Adaptive Video Transmission over MIMO Channels

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Abstract

Communication over wireless channels has matured considerably in the last decade. While voice and low end data content can be carried reliably and efficiently over contemporary wireless channels, communication of video content over these channels still remains an open research problem. Video data is complicated for transmission over wireless media because of its high bandwidth and low delay requirements. Furthermore, high computational cost of video encoding and decoding is prohibitive for battery- and resource-constrained mobile devices. Due to their high spectral efficiency (high data rates) and good diversity characteristics (low BERs), wireless systems with Multiple-Input-Multiple-Output (MIMO) physical layers are quite well-suited to mitigate the above problems. The two complementary approaches employed for transmission of data over MIMO systems are: Spatial Multiplexing (SM) and Space Time block Coding (STBC). SM maximizes throughput whereas STBC provides diversity gains. The benefits of STBC and SM can also be combined by adaptively switching between the two schemes in SNR regions where one scheme outperforms the other. In this thesis, we study adaptive video transmission over MIMO channels. We carry out this research in two steps. Firstly, we investigate a receiver-centric comparison of different video sequences over STBC and SM systems. Secondly, we propose cross-layer adaptive scheme that can intelligently switch between SM and STBC and can significantly improve the quality of video transmission over MIMO channels. In the receiver-centric comparison we use empirical SNR versus PSNR performance evaluations of H.264 video sequences to show that reasonable video quality can be provided using the basic (SM and STBC) diversity-multiplexing schemes. We identify three distinct channel SNR regions in which SM and STBC PSNR performance changes based on varying motion and channel characteristics. We observe that the boundaries of the classified regions are flexible and depend largely on the motion intensity of the video content, which directly impacts decoding performance. Using our deductions from the receiver-centric evaluation, out proposed cross-layer adaptive video transmission scheme uses the motion intensity of the video content and the received channel SNR to adaptively switch between SM and STBC. Since low BERs does not necessarily translates into improved video quality, our goal is to devise a switching scheme that takes into consideration characteristics of video data in order to achieve better PSNR. We show that a measure of motion intensity on the application layer of the transmitter should be used to compute the switching SNR–the SNR after which SM outperforms STBC. Experimental results show that the proposed scheme provides significantly better PSNR than standalone SM and STBC and existing content-unaware switching mechanisms.

Certificate of Originality

I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any degree or diploma at NUST SEECS or at any other educational institute, except where due acknowledgment has been made in the thesis. Any contribution made to the research by others, with whom I have worked at NUST SEECS or elsewhere, is explicitly acknowledged in the thesis.

I also declare that the intellectual content of this thesis is the product of my own work, except for the assistance from others in the project's design and conception or in style, presentation and linguistics which has been acknowledged.

Author Name: **Sobia Jangsher**

Signature: ________________

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Chapter 1

Introduction and Motivation

1.1 Introduction

Communication over wireless has matured considerably in the last decade. While voice and low end data application can be carried reliably over contemporary wireless channels, transmission of video content over these channels still remains an open research problem. Video data is complicated for transmission over wireless media because:

- Video communication is bandwidth intensive while wireless bandwidth is inherently limited and is in turn shared between multiple wireless receivers;
- Video is sensitive to delays and losses which are observed frequently on wireless channels due to mobility, fading, interference, attenuation and contention;
- Mobile devices are battery and resource (CPU, memory etc.) constrained while video encoding and decoding are complex processes which are typically implemented in application layer software.

Due to their high spectral efficiency (high data rates) and good diversity characteristics (low BERs), wireless systems with

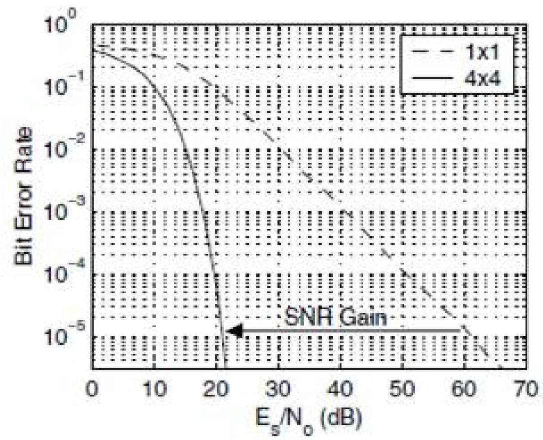
Multiple-Input-Multiple-Output (MIMO) physical layers are quite well-suited to mitigate the above problems. Two primitive approaches that are employed for transmission of data over MIMO channels are Spatial Multiplexing (SM) [1] and Space Time Block Code (STBC) [2, 3]. SM maximizes throughput by transmitting independent streams over the transmit antennas; however, it gives limited diversity benefit. STBC, on the other hand, enhances diversity by transmitting redundant data streams from the transmit antenna at the cost of lower throughput. High spectral efficiency and communication robustness makes MIMO wireless systems ideal for transmission of bandwidth-intensive video content. Figure 1.1(a) shows the decrease in BER from 1x1 Single Input Single Output (SISO) to 4x4 MIMO system and Figure 1.1(b) shows an increase in the spectral efficiency from 1x1 to 4x4 system [4].

In order to improve video quality, existing methods complement SM and STBC with enhanced source and channel coding strategies to improve video PSNR at a MIMO receiver [5, 6, 7, 8, 9]. These schemes ignore the following critical constraint of a practical wireless video communication;

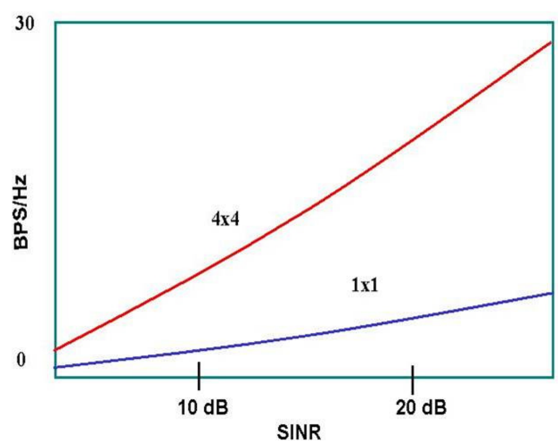
1. Most wireless receivers are resource-constrained and therefore cannot support complex video decoding;

2. A receivers MIMO hardware does not provide substantial control over the physical layer (PHY) and hence a practical scheme should operate on higher layers while using only the supported PHY configurations.

Keeping in view the above constraints, in this thesis we will study adaptive transmission of H.264 coded video over MIMO channels. We believe that STBC and SM alone with standard compliant error concealment is enough to achieve decent video quality. STBC and SM are already supported by modern communication standards [10],[11],[12].



(a) Decrease in BER from 1x1 SISO to 4x4 MIMO system



(b) Increase in Spectral efficiency from 1x1 SISO to 4x4 system

Figure 1.1: MIMO benefits in terms of Spectral Efficiency and BER as compare to SISO systems.

As a first step we will investigate a receiver centric comparison of transmission of different H.264 coded video sequences over a 4 x 4 STBC and SM system. More specifically, we will perform a one-to-one comparison of video transmission solely over STBC and SM with no control over the transmitter end. Due to receiver centric approach, we impose a constraint that no source and channel coding can be employed before the air interface. After one-to-one SM and STBC comparison for transmission of video, we will combine the benefits of both SM (maximizes throughput) and STBC (enhances diversity) using adaptive switching techniques.

Using our deductions from the empirical evaluation, our out proposed adaptive video transmission scheme uses the motion intensity of the video content and the received channel SNR to adaptively switch between SM and STBC. Since low BERs does not necessarily translates into improved video quality, our goal is to devise a switching scheme that takes into consideration spatio-temporal activity of a video data in order to achieve better PSNR.

We propose to use the average effect of Euclidean distance of a motion vector[1] as our measure of motion intensity or spatio-temporal activity of a video sequence and call it as *Motion Richness*. Based on the motion richness value a *Switching SNR*, the SNR after which SM outperforms STBC, is computed. In other words, switching SNR is defined as an SNR before which it is better to have a video with quantization error rather than video corrupted with channel errors and vice versa. The decision of the scheme to be used is taken by comparing the switching SNR with the channel SNR. We show that computation of motion richness at the application layer of the transmit end should be used to compute the switching SNR. We employ the proposed switching technique in our experimental setup. The experiments then reveal that the proposed technique provides significantly better

[1] Motion Vectors are a two dimensional vector and provides an offset from the coordinates in the decoded picture to the coordinates of the reference picture

video quality than stand alone SM and STBC configurations and existing content-unaware switching algorithms.

1.2 Contribution

1.2.1 Problem Statement

The problem statement of our research thesis is:

To design and evaluate video transmission schemes for MIMO wireless channels.

1.2.2 Problem Breakdown

Two aspects will be investigated:

1. Evaluation of existing receiver-centric MIMO video communication options.

2. Design and evaluation of a novel adaptive scheme for MIMO video transmission.

The research has been conducted according to the following program:

- *Implementation of Existing STBC, SM and EC Algorithms:* We will start off with the implementation of the basic algorithms for a 4 x 4 STBC, SM for video transmission and frame based error concealment algorithm for a received H.264 coded video. Based on the implementations we will perform a one-to-one comparison of STBC and SM for error concealed video transmission. This step would help us in analyzing the individual behavior of SM and STBC and later on will also help us in performance comparison with adaptive switching techniques.

- *Implementation of switching techniques:* In this step we will implement three different channel condition based switching techniques, Demmel condition number; Regular condition number; Determinant number. This will help in investigating the adaptive transmission of video over STBC and SM based on the channel conditions.

- *Design of content aware switching technique:* Keeping in mind the spatio temporal characteristic of a video, we will propose and implement a switching technique for video transmission over STBC and SM.

- *Performance Evaluation:* In the last phase, we will be evaluating the performance video communication over MIMO using the proposed switching technique and then, we will compare it with the existing switching techniques. The Quality metric that we will use be using to measure the performance improvement is Peak Signal to Noise Ratio (PSNR).

1.3 Thesis Organization

The remainder of the thesis is structured as follows:

Chapter 2 discusses the background of this domain, existing switching techniques and the related work that has been done in this domain.

Chapter 3 provides the details of the experimental setup used throughout the comparison of video transmission of SM and STBC and performance evaluation of motion adaptive switching and the existing switching schemes.

Chapter 4 performs a comparison of video transmission solely over SM and STBC and studies the PSNR and Mean Opinion Score (MOS) behavior of the received video stream over an SNR region of $10 - 40dB$.

Motion-Adaptive Switching is discussed in chapter 5 with detailed discussion on its architecture. Performance Evaluation of the Motion-adaptive scheme and its comparison with other existing switching schemes is done in chapter 6. Chapter 7 finally concludes the thesis.

Chapter 2

Literature Review

This chapter provides the background literature review of MIMO channels, the complementary schemes used for MIMO channels and the existing switching techniques .

2.1 MIMO model

MIMO systems are characterized by the presence of multiple antennas at both ends of a communication link. In a rich scattering environment, the capacity of a MIMO wireless system with M transmit and N receive antennas increases linearly with $n = \min(M, N)$ [13, 14]. Throughout this research work, we employ the commonly-used frequency non-selective Rayleigh fading channel model . The antenna elements in both the transmit and the receive arrays are assumed to be spatially uncorrelated. For a MIMO system with M transmit and N receive antennas, the system equation is

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}, \tag{2.1}$$

where $\mathbf{H}_{N\times M}$ is the complex channel matrix and is assumed to be constant for L symbol periods, $\mathbf{x}_{M\times 1}$ is the transmit signal vector, $\mathbf{y}_{N\times 1}$ received signal vector, and $\mathbf{n}_{N\times 1}$ is the noise vector containing Gaussian noise samples at the receive antenna elements.

The Complementary coding approaches of MIMO are Spatial Multiplexing and Space Diversity:

2.1.1 Spatial Multiplexing

The most dominating feature of using multiple input and multiple output antennas is the considerable increase in the throughput (data rate) for the same total transmitted power and the same bandwidth as compare to a single antenna system. Multiplexing gain which is required to increase the throughput is only provided by MIMO systems. This multiplexing gain is achieved using a technique known as Spatial Multiplexing (SM).

Spatial Multiplexing (SM) [4] or Space-Division Multiplexing (SDM) is an approach of MIMO where independent data streams of MIMO are transmitted in parallel over different transmit antennas for a single user to gain high throughput. In General it can be said that the data rate increases with the number of transmit antennas. For Example, a high rate bit stream is broken down into three independent 1/3 rate bit sequences which are simultaneously transmitted using 3 antennas, thus reducing the size of the nominal spectrum used (consuming one-third of the nominal spectrum).At the receiver the individual bit streams are separated after identifying the mixing channel matrix.

The vertical spatial multiplexing is referred as V-BLAST. V-BLAST stands for (Vertical-Bell Laboratories Layered Space-Time). It is a detection algorithm to exploit the high spectral capacity offered by MIMO channels. V-BLAST algorithm is a multi-layer symbol detection scheme which detects symbols transmitted at different transmit antennas successively in a certain data independent order. This algorithm offers highly better error performance than conventional linear receivers and still has low complexity. The information data are at first coded, interleaved and mapped into their corresponding symbols. Then, the symbols are demultiplexed to the M_t transmit antennas. Hence, the symbols transmitted are independent of each other which make it an interference avoidance technique. The steps for V-BLAST algorithms are Ordering (choosing the best channel), Nulling (ZF or MMSE), Slicing (making a symbol decision), Canceling (subtracting the detected) and Symbol Iteration (going to the first step to detect the next symbol).

2.1.2 Space Diversity

To overcome the effect of fading on error rate, diversity techniques are the immediate and the usual solution. The principle of diversity is to provide the receiver/transmitter (or both) with the multiple versions of the same signal. Each signal is considered as a diversity branch. These versions are provided by multiple antennas. If these antennas are placed at a reasonable distance, it can be assumed that their SNR fade independent of each other. This in other words means that the probability of all of these branches being in fade at one time is very low. Hence diversity hardens the link resulting in reduced error rate and better performance.

Space Time Block Code is one of the technique of MIMO to exploit the diversity benefits of MIMO. In [2, 3], STBC are discussed and it provides significant error improvement as compare to single input single output system. STBC is represented in the form of a matrix. The rows in the matrix represents the symbol's time slot whereas column represent one antenna's transmission over time.

$$G = \begin{bmatrix} s_{11} & s_{12} & \dots & s_{1n} \\ s_{21} & s_{22} & \dots & s_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ s_{m1} & s_{m2} & \dots & s_{mn} \end{bmatrix} \tag{2.2}$$

STBC codes are orthogonal in nature. Different transmission matrix based on the code rates required have been designed. The code rate of STBC is defined as the number of symbols transmitted over a single time slot. The transmission matrix with a code rate of 1/2 is

$$G = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \\ -x_2 & x_1 & -x_4 & x_3 \\ -x_3 & x_4 & x_1 & -x_2 \\ -x_4 & -x_3 & x_2 & x_1 \\ x_1^* & x_2^* & x_3^* & x_4^* \\ -x_2^* & x_1^* & -x_4^* & x_3^* \\ -x_3^* & x_4^* & x_1^* & -x_2^* \\ -x_4^* & -x_3^* & x_2^* & x_1^* \end{bmatrix} \tag{2.3}$$

The matrix is transmitting 4 symbols in a time period of 8 time slots which make 1/2 symbol in 1 time slot. The 4 symbols it is transmitting are x_1, x_2, x_3 and x_4.

Decoding of STBC symbols using Maximum Likelihood (ML) can be achieved using linear processing at the receiver end. The ML decoding of half rate code is discussed in [3].

2.2 Switching Techniques

Although it is desired to achieve the best of both Spatial multiplexing and diversity but practically it is not possible. There is a trade off between the two. Spatial multiplexing is chosen for the systems where higher data rate is required and where multi path effect is prominent enough to be changed into a benefit. However, diversity is applied in the design of the systems where our main objective is to minimize the probability of error or where a more reliable communication link is required. Switching is defined as a hybrid approach where a MIMO mode(SM or STBC) is chosen based on the criteria or favorable condition where one outperforms the other mode. Some of the existing switching techniques are:

2.2.1 Demmel Condition Number

Based on Demmel condition number, adaptive transmission can be achieved. Its a channel condition based switching technique. The number gives an intuition on the quality of a channel using the channel matrix. In other words it measures , how ill posed a given matrix is? In terms of mathematical expression it is defined as

$$k_D = \frac{||H_f||}{\lambda_{min}} \tag{2.4}$$

where H_f is the frobenius norm and λ_{min} is the minimum singular value of the channel matrix.

For Demmel condition number threshold is defined as

$$\tau_{th} = \frac{d^2_{min,sm}}{d^2_{min,stbc}} \tag{2.5}$$

where $d^2_{min,sm}$ and $d^2_{min,stbc}$ are the transmit minimum constellation distance for SM and STBC respectively.

The Algorithm is defined as:

```
if (k_D ≤ τ_th) then
    use SM
    else
    use STBC
end
```

2.2.2 Regular/Relative condition Number

Relative condition number gives a measure of channel suitability for SM. Its a ratio of the maximum singular value to the minimum singular value and in mathematical terms defined as

$$k = \frac{\lambda_1}{\lambda_{min}} \tag{2.6}$$

where λ_1 is the maximum singular value and λ_{min} is the minimum singular value. For Relative condition number threshold is defined as

$$\tau_{th} = \sqrt{\frac{\frac{d^2_{min,sm}}{d^2_{min,stbc}} M_t - 1}{M_t - 1}} \tag{2.7}$$

where $d^2_{min,sm}$ and $d^2_{min,stbc}$ are the transmit minimum constellation distance for SM and STBC respectively and M_t is the number of transmit antennas used.

The Algorithm is defined as:

```
if (k ≤ τ_th) then
    use SM
    else
    use STBC
end
```

2.2.3 Determinant

Channel matrix H contains complex attenuation between between transmit antenna and receive antenna. Determinant is a measure of how invertible a matrix is? The mathematical expression is given as

$$D = det(H^H H) \tag{2.8}$$

The Algorithm is defined as:

if $(D \leq \tau_{th})$**then**
use STBC
else
use SM
end

Thus for a MIMO channel it gives an indication of its suitability for SM and the areas where it is not. When the channel is highly correlated it results in serious degradation in the BER performance of SM system. Therefore SM is not advisable for highly correlated channels. Low values of determinant of a channel matrix means channel is highly correlated. Thus, we can say that for low determinant values SM should not be used.

2.3 Related Work

Existing schemes for wireless video employ MIMO systems complementing SM and STBC with enhanced source and channel coding techniques [5, 6, 7, 8, 9]. Their prime focus is to improve the received video quality mainly by over coming the errors introduced by the channel. OFDMA is used for video transmission in [5], while in [6] adaptive channel selection and modulation techniques have been used in conjunction with MIMO for efficient resource sharing and to cope with multipath effects on the physical layer. In [8], Multiple Description Coding (MDC) are employed, whereas in [9] LDPC codes have been used for transmission of video over SM and STBC. These schemes, however, result in the addition of undue decoding complexities at the wireless receivers which do not have much control over their physical layers and network devices beyond the air interface. Source coding techniques like MDC add to the decoding complexity of the receiver at higher layers [8]. Channel coding techniques like LDPC [9], in addition to being complex, are difficult to implement because of interconnect wiring and routing congestion which in turn leads to larger and slower decoders [15]. SNR-based switching threshold between SM and STBC are quite well investigated. Some criteria have been suggested in [16], [17] but in the case of video transmission, a specific threshold cannot be used for different video sequences having varying spatio-temporal characteristics.

Chapter 3

Experimental Setup

This Chapter discusses the MIMO and Video experimental setup used during the research work.

3.1 Video Experimental setup

3.1.1 Video Encoding/Decoding Setup

Four video sequences (Akiyo, Carphone, Mobile and Foreman) in blackQCIF format at a temporal resolution of 30 fps were selected for analysis. The first 150 frames from each video sequence were analyzed and a GOP size of 12 frames was used [IPPPPP...]. For the sake of simplicity we are not using B frames. For STBC, the sequences were encoded at approximately 20 kbps however the selected rate was 160 kbps for SM. A small quantization step size (QPI = 25, 24, 31 and 35 and QPP = 20, 27, 28 and 36 for Akiyo, Carphone, Mobile and Foreman respectively) is used for video content transmission over SM; it is kept coarse (QPI = 51, 50, 49 and 51 and QPP = 51, 49, 49 and 51 for Akiyo, Carphone, Mobile and Foreman respectively) for STBC schemes for a judicious comparison. The first I and P frame of the first GOP were assumed to be received free of channel error so that they can be used for error concealment. On the decoder side, error concealment was incorporated at the frame level.

The videos used have varying motion characteristics. Akiyo and Carphone are videos with low spatio-temporal variation as in envisioned mainstream 4G applications e.g., video call scenario. Foreman varies more in time and Mobile is both spatially and temporally active and can be characterized as *blacksports-type* content. In our simulations, the video sequences used for transmission were compressed using the H.264/AVC reference implementation (JM 13.5) [18].

3.1.2 Video transmission Setup

We transmit the videos over a 4×4 MIMO system over a received channel SNR range of 10 dB to 40 dB. Results at each SNR are averaged over 10^6 channel realizations for both STBC and SM configurations. The realizations for the path gain $\mathbf{H}$ of the channel were kept constant for a 100 symbol period, i.e., $L = 100$. The transmission bit rate of both the schemes was kept constant i.e., 160 kbps and QPSK modulation was applied. Channel coding was not applied in both cases. The simulations of the video channel and its transmission/reception were carried out in MATLAB.

3.1.3 Received Video Quality Evaluation

Primarily, two methods have been used for the assessment of the receive quality of the videos; PSNR and MOS. Results over 'Feature Extraction' and many other multivariate statistical analysis tools have not been included due to space constraints. The performance of the decoded video was quantified by PSNR computed between the original and received YUV sequences. MOS is the human quality impression usually given on a scale from 5 (best) to 1 (worst) shown in Table 3.1. An agreed conversion

Table 3.1: ITU-R Video Quality Scale and conversion to corresponding PSNR

MOS	Quality	PSNR
5	Excellent	≥ 37
4	Fair	31-36.9
3	Good	25-30.9
2	Poor	20-24.9
1	Bad	$\angle 20$

of PSNR to MOS [19] is also given in Table 3.1 and is used to quantify our results.

3.2 MIMO System Model

A configuration of 4x4 system is used. In order to analyze the SM configuration, the channel coefficients were assumed to be known at the receiver with zero-delay and were used to retrieve the transmit symbols using zero forcing (ZF) [4]. For STBC, we implement Tarokh et. al's 1/2 rate code [3].

Chapter 4

Receiver Centric Comparison

MIMO systems have been designed to overcome the bandwidth and BER limiting factors of wireless communication, these systems are anticipated to realize high-quality video communication in the next-generation mobile Internet systems [10],[11],[12].

In order to improve video quality, existing schemes for video transmission over MIMO channels complement SM and STBC with enhanced source and channel coding techniques [5, 6, 7, 8, 9]. While deferring details of these schemes to the next section, we note that these techniques do not cater for three critical constraints of practical wireless video communication:

1. Most wireless receivers are resource-constrained and therefore cannot support complex video decoding options;

2. A wireless receiver cannot dictate coding options to remote video servers;

3. A receiver's MIMO hardware does not provide substantial control over the physical layer (PHY) and hence a practical scheme should operate on higher layers while using only the supported PHY configurations.

With these constraints in mind, in this chapter we evaluate the performance of error-concealed video communication using only the basic SM and STBC configurations over a MIMO channel.

The increasing demand of ubiquitous availability of video services over hand-held low resource devices and the provision of the use of both SM and STBC in modern communication standards [10, 12] are the main motivations behind the inception and evaluation of this system. Therefore, we need to determine a generic yet simple architecture of the system using only SM and STBC, evaluate the received video quality of different videos and quantify the viewer response to the videos transmitted over the proposed system. In order to thoroughly evaluate the idea, the analysis needs to be carried out under exactly same physical parameters (i.e., modulation scheme, antenna configuration, transmission rate) to investigate and compare the performance of the two schemes for resource constrained receivers having no control over the physical layer transmission details.

To this end, we transmit different types of standard-complaint H.264-encoded video sequences over SM and STBC configurations. We first analyze our results on the basis of Peak Signal-to-Noise Ratio (PSNR) of the received video after standard error concealment. Our experimental results reveal that SM and STBC with error concealment are sufficient to achieve acceptable video quality in practical SNR regions. Thus, STBC and SM configurations which do not require transmitter/receiver modification below the application layer can provide good video quality at a low complexity cost. Traditionally, the spectral efficiency of these competing schemes is studied under different physical layer settings (mainly modulation and coding rate) in order to perform a judicious comparison by equalizing the spectral efficiency. Nevertheless, for a receiver-centric communication design that adaptively uses both the schemes, physical layer changes such as adapting to different coding and modulation rates not only increases the implementation complexity but also over kills the limited resources. In this chapter, we argue that for such a resource-constrained receiver it is more practical to equalize the spectral efficiency of the system at the application layer of the transmitter by adjusting the quantization error of the video for both SM and STBC. This indeed enables the system designers to implement light-weight simplified decoders which can be easily hosted on resource-constrained platforms. Our experimental results reveal several interesting insights. We identify three distinct channel SNR regions in which SM and STBCs PSNR performance changes based on varying content and channel characteristics; video quality in these regions is also evaluated using the subjective Mean Opinion Score (MOS). We show that for low spatio-temporal activity (e.g., video conferencing, broadcasting, etc.), basic SM and STBC can provide reasonably good video quality by switching to the appropriate (SM or STBC) scheme depending upon the SNR region of operation. In the case where the spatio-temporal variations are high and channel conditions are not favorable, video quality with SM can be improved significantly if residual errors are corrected by standard-complaint FEC at the MAC layer. In this case, the identified SNR based performance regions are different due to the agile content characteristics (i.e., highly varying in space and time). We study that the boundaries of the classified regions are flexible and depend on the video content complexity since the content agility of video data is a special feature which, in the present context, directly impacts decoding performance.

4.1 SNR vs PSNR Performance

In this section, we analyze the performance of SM and STBC over a wide range of SNRs with assumption of resource constraint as discussed earlier. We are interested in knowing that how effectively SM and STBC overcome the challenges of low bandwidth and high bit-error observed on wireless channels. Fig. 4.1 and 4.3 illustrate PSNR results. For analysis purpose, we divide the SNR vs. PSNR curve for each video into three distinct regions. These thresholds are source dependent and change from one video sequence to another. We defer the discussion on the flexibility of this threshold to the next section.

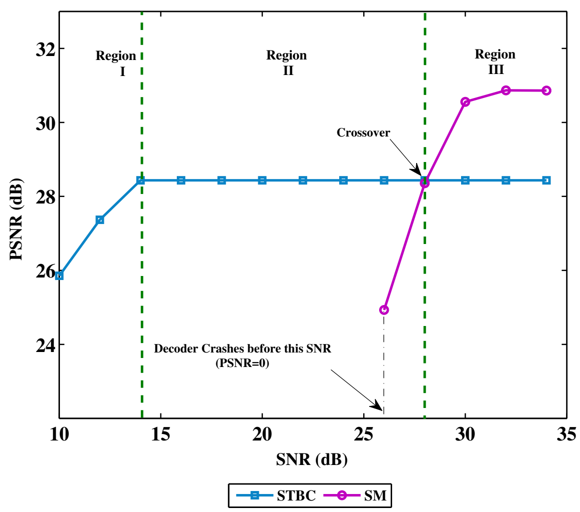
4.1.1 Region I

STBC provides diversity gain, it can be clearly observed that after 14 dB (Akiyo, Carphone and Mobile) and 16 dB (Foreman), the sequences transmitted using STBC are almost without channel error. This identifies our first SNR region (from $10-14$ dB for Akiyo, Carphone, and Mobile and $10-16$ dB for Foreman) within which the STBC videos converge to their maximum PSNR level. This steep convergence takes place due to the inherent redundancy present in the STBC configuration. On the other hand, videos transmitted using SM have very high BER in this region of SNR which increases the probability that the errors will corrupt critical video header information. As a result, it is not possible to decode the sequences transmitted using SM with standard error concealment options.

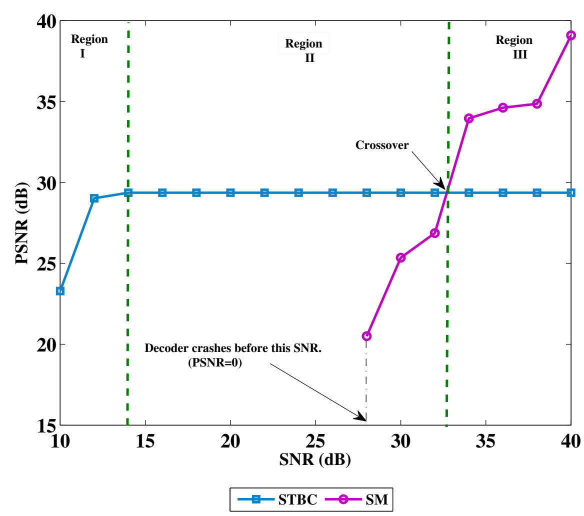
Hence, we deduce that for this relatively low SNR region: 1) STBC provides very good PSNR performance, clearly outperforming SM and, more importantly, precluding the need for more advanced source and channel coding schemes that were used by previous studies; and 2) STBC outperforms SM and provides a viable choice for video transmission in low channel SNR regions.

4.1.2 Region II

In the second region, marked from Akiyo: $14-28$ dB, Carphone: $14-33$ dB, Mobile: $14-40$ dB and Foreman: $16-38$ dB, the PSNR achieved through STBC remains at the same level because STBC's quantization error enforces an upper bound on



(a) Video sequence: Akiyo



(b) Video sequence: Carphone

Figure 4.1: PSNR vs SNR comparison between SM and STBC for low motion videos.

the achievable PSNR. SM videos begin to get decoded with low PSNRs at higher SNRs in this region. The PSNRs improve considerably with each dB increase in the channel SNR. Region II is upper-bounded by the SNR at which both SM and STBC yield identical PSNR. This point is henceforth referred to as the *crossover point*. In this region, although SM based videos begin to get decoded at higher SNRs, STBC continues to render better performance as compared to SM in this region.

We evaluate the frame number at which the decoder fails to decode on the SNR values of 15, 20 and 25 dB for SM based transmitted videos. The mean crashing points (frame number up till which the decoder decodes) and their standard deviations at 15, 20 and 25 dB of the decoder for SM based transmitted videos are reported in Table 4.1. The expected number of successfully decoded frames for all the four sequences increases with increase in SNR and their standard deviation also increases. This makes intuitive sense because with increasing SNR, the channel errors decrease and the probability of errors hitting the critical information which is required for successfully decoding the video once it is received also decreases. The decoder starts decoding completely after SNR of 26 dB, 28 dB, 30 dB and 30 dB for Akiyo, Carphone, Foreman and Mobile respectively.

Table 4.1: Means μ and Standard Deviations σ of Crashing points for SM.

Video Sequence		15dB	20dB	25dB
Akiyo	μ	25	64	98
	σ	0.6	7.3	12
Carphone	μ	20	30	61
	σ	3.1	6.4	23
Foreman	μ	18	24	70
	σ	2.2	4.6	9.9
Mobile	μ	17	24	40
	σ	1.9	5	11

Hence for Region II: 1) STBC again is more beneficial than SM without any advance source or channel coding scheme; 2)

STBC has reached its optimal achievable PSNR at the given level of quantization error and the value of PSNR is constant throughout this region; 3) SM sequences start getting decoded at higher SNRs in this region

4.1.3 Region III

In region III, SM starts to yield better video quality for all values of SNR. Hence, when the conditions are favorable, videos with much higher quality can be transmitted over a multiplexed MIMO system and recovered at the receiver while retaining their quality. Therefore, it can be concluded that at SNRs greater than the crossover point, the visual quality achieved by switching to SM is better than that of STBC.

4.1.4 Discussion

Based on the empirical analysis of this section, we conclude that low complexity video communication can be achieved using the basic SM and STBC MIMO configurations. However, an intelligent real-time selection needs to be made between the two schemes to reap the benefits of MIMO communication. It should be noted that this switching threshold varies from one video sequence to another and it is difficult to ascertain this threshold using only channel SNR information.

4.2 Video Content Characteristics vs PSNR Performance

Akiyo is a video with very little spatial and temporal motion. Carphone possesses some temporal motion. Foreman has notable spatial motion, and in Mobile both spatial and temporal motion is high. It can be demonstrated from fig. 4.1 and

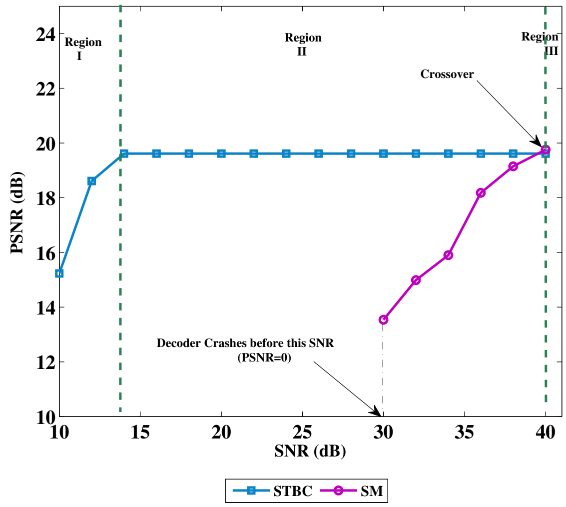
(a) $\text{Carphone}_{36\,\text{dB}}$: SM (left), STBC (right)

(b) $\text{Foreman}_{36\,\text{dB}}$: STBC (left), SM (right)

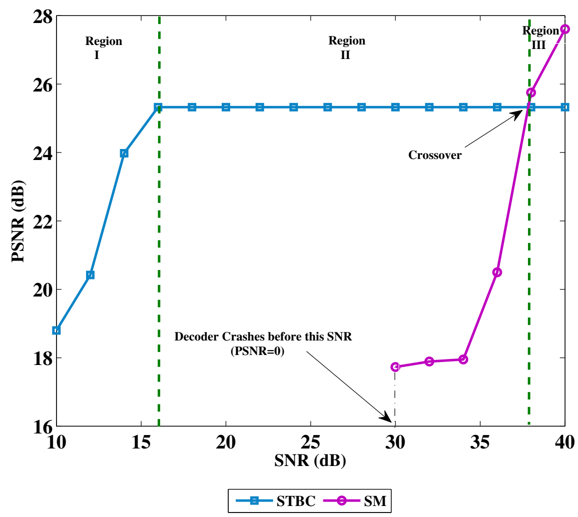
(c) Video sequence: mobile

Figure 4.2: Received/decoded frames over the best suited transmission scheme (left) vs. complementary scheme (right)

4.3 that the crossover point for a video with less movement (Akiyo/Carphone) occurs at a much lower SNR compared to that of a fast movement video sequence (Mobile); for Akiyo (low motion video), the crossover point is at 28 dB, whereas for mobile (high motion video) it is 40 dB. This shows that for common scenarios like video calls where the content possesses low spatio-temporal variations, high quality performance can be attained at comparatively low SNRs (corresponding to worse channel conditions) using simple SM. Under similar channel conditions, a compromise on information throughput and received video quality is made for videos like Mobile using STBC since SM fails for such a dynamic content. Nevertheless, in both the cases, the visual quality is quite acceptable which substantiates our argument that; 1) Low-complexity SM and STBC schemes



(a) Video sequence: Mobile



(b) Video sequence: Foreman

Figure 4.3: PSNR vs SNR comparison between SM and STBC for high motion videos.

can provide good video quality on resource-constrained wireless platforms and 2) Video content characteristics strongly dictate the switching point between SM and STBC to ensure high PSNR gains. These results validate our proposition that a simple wireless MIMO video transmission architecture with minimum decoding complexity at the receiver can only be designed if the impact of the spatio-temporal variations on the PSNR of the received video are given due importance along with the channel state information.

4.3 Subjective Evaluation of the Received Video quality

Before we explore the design possibilities of a content and CSI based adaptive video communication setup, we provide results of some subjective MOS tests using standalone SM and STBC configurations in fig. 4.4. Note that once all the spatial multiplexed videos start getting decoded (30dB), we get good video quality for Akiyo and Carphone due to the higher encoding rate of SM video. Under identical channel conditions, STBC produces a lower quality video for Akiyo and Carphone due to the upper bound imposed by its encoding rate which was explained in previous discussions. The visual quality of Foreman and Mobile remains unacceptable using SM at the same SNR. Contrary to Akiyo and Carphone, for high motion videos, STBC despite its lower encoding quality yields better visual results at the receiver. Intuitively, it can be justified that due to the agile characteristics of the video content, the inherent error resilience of H.264 coding and standard error concealment procedures do not produce acceptable results for SM and the redundancy/diversity benefit of STBC becomes more pronounced.

As the visual quality is assessed at higher SNRs, the performance of SM improves continuously for Akiyo and Carphone and finally converges to excellent video quality (see Table 3.1).

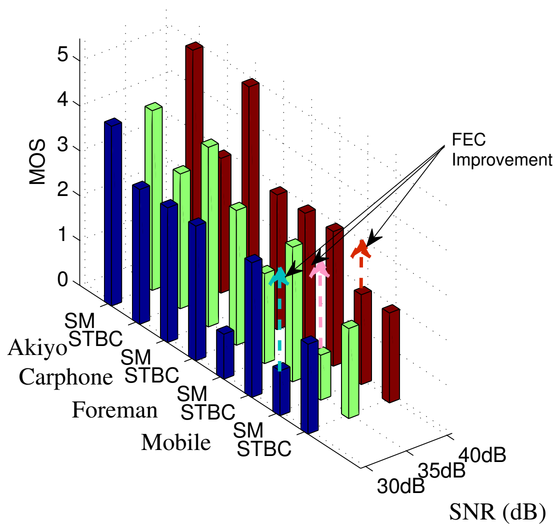


Figure 4.4: MOS scores

We did not observe a significant improvement in the quality of STBC video followed from the constant PSNR value of STBC in region II and III of fig. 4.1. Note that the overall performance of both SM and STBC can be increased by proportionally increasing their encoding rates. For the sake of simplicity, we only report our results at one pair of encoding rates.

It is evident from fig. 4.3(a) that Mobile has the highest spatial and temporal activity which results in the lowest PSNR performance. The MOS for both Foreman and Mobile shows poor visual experience, thus questioning the performance of the system in the present scenario where complexity is an important design constraint and video content is agile.

Most emerging wireless communication standards use a block FEC code above the air interface's physical layer to recover from residual error[1] [11, 12]. While this MAC layer FEC cannot recover from large fading effects, it can cater for low rate bit-error phenomena. We observed that if we introduce such a channel coding scheme at the MAC layer, video results can be substan-

[1]i.e., the errors which were not corrected by physical layer processing [20].

tially improved for SM without increasing the encoding rate. The dotted bars in fig. 4.4 show that for an MDS block FEC code of rate of 3/4, the MOS can be brought up to fairly acceptable level. We report FEC results only for the Mobile sequence since it is the most agile sequence.

Chapter 5

Switching Framework

In this chapter, we explain in detail our framework for adaptive video communication over MIMO channels. Our Proposed scheme exploits the fact that the switching SNR (SNR after which SM performs better than STBC) changes with the change in motion intensity of a sequence as studied in detail in chapter 4 by transmission of video sequences with varying spatio-temporal content individually over SM and STBC schemes. Using these results, we propose a framework to switch between SM and STBC based on motion intensity of a sequence and the received channel SNR.

5.1 Algorithm

An average Euclidean distance of motion vectors of a video is used as our measure of motion intensity which we call Motion Richness. Motion vectors are computed during the motion estimation process when the video is encoded [21]. An empirical relationship between motion richness and switching SNR is formed by transmitting standard video sequences individually over SM and STBC.

The block diagram of the framework is shown in figure 5.1. In the first step the video is encoded at a specified rate and a

GOP is transmitted to the *Motion Richness Computation* block. This block computes the motion richness value of the GOP received. We are doing it GOP by GOP as we cannot change the quantization parameter between the GOP without using switching frames. This application layer information (motion richness value) is shared with the information repository. A low delay feedback path is present between the receiver and the transmitter which provides the value of the received channel SNR to the information repository (transmitter side). Some emerging wireless communication standards (e.g., LTE) already provide a low delay SNR path from the receiver to network core entities. Even if a feedback path is not supported in the standard, existing video communication technologies implement it using transport and application protocols (e.g., RTCP, HTTP, etc.). SNR information is assumed to remain constant for a L symbol periods and is made available to the shared information repository.

The motion richness value and the receive channel SNR value is known to the information repository and in turn it has been assigned the task of deciding between the scheme to use for transmission. Using the motion richness value, switching SNR value α_n for each GOP of the sequence is calculated and the best suited transmission mechanism (SM or STBC) is selected for the transmission of the GOP. As shown in Chapter 4, STBC is more suitable in low SNR regions. Hence STBC is chosen if $\text{SNR}_n < \alpha_n$. The *Information Repository* layer passes the decision of the scheme to be used to the physical layer and the encoding rate for the scheme is dictated to the *Video Encoding* block .

The main components in the framework are the *Motion Richness Computation* and the *Decision Logic* block. The latter half of this section will specifically discuss, a) how is the Motion Richness value computed?; b) what is the relationship between

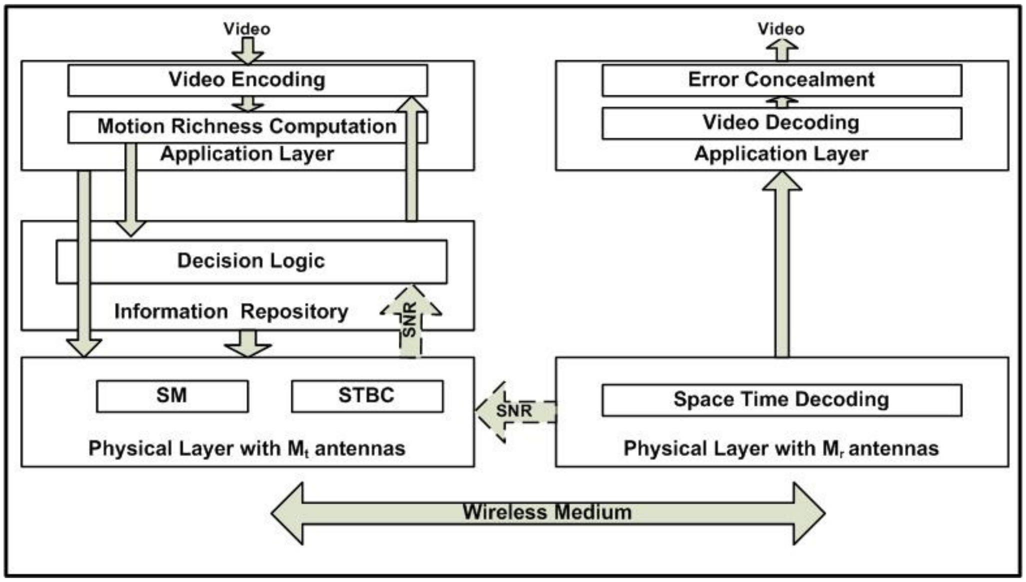


Figure 5.1: Design for adaptive switching between SM and STBC

motion richness and α_n? and c) what is the decision criteria in the decision logic block?

5.2 Motion Richness

Motion activity/intensity of a video sequence can be measured in uncompressed (color based calculation) as well as the compressed domain (using motion vectors). Compressed domain motion intensity extraction is computationally less complex than color base extraction. Thus, we choose to compute the motion intensity in compressed domain. Intensity of motion activity of a video sequence in compressed domain is defined in term of its motion vectors. Motion Richness give an average effect of a motion vector (mv) on the motion intensity of a video.

As already discussed a ratio of 1 : 8 is maintained between the encoding rates of STBC and SM respectively to equalize their spectral efficiency. A video stream with 8 times more quaniza-

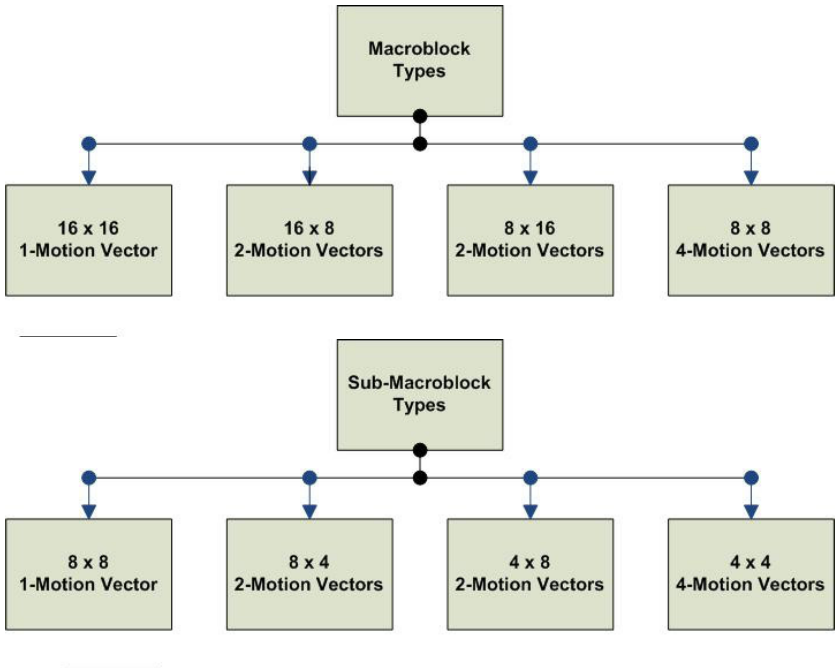


Figure 5.2: Macro Block Partition

tion error (video encoded for STBC) is transmitted to the motion richness block. We decided to use video encoded at the same rate as the one used for STBC for calculating motion richness because this scheme works on higher proportion of the SNR scale from $10-40dB$ as observed in section 4.1. Figure 4.1 shows that even in akiyo, which was the worst scenario in terms of using STBC, employed STBC on 60 percent of the channel SNR scale.

In H.264 each macro block can have sub macro blocks which can be further divided. A macro block contains different numbers of motion vectors as shown in figure 5.2. We compute the Euclidean distance of all the motion vectors (of macro blocks , sub macro blocks etc) present in a sequence using

$$h(x, y) = \sqrt{x^2 + y^2}, \tag{5.1}$$

where x and y are the motion vector in x and y directions respectively.

The Euclidean distance is a dimensionless positive value. We sum up the Euclidean distance of all the motion vectors in a GOP using

$$w_g = \sum_{i=1}^{\hat{T}} h_i(x, y), \tag{5.2}$$

where, w_g is the sum of the distances of the motion vectors in a GOP. We computed the average effect of a motion vector on the motion intensity of a sequence referred to as the motion richness b. Thus, b is

$$b = \frac{w_g}{\hat{T}}, \tag{5.3}$$

where $\hat{T}$ represents the total number of motion vectors present in the GOP. Again b is a dimension less positive number. The higher the value of b is, the higher will be the value of intensity of a motion present in a sequence.

5.2.1 Complexity level of Motion Richness Computation

The worst case time complexity of motion richness computation is observed when every frame is divided into sub macro blocks and every sub macro block is further divided. on the other hand, the best case complexity is when the macro blocks are not further divided.

5.3 Relationship between Motion Richness and Switching SNR

We have determined the Motion Richness and empirically computed α of different videos (four of those are discussed in detail in section 4.1) These videos are widely used and representative of all different kinds of spatio-temporal behaviors. In addition

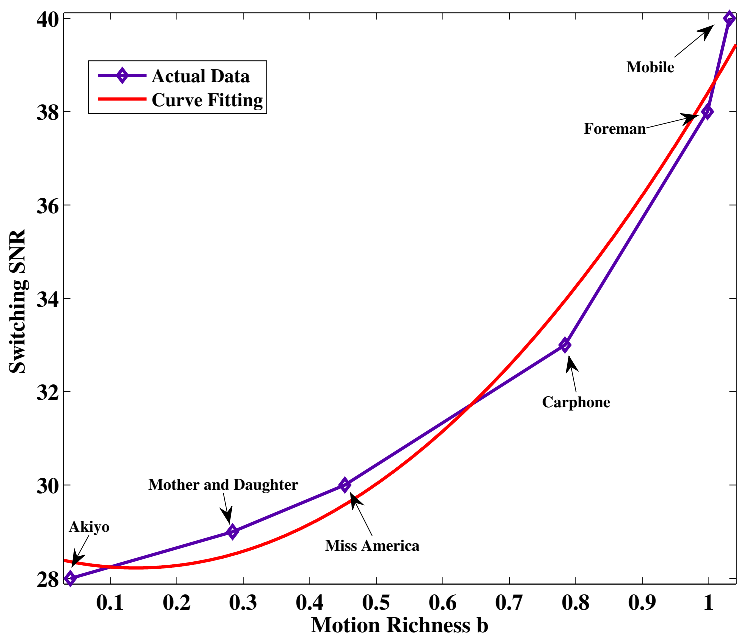


Figure 5.3: Relationship between Motion Richness and Switching SNR

to the α of the four sequences, we computed the α of two more sequences that are *Mother and Daughter* and *Miss America* to form a relationship between motion richness and α. More the number of videos a more accurate relationship can be formed. Figure 5.3 depicts the relationship between Motion Richness and α_n. A quadratic relation between the two can be clearly observed from the plot. On application of quadratic regression on the plot, we got the following relationship

$$\alpha_n = \left\lceil 13.77b^2 - 3.802b + 28.49 \right\rceil, \tag{5.4}$$

where α_n is the switching SNR and b is the motion richness of a *GOP*.

The decision logic block follows this relation 5.4 to compute α. On receiving the value of b from the motion richness computation block, the decision logic uses the equation given in 5.4 to compute the α_n.

5.4 Decision Criteria in Decision Logic

The final decision is reached by comparing the α_n value with the receive channel SNR value.

---

if $SNR \leq \alpha_n$**then**
    use STBC
    else
    use SM
end

At lower SNRs, as compared to α_n, an 8 times quantized version of the video is transmitted with additional redundancy to protect it from channel errors. In case the SNR is greater than the α_n , the channel is less prone to errors as compare to the channel at low SNRs. Consequently, the whole capacity of the channel can be utilized to transmit video without any redundancy to protect it from channel errors. Thus, before α_n it is better to have quantization error (present in videos transmitted over STBC) as compare to errors induced by the channel(SM based videos) and vice versa after α_n.

Chapter 6

Adaptive Framework: Performance Evaluation

In order to illustrate the performance of the motion-adaptive switching, in this chapter we present the results of the switching framework proposed in chapter 5. We simulated the experiments for a 4x4 MIMO system. We encoded a video sequence *news* for transmission over our simulated system. The experimental setup used is the same as discussed in chapter 3.

We used a GOP size of 12 and the motion richness of each is computed with the video encoded at $20kbps$. The GOP by GOP motion richness of the video to be transmitted (news) is shown in figure 6.2. The starting GOPs of the news sequence has low motion richness value whereas the higher GOPs have high motion richness value as compare to the starting GOPs. Based on the motion richness value a GOP by GOP, α_n is calculated using equation 5.4.

6.1 Performance Evaluation of Motion Adaptive Frame work

We use PSNR values and MOS scores to evaluate the performance of the proposed framework. The averaged PSNR re-

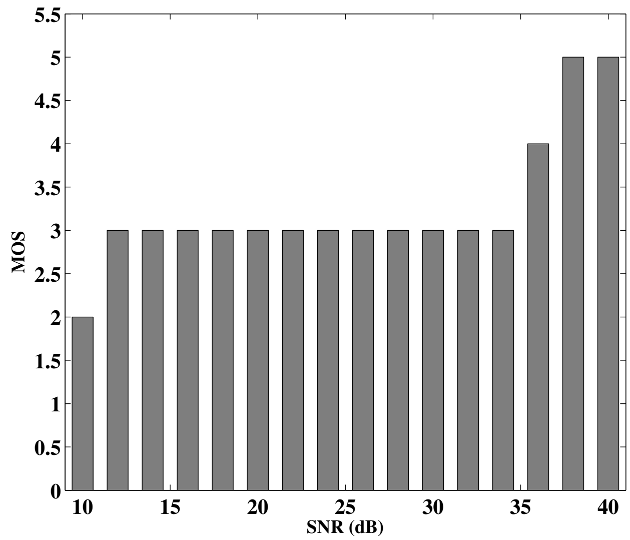


Figure 6.1: MOS scores for the sequence news

sults of the sequence *news* transmitted over an SNR range of $10-40dB$ are computed by taking decision of the scheme to be used after each GOP. Figure 6.1 and figure 6.4 shows the MOS score and the PSNR results respectively when transmitted over adaptive switching scheme.

The average time for the computation of motion richness value for 96 GOPs of different video sequences is $432ms$. This was performed on a computer with Inter Core2 Quad $2.4GHz$ processor and $1GB$ of memory.

6.2 Comparison with standalone SM and STBC

The PSNR performance of video over stand alone SM and STBC are shown in figure 6.4. In case of adaptive transmission, it can be observed that before 28dB, the PSNR results observed are same as that of STBC. This is because the motion richness value of the all the GOPs gives a switching SNR of greater than or equal to 28dB. Whereas after $36dB$, the observed PSNR values

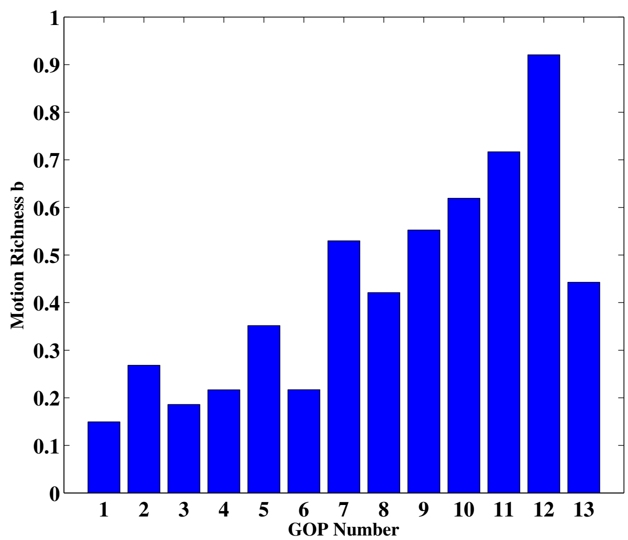


Figure 6.2: GOP by GOP motion richness analysis of news.

Figure 6.3: Frame number 137 (left most) transmitted over STBC and frame number 138 , 139 and 140 (second, third and fourth) transmitted over SM at an SNR of 28dB

for adaptive scheme is equivalent to those of SM because the switching SNRs computed using the motion richness values are less than or equal to $36dB$ for all the GOPs of the transmitted

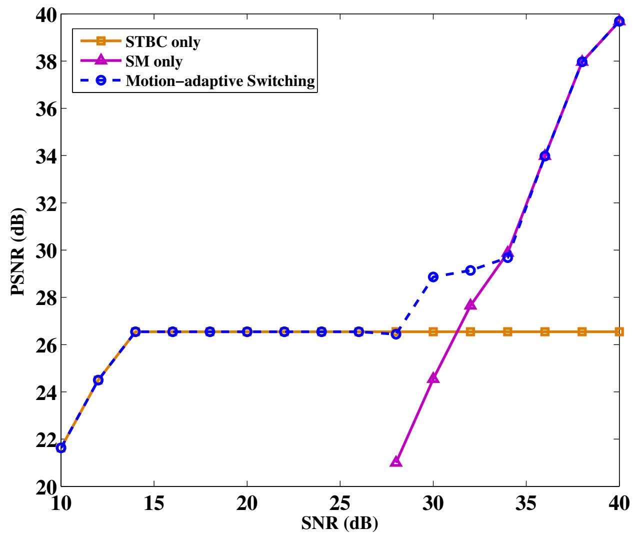


Figure 6.4: PSNR values for video news

stream. However, between $28dB$ and $36dB$ the adaptive scheme switches between SM and STBC.

Figure 6.3 shows the quality of different frames in case of different schemes used for transmission at $28dB$. A significant video quality improvement is observed when transmitted over motion adaptive scheme as compare to SM and STBC only.

6.3 Comparison with other Switching Techniques

Figure 6.5 compares the PSNR results of motion-adaptive switching with the existing switching schemes. The three existing switching schemes with which we compared our work are demmel condition number, relative condition number and determinant of channel matrix H based switching schemes. These schemes switch based on BER performance of the transmitted data whereas our motion-adaptive scheme switches based

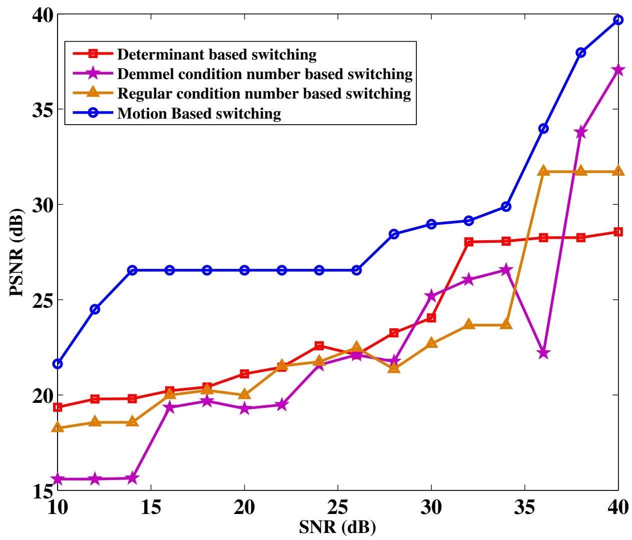


Figure 6.5: Comparison with other Switching Techniques

on PSNR of the received video. A gain in PSNR value for our motion adaptive scheme can be observed. For a SNR region of $10 - 25dB$ an an approximate gain of $3 - 7dB$ in PSNR is present as compare to all three existing switching schemes and on a scale of $25 - 40dB$ a gain of approximately $2 - 5dB$ is observed.Thus, a rise in PSNR is observed throughout the SNR scale as compare to the existing switching techniques which further strengthen our claim to use motion intensity in addition to the channel condition for switching between SM and STBC.

6.4 Discussion

Based on the empirical observations we conclude that spatio-temporal characteristics of a video plays an integral role in the decision to use a MIMO mode. Thus, while deciding the switching threshold motion intensity of a video stream and the channel conditions should be taken into consideration.

Chapter 7

Conclusions and Future Work

7.1 Conclusions and Summary

In this thesis, we performed a receiver centric comparison of video over SM and STBC under practical receiver constraints. We on the basis of the performance evaluation concluded that 1) SM and STBC without any enhanced source and channel coding are enough to provide reasonable video quality; 2) The cross-over point(SNR after which SM outperforms STBC) for a video depends on motion intensity of the video stream and 3) The video quality of the video with same encoding rate is lower for a sequence with high spatio-temporal motion.

The conclusions of performance evaluation resulted in a motion adaptive switching scheme for video transmission between the two schemes of MIMO i.e, SM and STBC. The decision of scheme (SM and STBC) to be used for video transmission should take the motion intensity of the stream into account before deciding the scheme. Based on the motion richness value, the transmitter knows its threshold at the transmitter side to switch on receiving a channel SNR from the receiver end. This threshold is the point before which videos with quantization error gives better performance than the channel based errors. We also want to emphasize the fact that BER does not transform into good quality video, thus we used PSNR as our switching criteria. Our simulation results show that the adaptive system performs better as compared to the the videos which are transmitted over STBC and SM only and content unaware switching technique

7.2 Future Work

The work is studied as a relationship between quantization error and channel error and can be studied with same quantization and different constellation size. It can also be extended for other encoding rates. In future, work can be done on rate independent formulation of mathematical theory for switching threshold keeping in view the tradeoff between spatial multiplexing and space time block code. This work should also be explored for other receiving algorithm of spatial multiplexing and for different coding rate of space time block code. An optimization model for this work can be investigated with an objective to maximize the video quality.

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