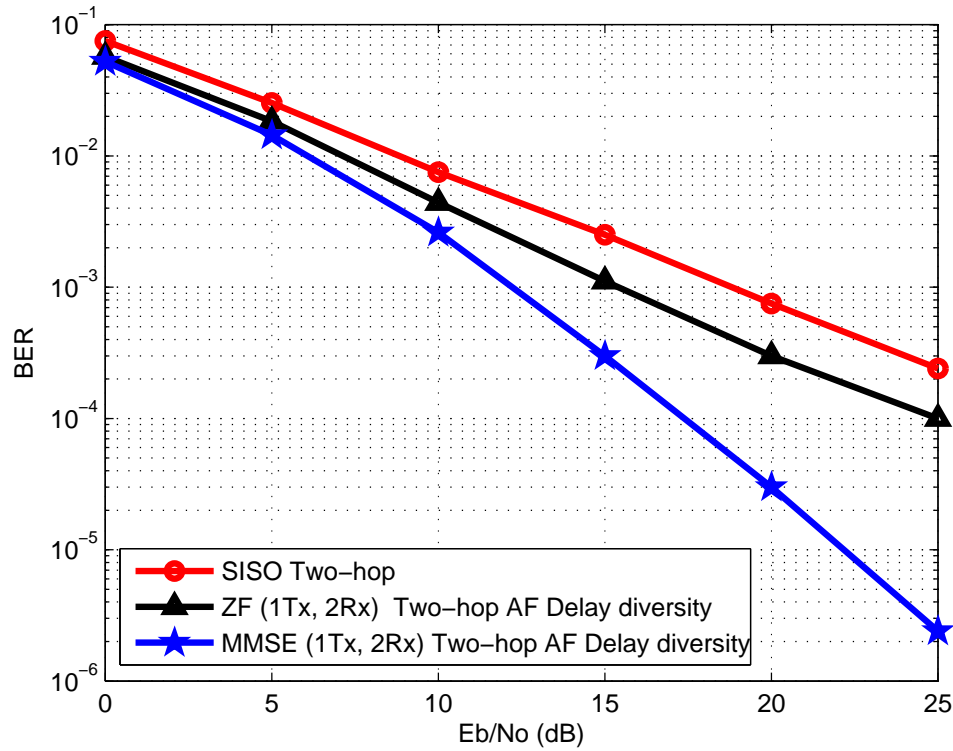
Figure 6.8: Simulated BER performance comparison of Delay diversity based ZF and MMSE ANF relay systems.

ZF and MMSE based ANF delay diversity results. The scenario definitely highlights that Transmit delay diversity does perform well for ANF multi-hop systems. ANF systems are simpler to implement and require less processing requirements, whereas DNF systems require relatively more processing requirements at the intermediate node. Therefore, both the systems have their significance and can be used as per their requirement and application of use.

6.5   MIMO HARQ Multi-hop Relay Systems

Multi-hop relay transmission improves coverage as well as overall throughput of a wireless communication system [21]. Considering a two-hop relay system where the relay station (RS) is employed at mid-point between the source and

destination. It is capable of decoding and forwarding the signal and can generate its own feedback to the source node. A SISO based Relay ARQ system in [78] uses a relay acknowledgement (RACK) to inform the source that the packet is received correctly at the relay. The advantage of RACK is that in case a data unit reaches the RS correctly but not at the destination, the source will not retransmit it again. The responsibility of forwarding this packet to the destination shifts to the RS. Based on the RACK concept, we propose a new MMARQ relay protocol using the proposed MIMO HARQ processes. As MMARQ uses N_t parallel substreams, independent ACKs/NACKs are used to control each parallel HARQ process. Basic operation of the proposed protocol is as follows:

1. All the substreams will be transmitted to the relay. If a substream is received correctly, the RS will send a RACK to the source, and forwards the substream to the destination.

2. If a substream is in error, a NACK will be sent to the source requesting a retransmission for that substream. Upon receiving the NACK, the source will then retransmit the erroneous substream together with new substreams on other antennas. RS will perform one of the proposed MMARQ combining operations.

3. In case the destination node does not receive a substream correctly from the RS, it sends a NACK to the RS. The RS will then retransmit this substream, together with new substreams to the destination. When the retransmitted substream is received, the destination node will perform the proposed MMARQ combining and checks its integrity again.

4. If the number of substreams to be forwarded by the RS is less than the number of transmit antennas, the RS will utilise all the transmit power for these substreams. With less substreams to send, the receiver takes

advantage of receive diversity. This will improve the signal quality at the destination node and will improve the overall performance of the system.

6.5.1 Link Level Simulation Results

The performance of the proposed MMARQ relay protocol is presented in Fig.6.9. A two-hop 4×4 relay system is considered with $K_{max} = 4$. A $1/2$ rate convolutional code in single-hop case is used. To provide a fair comparison between single-hop and multi-hop, path loss is considered as in (6.4). The distance d is set to be 500 meters. For the case of two-hop, the relay is placed at the mid-point. A two-hop link will have a 6dB relative path loss advantage compared to single-hop case. Single-hop MSARQ and MMARQ with post-combining are compared with two-hop MMARQ schemes to highlight the throughput performance advantage achieved by use of a relay node. Simulation results show that throughput performance of MMARQ based schemes is significantly better than single-hop MMARQ, whereas the proposed joint pre and post-combining method performs the best.

6.5.2 Throughput Rate Results and Analysis

Cutoff rate analysis for multi-hop MIMO MLD and V-BLAST is presented considering relative path loss advantage.

Multi-hop MIMO MLD

Considering the throughput analysis of a multi-hop MIMO MLD, the cutoff rate is calculated for source to relay link and relay to destination link. In case the throughput rate of source-relay link is greater than the cutoff rate of source-relay link, then it is considered as a successful reception. The successful substreams
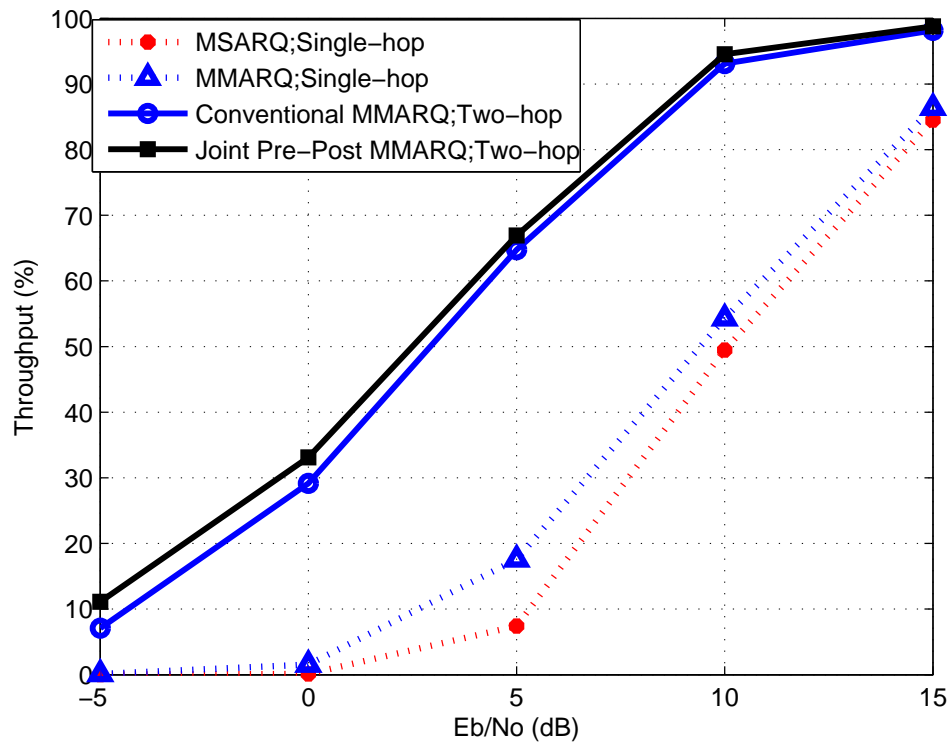
Figure 6.9: Throughput results of proposed joint pre and post-combining scheme employed in a two-hop relay system with Conventional MMARQ and MSARQ schemes for a (4,4) V-BLAST system. The value of $K_{max} = 4$

are forwarded to destination link by computing the throughput rate of relay-destination link. In case the throughput rate of relay-destination link is higher than the cutoff rate, then we consider that the data sunstreams reached the destination successfully. For source to relay link, cutoff rate $(R_{0|\mathbf{H}_{sr}})$ is developed while considering the conditioning on the source-relay fading channel $\mathbf{H}_{sr}$ as in [74] and expression for an equally likely transmit vector $\mathbf{s}$ is

$$2^{-\mathbf{R}_{0|\mathbf{H}_{sr}}} = \int_{\mathbf{y}} \left[\frac{1}{A^{N_t}} \sum_{\mathbf{s}} \sqrt{f_{\mathbf{y}}\left(\mathbf{y}|\mathbf{s}, \mathbf{H}_{sr}\right)} \right]^2 d\mathbf{y}, \tag{6.5}$$

where $\sqrt{f_{\mathbf{y}}\left(\mathbf{y}|\mathbf{s}, \mathbf{H}_{sr}\right)}$ is the channel pdf of source to relay link. Conditional cutoff rate for this link can be written as

$$R_{0|\mathbf{H}_{sr}} = \log_2 \left(\frac{1}{A^{N_t}} + \frac{\sum_{\mathbf{s}} \sum_{\mathbf{s} \neq \mathbf{z}} \beta\left(\mathbf{s} \to \mathbf{z}|\mathbf{H}_{sr}\right)}{A^{2N_t}} \right)^{-1} \tag{6.6}$$

Here,

$$\beta\left(\mathbf{s} \to \mathbf{z}|\mathbf{H}_{sr}\right) = \exp\left(-\frac{L_p(P/2)}{4N_t N_0} \left\| \mathbf{H}_{sr}\left(\mathbf{s} - \mathbf{y}\right) \right\|_F^2 \right), \tag{6.7}$$

is the Chernoff upper-bound on the probability that the receiver decodes transmitted codeword $\mathbf{s}$ as codeword $\mathbf{z}$ assuming Maximum Likelihood Decoding (MLD). L_p denotes the relative pathloss advantage as compared with a single-hop source to destination link. We divide the total transmit power P of source-relay as well as relay-destination links by 2 to normalize it to that of a single-hop system. This makes the total transmit power of two-hop and single-hop systems equal and provides a fair comparison of both the systems. Similar to (6.7), the equation for relay-destination link can be written as

$$\beta\left(\mathbf{s} \to \mathbf{z}|\mathbf{H}_{rd}\right) = \exp\left(-\frac{L_p(P/2)}{4N_t N_0} \left\| \mathbf{H}_{rd}\left(\mathbf{s} - \mathbf{y}\right) \right\|_F^2 \right). \tag{6.8}$$

Therefore, the cutoff rate over $k \leq K_{max}$ transmissions for source-relay link is

$$R_{0|\{\mathbf{H}_{sr}\}}^k = \sum_i^k R_{0|\mathbf{H}_i}.$$

(6.9)

Cutoff rate of relay-destination is calculated in the similar manner. The above equations are true for MIMO-MLD post combining scheme. In case of proposed joint pre-post combining scheme for MLD, once all the substreams are found in error, the channel statistics of current transmission are pre-combined with the channel of the previous transmission. Each muli-hop link, uses independent HARQ processes and combining operation. Therefore, the combined channel for pre-combining cutoff rate for source-relay link will be

$$\mathbf{H}_{pre-sr} = \sum_i^k \mathbf{H}_{sr,i}^H \mathbf{H}_{sr,i}.$$

(6.10)

The combined channel staistics are used in (6.7) for joint pre-post combining scheme,

$$\beta\left(\mathbf{s} \to \mathbf{z}|\mathbf{H}_{pre-sr}\right) = \exp\left(-\frac{L_p(P/2)}{4N_tN_0} \|\mathbf{H}_{pre-sr}\left(\mathbf{s} - \mathbf{y}\right)\|_F^2\right).$$

(6.11)

On the other hand if at least one of the substreams is correct, post-combining procedure is employed as per (5.22) for the erroneous substreams. The overall throughput rate performance is calculated by

$$\eta_{Total} = \eta_{sr} + \eta_{rd}$$

(6.12)

where η_{sr} is the throughput rate performance of source-relay link and η_{rd} is the throughput rate performance of relay-destination link.

Multi-hop V-BLAST

Similar to multi-hop MIMO-MLD, the cutoff rate is calculated from source to relay and relay to destination links. The MMSE covariance matrix in (5.22) can be modified for multi-hop V-BLAST source-relay link as

$$\mathbf{Q}_{sr} = \left(\mathbf{I}_{N_t} + \frac{L_p(P/2)}{N_t N_0} \mathbf{H}_{sr} \mathbf{H}_{sr}^H \right)^{-1}. \tag{6.13}$$

where $\mathbf{H}_{sr}$ denotes the channel matrix for source-relay link. L_p denotes the relative pathloss advantage as compared with a single-hop source to destination link. The total transmit power P of source-relay as well as relay-destination links is divided by 2 to normalize it to that of a single-hop system. Similar equations are used for the relay-destination link by replacing this with $\mathbf{H}_{rd}$. The SINR for the post processed l-th substream for source-relay link is represented as

$$\gamma_{l-sr,k} = \left(\left[\mathbf{Q}_{sr,k} \right]_{l,l} \right)^{-1} - 1. \tag{6.14}$$

where, $[\mathbf{A}_{l,l}]$ denotes the l-th diagonal element of a matrix $\mathbf{A}$. All substreams go through MMARQ dectection where each substream has its own independent HARQ process and cutoff rate for each substream is calculated independently. Therefore, cutoff rate per substream for QPSK modulation can be calculated as

$$\mathbf{R}_{0,l,i} = -\log_2 \left(\frac{1}{q} \sum_{j=0}^{q-1} \exp\left(-\gamma_{l-sr,i} \sin^2(\pi j/q) \right) \right). \tag{6.15}$$

The above equations are true for V-BLAST based MMARQ post combining scheme. In case of proposed joint pre-post combining scheme for V-BLAST, once all the substreams are found in error, the channel statistics of current transmission are pre-combined with the channel of the previous transmission. Each muli-hop link, uses independent HARQ processes and combining operation. Therefore, the

combined channel for pre-combining cutoff rate for source-relay link will be

$$\mathbf{H}_{pre-sr} = \sum_{i}^{k} \mathbf{H}_{sr,i}^{H} \mathbf{H}_{sr,i}. \tag{6.16}$$

Therefore, MMSE covariance matrix for source-realy link can be written as

$$\mathbf{Q}_{pre-sr} = \left(\mathbf{I}_{N_t} + \frac{L_p(P/2)}{N_t N_0} \mathbf{H}_{pre-sr} \mathbf{H}_{pre-sr}^{H} \right)^{-1}. \tag{6.17}$$

Similary, the equation for relay to source link can be written as

$$\mathbf{Q}_{pre-rd} = \left(\mathbf{I}_{N_t} + \frac{L_p(P/2)}{N_t N_0} \mathbf{H}_{pre-rd} \mathbf{H}_{pre-rd}^{H} \right)^{-1}. \tag{6.18}$$

In case if at least one of the substreams is correct, post-combining procedure is employed as per (6.13) for the erroneous substreams.

Fig. 6.10 shows the throughput rate comparison of two-hop MIMO-MLD and V-BLAST MMARQ with conventional and proposed combining schemes. QPSK modulation is assumed with SNR being set to $P/N_0 = 0$ dB. A $(4, 4)$ MIMO configuration is considered and $K_{max} = 4$. The cutoff rate is set at $R \leq 8$ b/s/Hz. The results clearly indicate that the proposed scheme performs better than conventional post combining for both MLD as well as V-BLAST systems. The scheme provides throughput capacity gain once the cutoff rate approaches 4 and the gain continously increase till the value of cutoff rate is 8. This throughput capacity gain highlights the importance of the proposed MMARQ joint pre-post combining scheme as compared to MMARQ post combining in this two-hop scenario. The other advantage of the proposed scheme is that it is generic and is not restricted to V-BLAST based systems only.
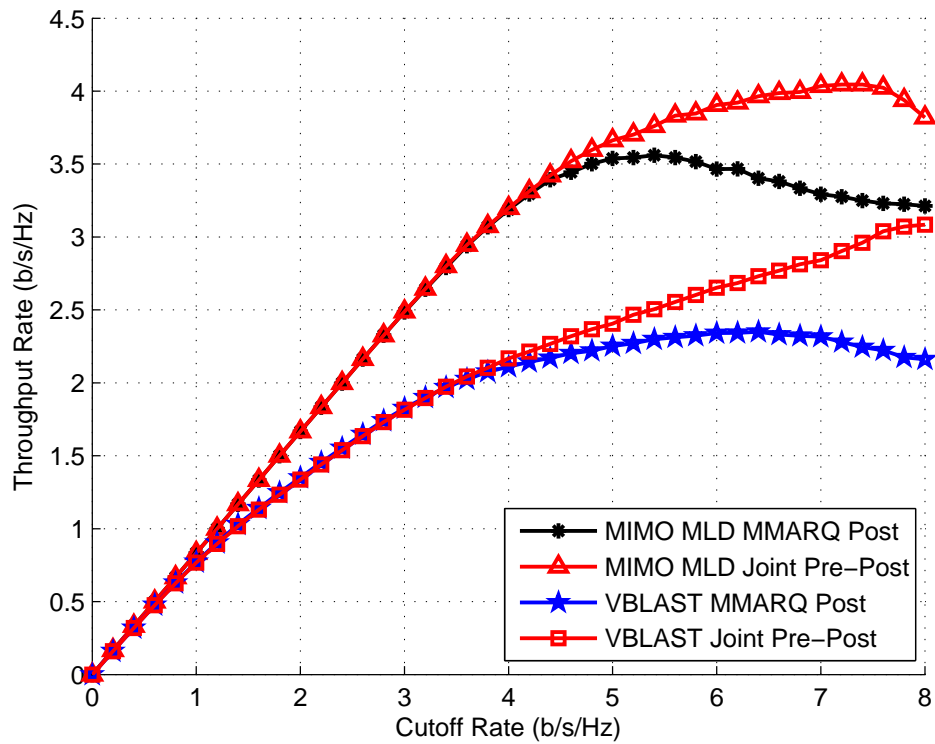
Figure 6.10: Throughput rate results of MIMO-MLD and V-BLAST MMARQ with conventional and proposed combining schemes employed in a two-hop relay scenario. A maximum of 4 retransmissions are used.

6.5.3 Configurations for Relay-Destination Link

Relay station is responsible for forwarding the data substreams to the destination but in case of MMARQ, all substreams may not be found correct to send forward. In case, all the substreams at RS are not correct, the RS only sends the correct substreams to the destination. We consider a (2,2) MIMO system with only one substream correctly detected in the RS. Hence although there are 2 transmit antennas in the RS, there is only one substream to forward. Various relay-destination link configurations are explored as in the following scenarios,

- V-BLAST SIMO (1,2): V-BLAST is used for Source-relay and relay-destination link. The correct substream is forwarded by using SIMO (1,2).

- V-BLAST STBC (2,2): V-BLAST is used for Source-relay and relay-destination link. The correct substream is forwarded by using STBC (2,2).

- MIMO-MLD SIMO-MLD (2,2): MIMO-MLD is used for Source-relay and relay-destination link. The correct substream is forwarded by using SIMO-MLD.

The results are presented in Fig. 6.11. MIMO-MLD has the best performance and behaves as a reference system for this throughput rate analysis. The scenario with SIMO transmission shows the worst performance whereas scenario with STBC (2,2) system performs better than SIMO. This result highlights that the techniques used to forward data substream from relay to destination are very important and can perform a significant role in improving the overall system performance.
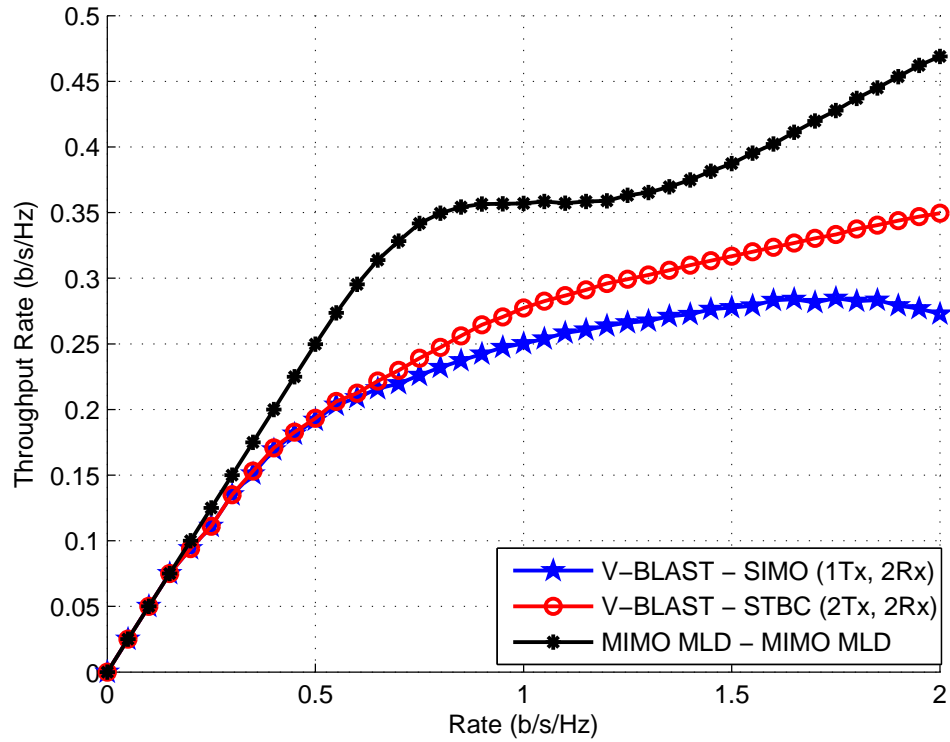
Figure 6.11: Throughput rate results of MIMO-MLD, V-BLAST SIMO and V-BLAST STBC configurations are presented in a two-hop relay scenario. A maximum of 4 retransmissions are used.

6.5.4   Delay Evaluation

Once a RS is introduced, an additional time slot delay will be involved in the relay transmission. This would increase the overall time taken by the signal to reach the destination. This additional delay may not be acceptable for the overall performance of the system. Considering the importance of delay aspect, a delay evaluation of the system is carried out. To maintain the same time efficiency in the comparison, 16 QAM is considered for the two-hop system while QPSK is used for single-hop. By using higher modulation scheme like 16 QAM for two-hop scenario, higher data throughput can be achieved under same parameters

as compared to QPSK modulation rate of single-hop system. Simulation results in Fig. 6.12 present the delay performance of MSARQ single-hop, MMARQ single-hop and MMARQ based two-hop systems. In order to evaluate the delay involved, the maximum number of total transmissions is set to be infinity. In other words, a substream is re-transmitted until it reaches the destination correctly. By considering the number of transmission time intervals (TTI) involved (until the packet is correctly detected) and the modulation rate, the normalized delay is defined as

$$\text{Normalized delay} = \frac{\text{No. of TTIs} \times \text{modulation rate of considered scheme}}{\text{one TTI} \times \text{QPSK modulation rate}}.$$

(6.19)

In other words, the normalized delay is a measure of the additional TTI to correctly decode the same amount of data for a single-hop QPSK packet. For the two-hop scenario, as the modulation rate is doubled (16 QAM), each packet contains double amount of data. Therefore, although a packet takes at least two timeslots to reach the destination for the two-hop case, data throughput is doubled as compared to single-hop. Hence, if the packet is received correctly at the destination, one packet transmission requires only one normalized delay. The normalized delay is plotted with respect to path loss exponent. These results are compiled keeping total received SNR fixed at 15 dB for all scenarios. The proposed 16 QAM two-hop MMARQ system undergoes minimum delay as compared to conventional MMARQ and other HARQ schemes. As the path loss exponent increases, the proposed system undergoes less delay as compared to other systems because high value of path loss exponent means relative path loss advantage also increases (channel conditions becomes severe). This helps relay based systems to perform better than direct links. Delay in case of single-hop systems becomes very high for higher path loss exponent values. It highlights that relay based systems are capable of providing less transmission delay as compared to single-hop
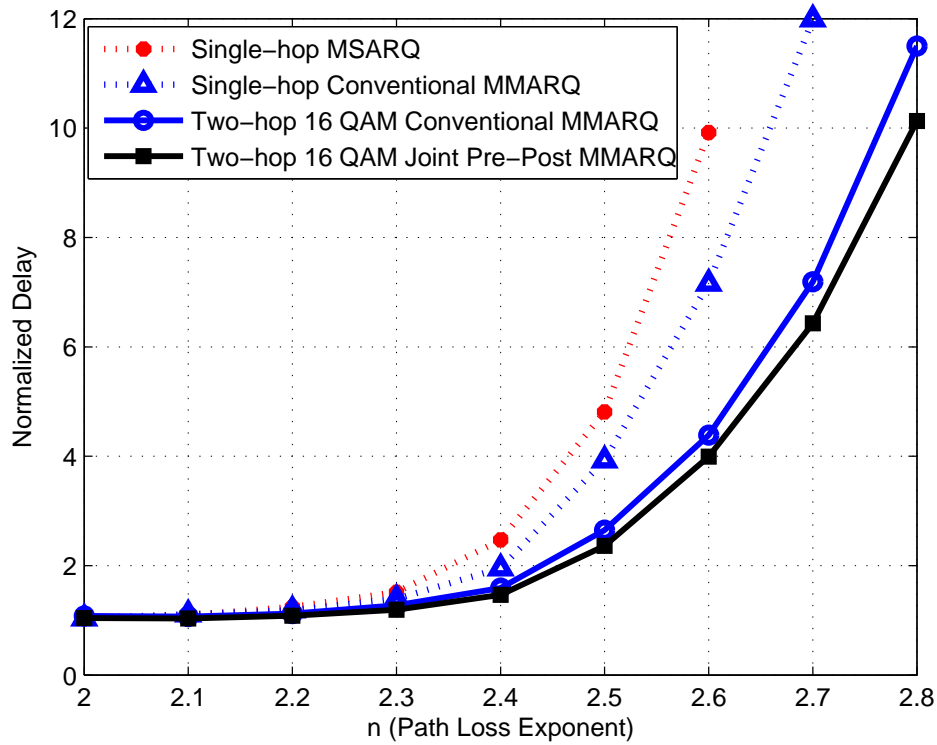
Figure 6.12: Delay analysis of 16 QAM two-hop MMARQ with joint pre and post-combining, 16 QAM conventional two-hop MMARQ, QPSK based conventional two-hop MMARQ, QPSK MSARQ and MMARQ single-hop (4,4) systems.

systems, especially under severe channel conditions. It is important to note here that relay is normally required when the received SNR at the receiver is very low and the range is extended by use of relay node. Due to the worse conditions relay provides better received SNR performance at the receiver despite of adding additional delay. This does not mean that use of relay will be feasible in every situation. In case source to destination link has reasonable receive SNR to decode the signal, then introducing a relay might not benefit the overall performance of the system as it will introduce delay in the system without improving the overall receive SNR. Therefore, relay nodes are normally employed when distances are large or the conditions are worse due to poor channel conditions.

6.6   Summary

In this chapter we have discussed basics of multi-hop relay systems and have extended the proposed and existing MIMO HARQ schemes into the multi-hop scenario. We have carried out link level simulation of all schemes and have presented the throughput analysis. The proposed scheme performs better than the existing MMARQ scheme. We have also carried out capacity analysis of the proposed and existing schemes which also highlights the performace advantages of proposed scheme. At the end, we presented a delay analysis which highlights that the relay based systems are capable of providing less transmission delay as compared to single-hop systems when higher modulation order is used.

Chapter 7

Energy Efficiency of MIMO HARQ Systems

7.1 Introduction

Wireless communication market has seen a hugh growth in the recent times and mobile devices have become an integral and essential part of our lives. Despite of this success, there are still challenges to overcome in terms of more capacity, quality of service, cost and energy efficiency. Energy is a critical resource once it comes to using portable devices in terms of battery consumption. In addition, considering the rising operating costs to run wireless networks and potential adverse impact on the environmental changes, there is a huge need to reduce energy consumption by these networks. However, to reduce the energy consumption of a system, one has to clearly know the energy efficiency of it. Therefore, there is a need to develop innovative techniques to reduce total energy needed to operate the system. In this chapter, we present an energy efficiency analysis of conventional and proposed MIMO HARQ techniques in single-hop as well as multi-hop scenarios.

7.2 Energy Efficiency for Green Radio

The recent growth of cellular mobile networks and increased demand of data services has increased the overall energy consumption of the these networks [79]. If this growth continues then serious issues will arise like increased energy supply requirement and adverse environmental issues [80]. Research is already underway to find out *Green* solutions for reducing energy consumption for existing and future radio networks. To evaluate these green techniques various evaluation metrics are used to measure the energy efficieny. One of the most common metric used is known as the energy consumption ratio (ECR), which is the ratio of average power consumption to effective throughput [81].

Generally, energy efficient techniques focus on reducing transmission energy whereas energy consumed by circuit components is equally important. Energy consumption of SISO and MIMO systems including power amplifiers and circuit components for sensor networks was carried out in [1, 60]. Protocols like HARQ are energy efficient for delay insensitive applications and various HARQ protocols are evaluated for SISO sensor networks in [82].

In this thesis, we extend our work to evaluate the energy efficiency of HARQ protocols for MIMO systems in single and multi-hop systems. The energy efficiency analysis are carried out for sensor networks and relay-assisted cellular networks.

7.2.1 Basic Metrics in Green Radio

The energy efficiency metrics are used to quantify the energy consumption. In general, energy metrics are defined as energy comsumption normalized per some quantity of the network under consideration like throughput, distances involved or number of subscribers etc. One of the most common energy effciency metric is ECR defined as the ratio of the power to the data rate [79].

$$\text{ECR} = \frac{\text{Power}}{\text{Data Rate}} \left[\frac{\text{Joule}}{\text{bit}} \right]. \tag{7.1}$$

The ECR metric can be utilized for whole radio network as well as for one cell or a sector considering the power consumed per given data rate. Another important energy metric is known as Energy Consumption Gain (ECG). It is defined as the ratio between the energy consumption of two systems under consideration, for example, a baseline reference system and a system which is more energy efficient [80]. It highlights the improvement in the energy effciency of a system under trial with a common reference system.

$$\text{ECG} = \frac{\text{ECR baseline system}}{\text{ECR new system}}. \tag{7.2}$$

In some cases, the Energy Reduction Gain (ERG) is also used and is expressed in percentage [79]. It is derived from ECG metric as

$$\text{ERG} = \left[1 - \frac{1}{\text{ECG}} \right] \times 100 \, [\%]. \tag{7.3}$$

7.3 MIMO HARQ Energy Evaluation for Sensor Networks

Power saving is a very important issue in wireless sensor networks due to the use of battery operated devices. Communication of one bit over a wireless medium consumes several orders of magnitude more energy than processing that bit even for short distances [83]. It is difficult to recharge batteries of sensors, thereofore to obtain longer operating durations one has to look critically to the issues related to energy efficiency. The energy consumption model developed by Cui *et.al.* [1] for sensor networks is used to carryout ECG analysis for our proposed scheme.

7.3.1 Single-hop MIMO HARQ System

We extend the energy efficiency analysis of MIMO HARQ schemes for single-hop link as per [1]. For completeness of presentation some of the important equations in [1] are revisited in this thesis. The transmission energy is given by

$$P_{out} = \frac{E_b R_b}{N_t} \frac{(4\pi d)^\gamma}{G_t G_r \lambda^\gamma} M_l N_f \qquad (7.4)$$

where E_b is the required energy per bit at the receiver, R_b is the bit rate, d is the transmission distance, γ is the path loss exponent, N_t represents number of tranmit antennas, G_t is the transmitter antenna gain, G_r is the receiver antenna gain, λ is the carrier wavelength, M_l and N_f represent link margin and receiver noise figure respectively. The power consumption of the power amplifier can be approximated as

$$P_{pa} = (1 + \alpha) P_{out} \qquad (7.5)$$

where $\alpha = \frac{\epsilon}{\eta} - 1$, with η the drain efficiency of the RF power amplifier and ϵ the peak to average ratio, which depends on the modulation scheme and the associated constellation size M [1]. As we use QPSK modulation, $\epsilon = 1$ and (7.5) can be simplified as

$$P_{pa} = \frac{P_{out}}{\eta} \qquad (7.6)$$

Power consumed by various circuit blocks is considered at the transmitter as well as the receiver. The power consumption of all circuit blocks at transmitter and receiver along with the signal path is given by

$$P_{cct} \approx N_t \left(P_{DAC} + P_{mix} + P_{filt} \right) + 2P_{syn}$$
$$+ N_r \left(P_{LNA} + P_{mix} + P_{IFA} P_{filr} + P_{ADC} \right) \qquad (7.7)$$

where P_{DAC}, P_{mix}, P_{filt} are the transmitter power consumptions values of the digital-to-analog converter (DAC), the mixer, the active filter. P_{LNA}, P_{IFA}, P_{filr}, P_{ADC} are the receiver power consumptions values of low-noise amplifier, the intermediate frequency amplifier, the active filter, and the analog-to-digital converter (ADC) respectively. P_{syn} is the frequency synthesizer one each at transmitter and receiver. N_t and N_r is the number of RF chains involved in one complete transmission at transmitter and receiver side respectively. Therefore from (7.1) we can write the ECR per bit as

$$\mathbf{ECR}_{bit} = (P_{pa} + P_{cct}) / (Throughput \times R_b).$$ (7.8)

Putting (7.4) and (7.6) in (7.8) we get ECR per bit as ,

$$\mathbf{ECR}_{bit} = \frac{\frac{1}{\eta}\left[\frac{E_b R_b}{N_t}\frac{(4\pi d)^\gamma}{G_t G_r \lambda^\gamma}M_l N_f\right] + [P_{cct}]}{Throughput \times R_b} \quad \left[\frac{\text{Joule}}{\text{bit}}\right].$$ (7.9)

Here detailed terms of circuit power P_{cct} from (7.7) have not been substituted in (7.9) to keep the equation simple. In this analysis, processing power is assumed to be similar for all the considered systems because all systems use a (4,4) MIMO configuration and similar HARQ procedure for processing the data substreams. It is also important to highlight that the power consumed by the system for processing is in milliwatts whereas the overall power consumption by the base station is in watts. Therefore, even if the system consumes high power in processing, it will not increase the overall consumed power due to the high values of parameters like site cooling, transmit power etc. Simulation results for energy analysis are presented in section 7.3.3.

7.3.2   Multi-hop MIMO HARQ System

We consider a two-hop relay system similar to section 6.5, where the RS is at mid-point between the source and destination and can decode and forward the signal. It uses a RACK to communicate with the source and is responsible of forwarding the packet to the destination. As there are two-hops involved, therefore Eq. (7.9) can be modified as

$$\mathbf{ECR}_{bit} = \frac{\frac{1}{\eta}\left[\frac{E_b R_b}{uN_t}\frac{(4\pi(d/u))^\gamma}{G_t G_r \lambda^\gamma}M_l N_f\right] + [uP_{cct}]}{Throughput \times R_b}\left[\frac{\text{Joule}}{\text{bit}}\right] \qquad (7.10)$$

where u represents the total number of hops from source to destination and in a two-hop case, $u = 2$. Therefore, we normalise the energy per bit by using u. The distance of each link becomes halved in this case as the relay is placed at the mid-point. As the signal is transmitted and received twice due to a relay involved, therefore, we multiply the P_{cct} by u. Due to shorter distances involved for each two-hop link (source to relay and relay to destination), a two-hop link experiences less combined path loss compared to single-hop case. This aspect improves overall performance for a two-hop link over a single-hop.

7.3.3   Simulation Results

System parameters used for simulations are as per [1] and presented in Table 7.1. A Rayleigh flat fading channel is assumed and source to destination distance is considered as $d = 100m$. The value of path loss exponent is $\gamma = 3$. We use a QPSK modulation and 4 transmit and receive antennas. A 1/2 rate convolutional code is used with constraint length $m = 3$ and actual CRC is assumed.

Table 7.1: System Parameters-Sensor Networks [1]

$f_c = 2.5$ GHz	$\eta = 3.5$
$G_t G_r = 5$ dBi	$N_0 = -174$ dBm/Hz
$B = 10$ KHz	$\beta = 1$
$P_{mix} = 30.3$ mW	$P_{syn} = 50.0$ mW
$P_{filt} = P_{filr} = 2.5$ mW	$P_{LNA} = 20.0$ mW
$N_f = 10$ dB	$M_l = 40$ dB

Fig. 7.1 presents ECR results for post combined MSARQ, MMARQ and proposed joint pre-post combining V-BLAST schemes. The results are compiled for single-hop as well as two-hop scenario. ECR per bit is represented in dBW/bps against receive E_b/N_0 at the receiver. MSARQ is the most energy inefficient technique, whereas, MMARQ performs better than MSARQ. The proposed joint pre-post combining scheme is the most energy efficient in the single-hop scenario. Similarly, the proposed joint pre-post scheme also performs better than MMARQ scheme in the two-hop scenario.
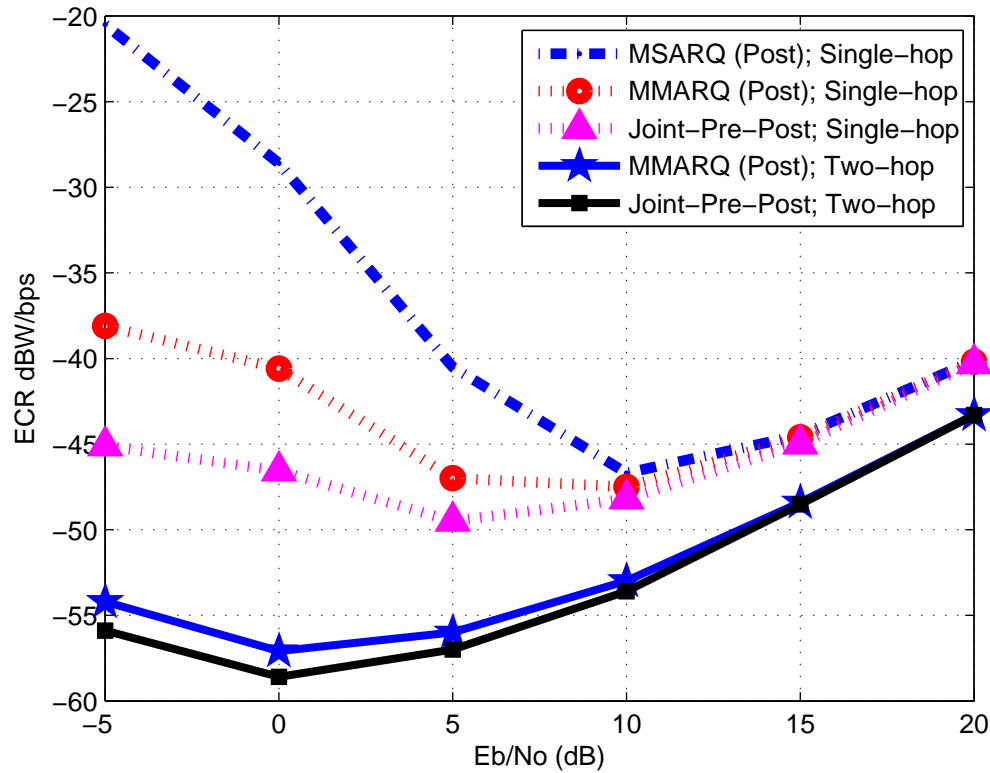
Figure 7.1: ECR results of Post combined MSARQ, MMARQ and Joint Pre-Post combined V-BLAST schemes in single-hop arrangement for sensor networks. Results of two-hop scenario are also presented for MMARQ and Joint Pre-Post techniques.

We present ECG analysis in Fig. 7.2 for post combined MMARQ and proposed joint pre-post combining V-BLAST schemes. MSARQ scheme is used as a baseline reference system. The results are compiled for single-hop as well as two-hop scenario. ECG is represented in dB against receive E_b/N_0 at the receiver. The proposed joint pre-post combining scheme performs better than MMARQ in the single-hop as well as in the two-hop scenario.
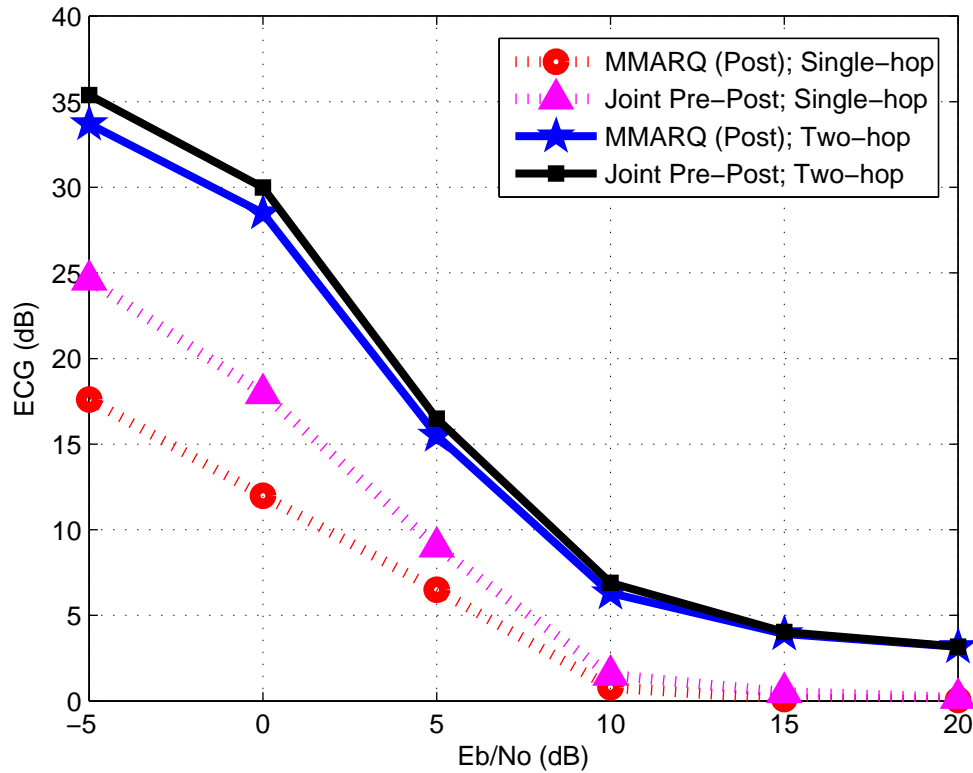
Figure 7.2: ECG results of MMARQ and Joint Pre-Post combined V-BLAST schemes in single-hop arrangement for sensor networks. Results of two-hop scenario are also presented for MMARQ and Joint Pre-Post techniques.

7.4 MIMO HARQ Energy Evaluation for Relay-Assisted Cellular Networks

Latest increase in data traffic due to increased use of wireless devices is increasing energy consumption as well as environmental issues. Deployment of low power base stations or relay stations in traditional macro cells is expected to reduce the total energy consumption of cellular radio networks [2]. We develop a model based on [2] with a single user being connected through a relay station within

a macro cell. The relay station is responsible for sending the data from macro base station to a user in the two-hop scenario. We carry out energy efficiency analysis of MIMO HARQ protocols for single-hop (macro to user) and two-hop (Macro-relay-user) scenarios.
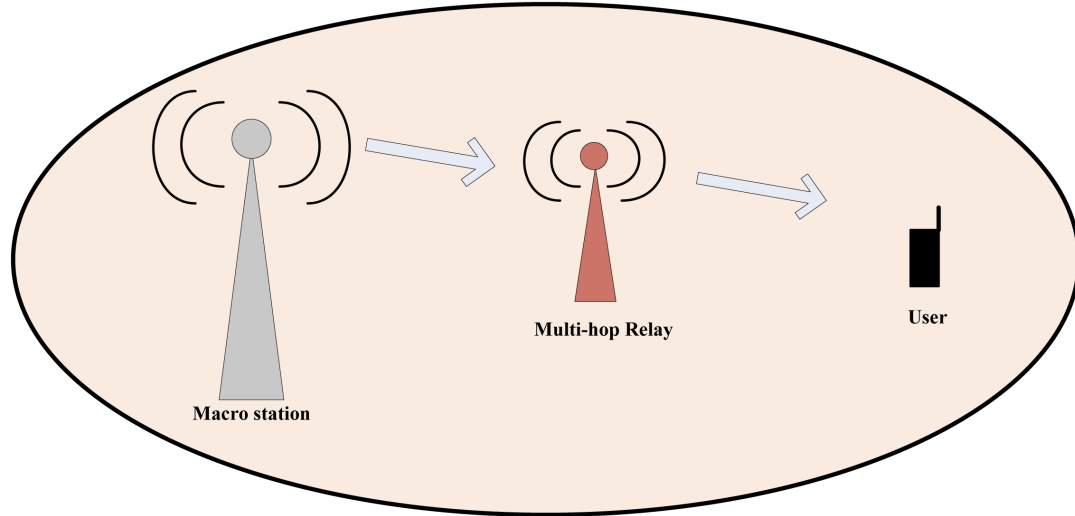
Figure 7.3: Relay-Assisted Cellular Network Scenario

7.4.1   Single-hop MIMO HARQ System

The energy consumption model developed in [2] for hetereogenious cellular networks is used to carry out ECG analysis for our scheme. For completeness of presentation some of the important equations in [2] are revisited in this thesis. The transmission power is given by

$$P_{out} = \frac{E_b R_b}{N_t} \frac{(4\pi d)^\gamma}{G_t G_r \lambda^\gamma} L_{pen} L_{sh} N_f \qquad (7.11)$$

where E_b is the required energy per bit at the receiver, R_b is the bit rate, d is the transmission distance, γ is the path loss exponent, N_t represents number of tranmit antennas, G_t is the transmitter antenna gain, G_r is the receiver antenna gain, λ is the carrier wavelength, L_{pen} is the penetration loss, L_{sh} and N_f represent

shadowing loss and receiver noise figure respectively. The power consumption of power amplifier and all circuit blocks along with base band unit, feeder network and site cooling system are considered. Therefore, the total consumed power can be given by

$$P_{total-ma} = \alpha_{ma} P_{out-ma} + P_{fix-ma} \tag{7.12}$$

where P_{out-ma} is the radiated power, α represents power consumption that scales with the radiated power due to power amplifier, and P_{fix-ma} models site power consumed by signal processing units, site cooling etc. The subscript ma represents terms related to macro cell. Considering the values of α_{ma} and P_{fix-ma} for a macro cell as per [2], we get

$$P_{total-ma} = 3.8 P_{out-ma} + 68.8 \ [W] \tag{7.13}$$

Therefore, ECR per bit can be calculated as

$$\mathbf{ECR}_{bit-ma} = \frac{P_{total-ma}}{Throughput \times R_b} \ \left[\frac{\text{Joule}}{\text{bit}} \right] \tag{7.14}$$

Similar to sensor network analysis the aspect of processing power is assumed to be similar for all the considered systems because all systems use a (4,4) MIMO configuration and similar HARQ procedure for processing the data substreams. Simulation results for energy analysis are presented in section 7.4.3.

7.4.2   Multi-hop MIMO HARQ System

We consider a multi-hop relay scenario with two-hops similar to section 6.5 and assume the RS at the mid-point between the macro station and the user as shown in Fig. 7.3. Eq. (7.15) represents a general equation for a relay and is similar to (7.10).

$$P_{out-relay} = \left[\frac{E_b R_b}{u N_t} \frac{(4\pi(d/u))^{\gamma}}{G_t G_r \lambda^{\gamma}} L_{pen} L_{sh} N_f \right] \tag{7.15}$$

A relay based scenario in a macro cell can be calculated as Eq.(7.16), where total power P_{Total} is

$$P_{Total} = [3.8 P_{out-ma} + 68.8] + [5.5 P_{out-rel} + 38] \ [W] \tag{7.16}$$

The ECR per bit from source to destination can be found as

$$\textbf{ECR}_{bit} = \frac{P_{Total}}{Throughput \times R_b} \left[\frac{\text{Joule}}{\text{bit}} \right] \tag{7.17}$$

7.4.3 Simulation Results and Analysis

We use all the system parameters as per [2] and all the parameters are presented in Table 7.2. We use QPSK modulation and number of transmit and receive antennas are $N_t = N_r = 4$. A 1/2 rate convolutional code is used with constraint length $m = 3$ and actual CRC is assumed. The source to destination distance is assumed $d = 400m$ and value of path loss exponent $\gamma = 4$. The free space ideal model provides a path loss exponent equal to 2, whereas most of the real-case scenarios take values from 3 to 4 for the low-attenuation regime, whereas values above 4 define the high-attenuation regime [84]. Use of relay stations in case of wireless networks is normally done to cover a dense area and therefore, we select a path loss exponent value as 4. All the parameters for a relay node are considered same as of a pico cell.

Table 7.2: System Parameters-Cellular Networks [2]

$f_c = 2.5$ GHz	$\alpha = 3.8$
$G_t G_r\,(ma) = 14$ dBi	$G_t G_r\,(pi) = G_t G_r\,(rel) = 5$ dBi
$G_t G_r\,(User) = 0$ dBi	$N_f = 7$ dB
$B = 10$ Mbps	$N_0 = -174$ dBm/Hz
$L_{pen}(ma) = 20.0$ dB	$L_{pen}(pi) = 20.0$ dB
$L_{sh}(ma) = 8.0$ dB	$L_{sh}(pi) = 8.0$ dB
$P_{fix}(ma) = 68.8$ W	$P_{fix}(pi) = 38$ W

Fig. 7.4 presents ECR results for post combined MSARQ, MMARQ and pro-posed joint pre-post combining V-BLAST schemes. The results are compiled for single-hop as well as two-hop scenario. ECR per bit is represented in dBW against receive E_b/N_0 at the receiver. MSARQ is the most energy inefficient technique, whereas MMARQ performs better. The proposed joint pre-post combining scheme is the most energy efficient in the single-hop scenario. Similarly, the proposed joint pre-post scheme also performs better than MMARQ scheme in the two-hop scenario.

Figure 7.4: ECR analysis of Post combined MSARQ, MMARQ and Joint Pre-Post combined V-BLAST schemes in single-hop arrangement for cellular networks. Results of MMARQ and Joint Pre-Post are also presented for two-hop scenario.

Few aspects are highighted below while comparing the ECR results of sensor networks and cellular networks,

- Sensor networks operate in smaller distances,use battery operated nodes and have less power consumption overheads. On the other hand, cellular networks operate in larger distances, use power operated pico and relay cells and have more overheads like site cooling etc.

- In sensor networks, power consumption values of fixed overheads are much lower (in milli-watts) as compared to cellular networks where these values are very high (in watts). Therefore, the overall power consumption of

cellular networks is higher than sensor networks.

- Due to this aspect overall more power is consumed in case of cellular networks as compared to sensor networks. The greener point shifts towards higher SNR values on the graph for cellular networks in Fig. 7.4 compared to results of sensor networks in Fig. 7.1. In other words, once the throughput of the system is low in case of cellular networks more power is consumed (due to higher overheads) as compared to sensor networks case.

- Importantly, the proposed joint pre-post scheme performs better in both the networks which shows that the proposed scheme is generic in nature and can be employed for MIMO HARQ systems regardless of the considered network.

We present ECG analysis in Fig. 7.5 for post combined MMARQ and proposed joint pre-post combining V-BLAST schemes for single-hop and two-hop scenarios. MSARQ scheme is considered as a baseline reference system. ECG is represented in dB against receive E_b/N_0 at the receiver. The proposed joint pre-post combining scheme shows more gain than MMARQ in the single-hop as well as in the two-hop scenario.
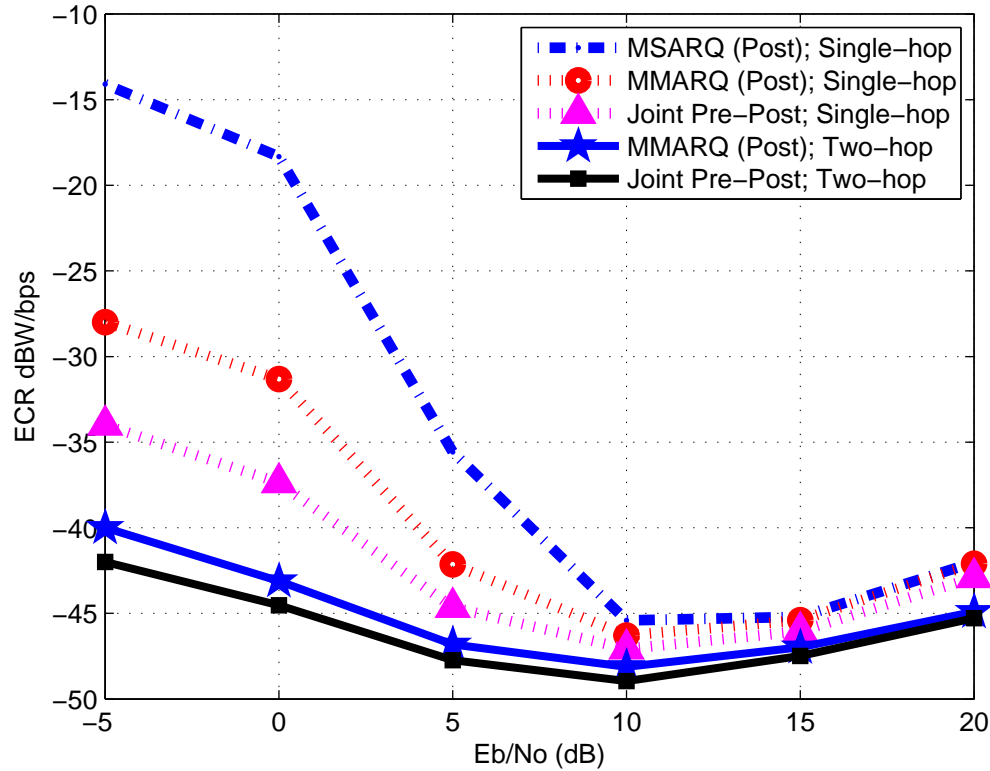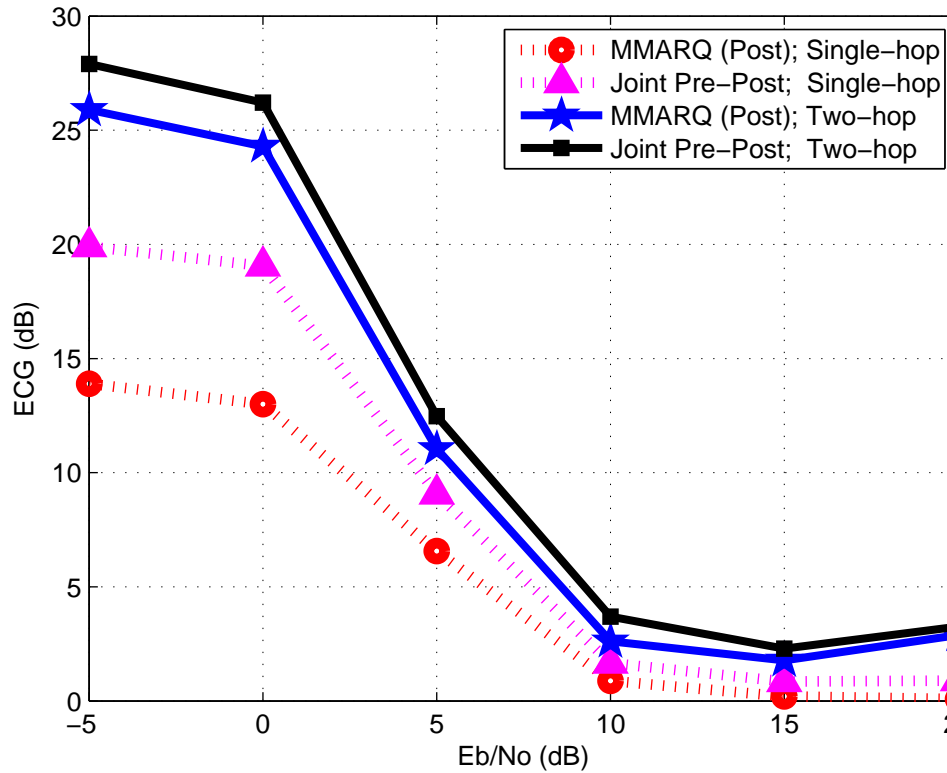
Figure 7.5: ECG analysis of MMARQ and Joint Pre-Post combined V-BLAST schemes in single-hop arrangement for cellular networks. Results of MMARQ and Joint Pre-Post are also presented for two-hop scenario.

7.5   Summary

In this chapter we have discussed the basics of energy efficiency metrics for green radio communication. We considered sensor netowrks and cellular networks for energy efficiency evaluation of MIMO HARQ protocols in single-hop as well as multi-hop scenarios. This analysis highlight that the proposed joint pre-post scheme is more energy efficient as compared to post combining based schemes.

Chapter 8

Conclusions and Future Work

8.1 Conclusions

In this thesis, basics of MIMO wireless communication systems have been studied. Various HARQ schemes have been ustilized in MIMO environment but most of the schemes assume post combining based HARQ process for MIMO systems. Pre-combining scheme produces better performance than post-combining based HARQ systems. Pre-combining scheme has not been considered for MIMO HARQ systems before. Therefore, we investigated the use of pre-combining based HARQ schemes for MIMO single-hop systems. We proposed two novel MIMO MMARQ schemes using pre-combining technique and a joint pre and post-combining scheme. Both the proposed schemes take the performance advantage of pre-combining and it is shown that the proposed schemes can enhance the overall system throughput performance of an MMARQ system. MIMO HARQ schemes have not been extended to relay based MIMO systems before, therefore we carryout a detailed study of these schemes for MIMO multi-hop relay systems. The proposed joint pre-post scheme show throughput performance improvement in relay based scenario compared to conventional post combined schemes. We also carried out a throughput rate analysis of proposed joint pre-post scheme by

employing a conditional cutoff rate metric to show throughput capacity of the system. The proposed scheme also shows an improvement in system throughput capacity as compared to conventional combining schemes. In addition, we extend the work to multi-hop MIMO systems, and propose a MMARQ multi-hop relay scheme. The proposed scheme performs well in the multi-hop scenario and provides significant gain in throughput performance as well as throughput rate. Delay evaluation for the proposed MMARQ multi-hop relay scenario shows that even though with an additional transmission timing interval, the delay involved by using RS is significantly lower than the single-hop case.

Considering the increased energy consumption due to growth of wireless networks and its potential adverse impact on the environmental changes, we evaluated the energy efficiency of existing and proposed MIMO HARQ techniques for sensor and cellular networks. The results show that the proposed joint pre-post combining scheme is more energy efficient than the other schemes in single-hop as well as multi-hop scenarios.

8.2   Future Work

We list in the following several possible research directions in this research area.

- **Extended analysis of relay-destination link protocol**

  We have carried out a limited throughput rate analysis of relay-destination link using SIMO and STBC techniques for forwarding the data to destination. This analysis can be extended to include more techniques or different configurations to give further insights into this aspect and it may be possible to improve performance even further.

- **Cooperative relay communication**

  Considering the growing interest in cooperative relay diversity techniques,

this work can be extended to cooperative relay scenario where a relay can be used for cooperative communication and exploit the advantage of spatial diversity in a distributed fashion.

- **Dynamic adaptive modulation for MIMO HARQ schemes**

  Adaptive modulation systems show performance enhancements by adapting various modulation schemes according to the quality of the radio channel. It would be interesting to model the MIMO HARQ schemes with dynamic adaptive modulation to expoit various channel conditions. Once the channel conditions are worse, the system can use lower rate modulation scheme to keep the important data flowing whereas, higher modulation schemes can be employed in case of better channel conditions.

- **Multi-user MIMO with pre-coding**

  In the proposed scenario, it is assumed that there is a reverse channel available to carry feedback of HARQ processes to the source. This reverse channel can be used to forward channel state information to the transmitter which could provide further oppurtunities to exploit multi-user MIMO schemes like pre-coding with MIMO HARQ schemes.

- **Relay selection**

  In this research, we assumed the presence of a relay station to forward the data to the destination node. However, in practical scenario there are typically several fixed relay nodes in the region. One has to determine which of these potential relays should be selected for forwarding the data. Therefore, this research model can be made more practical by employing a relay node selection scheme.

- **Green communication**

  Considering the rising growth in use of portable devices, high operating

costs to run wireless networks and potential adverse impact on the environmental changes, there is a huge need to reduce energy consumption by these networks. The future needs energy efficient devices, energy efficient techniques to run these networks keeping power consumption low and still manage a reasonable capacity increase. More indepth research can be done to improve the energy efficieny of the considered techniques and protocols further.

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