# Real-Time Video Transmission over MIMO OFDM Channels Using Space-Time Block Codes

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# REAL-TIME VIDEO TRANSMISSION OVER MIMO OFDM CHANNELS USING SPACE-TIME BLOCK CODES

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**ABSTRACT**

In this paper we consider the problem of faded wireless image and video transmission schemes over Multi-Input Multi-Output (MIMO) Orthogonal Frequency Division Multiplexing (OFDM) channels that are energy and the bandwidth constrained. A computationally inexpensive analytic mean square error (MSE) Distortion Rate (D-R) estimator for progressive wavelet coders which generates an exact D-R (distortion rate) function for 2-D and 3-D SPIHT algorithm is utilized from our previous work. Using the D-R function, a joint source-channel coding scheme using optimal equal error protection (EEP) is presented. Both analytic and Monte-Carlo simulations are presented for image and video sources. A system that uses two transmit antennas and two receive antennas expends 12 dB less in energy per bit for the same performance as a SISO system. Our results are also significantly better than outage probability JSCC schemes used by other authors. The joint source-channel coding (JSCC) scheme demonstrates that MIMO OFDM can achieve real-time high quality video transmission in low energy regions and the system is robust against the delay spread and doppler frequency shift.

## 1. INTRODUCTION

The public's demand for wireless multimedia is stimulating research in efficient transmission of visual information over wireless channels. Third generation systems are required to provide a data rate of 2 Megabit/s for fixed users and 384 Kb/s for mobile users. Both energy and bandwidth are constrained in such systems so that the maximum number of users per cell is limited. An example of an energy constrained cellular system is the Code Division Multiple Access (CDMA) system. CDMA multi-user designs have been proposed for many present and future cellular systems. The capacity of CDMA systems is interference limited. The performance of each user increases as the interference from other uses using the same frequency decreases. In CDMA systems the capacity is maximized if each mobile transmitter power level is constrained so that a signal arrives at a destination with the minimum required signal-to-interference (SIR) ratio. This is referred to as power control. If the power used by the mobile unit is too great, it will add undesired interference to other users. If the power is low, then high quality image and video transmission may not be possible. In this paper we consider the problem of Joint Source-Channel Coding (JSCC) of image and video in such energy and bandwidth constrained systems.

The rate required to send an uncompressed natural image may not be supported in real time due to bandwidth constraints and naturally the need for compression is realized. Progressive image and video transmission is problematic in the presence of noisy fading channels. Progressive source coders like Image SPIHT [1] and Video SPIHT [7] use a variable length format where the correct decoding of future bits depend upon the correct ceception of past bits. Decoding after the first single bit error can increase the expected distortion at the receiver and the best strategy is to stop decoding before the first bit error. In wireless communications, transmission errors can occur frequently, especially in fading channels where errors occur randomly in bursts. A good model that is also used in this paper to describe such channels is the Rayleigh fading channel [12] [13].

We are interested in the *spatial diversity* that the MIMO systems offer. Spatial diversity exploits the fact that the fading experienced by the multiple antennas will be independent when the there is a sufficient separation between the antennas. By coding across both space and time, Orthogonal Space-Time Block Coding (OSTBC) [10] [9] [14] [11] can be used to achieve maximal diversity even when the transmitter has no knowledge of the channel. Another advantage of OSTBC codes is that they decouple the MIMO channel into parallel space-time (ST) channels which leads to a linear time maximum likelihood (ML) detection. A combination of OSTBC and OFDM (Orthogonal Frequency Division Multiplexing) leads to Space-Time OFDM (ST-OFDM). This system is robust against inter-symbol interference (ISI) and deep fades due to the time-varying nature of the channel [14] [11].

A notable paper in the design of JSCC for MIMO systems is the paper of Song and Liu [8]. They used a combination of OSTBC and OFDM for progressive SPIHT transmission of the Lena image over Rayleigh fading channels. They proposed a UEP (Unequal Error Protection) JSCC scheme based on dynamic programming method and used solely RS (Reed-Solomon) coding because of their excellent burst error correction capabilities. Because of the great amount of simulation required at each energy transmission point, they only simulated the *Lena* image 300 runs at only one transmis-

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sion rate. Their JSCC scheme was designed based on target energy. The actual transmission energy was much greater than target energy which the JSCC was optimized over. This was done in order that a certain outage probability may be achieved.

In this paper we consider designing our JSCC based on average probability of error. We use optimum equal error protection (EEP) because of real-time considerations. By using interleaving as well as longer block codes , we will show a significant reduction in energy expended per bit relative to Song [8]. In Section 2 we describe our D-R (Distortion Rate) estimator and the optimal EEP parity allocation to match the D-R function. We also explain the loss characteristics between a mismatch of the source and channel through simulation. In section 3 we give brief overview of our MIMO-OFDM JSCC mode. In section 4 we use the already well studied performance of the RAKE receiver and obtain some analytical simulation results. In section 5 we consider Monte-Carlo simulations using the modified Jakes model proposed by Dent *et. al.* [16]. In Section 6, we present concluding remarks.

## 2. RATE DISTORTION PROFILE OF SPIHT

In our previous work [5], we demonstrated a simple method of obtaining the D-R curve for 2-D and 3-D SPIHT. We will keep track of the number of the newly found significant bits for each pass of the bit plane coder as well as the total number of bits per each pass. We assume that the bit plane decoding starts at the level $\tau = 2^n$ . Let us denote by $N_{SBS}(i)$ as the number of sign bits in pass $i$ and by $Nd_{SBS}(i)$ the number of sign bits decoded in pass $i$. Note that $N_{SBS}(i)$ is equal to the number of coefficients found significant at pass $i$. These quantities are easily generated by the SPIHT coder at virtually no cost in the computational complexity of the algorithm. Since SPIHT finds all the coefficients that are significant relative to a threshold at each pass, then $N_{SBS}(i)$ is equivalent to the number of transformed coefficients whose magnitude is greater than or equal to $2^i$ and less than $2^{i+1}$. Assuming that we stopped decoding during the sorting pass of the significance level $\tau = 2^k$, a good approximation for $D(R)$, denoted by $\hat{D}(R)$ is given by

$$\begin{aligned}\hat{D}(R) &= \frac{1}{K}\Bigg[\sum_{i=k+1}^{n} N_{SBS}(i)\frac{2^{2i}}{12}(\frac{1}{4})^{i-(k+1)}+ \\ & \frac{2^{2(n-k)}}{12}Nd_{SBS}(n-k)+ \\ & [N_{SBS}(n-k) - Nd_{SBS}(n-k)]\,\frac{7}{3}2^{2(n-k)}+ \\ & \sum_{m=0}^{n-k-1} N_{SBS}(m)\frac{7}{3}2^{2m}\Bigg] \qquad (1)\end{aligned}$$

Due to the progressive nature of the source coder bitstream, we stop decoding prior to the first decoding failure. Since all packets after an erroneous packet are corrupted due to their dependency on the incorrect packet, the expected distortion $E(D)$ depends on the location of the first packet error. The probability of the event that we successfully decode all blocks up to and not including block $m$ is given by

$$P_{bl}(m,t_m)\prod_{j=0}^{m-1}(1-P_{bl}(i,t_j)),$$

where $P_{bl}(i,t_i)$ is the probability of losing block $i$ which has a total of $2t_i$ parity bytes and expends $E_i$ energy per bit for block $i$. If all blocks before block $m$ are successfully transmitted then we denote the remaining distortion by $D_b(m)$. Then the expected end to end distortion $E(D)$ under a block budget constraint of $N$ and total source rate $R_s$ bits is given by:

$$\begin{aligned}E(D) &= \textstyle\sum_{i=0}^{N-1} D_b(i)P_{bl}(i,t_i,E_i)\prod_{j=0}^{i-1}(1-P_{bl}(i,t_i,)) \\ & +D(R_s)\prod_{i=0}^{N-1}(1-P_{bl}(i,t_i)) \qquad (2)\end{aligned}$$

The optimization of Equation 2 with fixed energy forms the objective function of the joint source channel coding scheme analyzed in [8][2] amongst many other papers mentioned therein. In our previous work [5]we obtained the optimal EEP and optimal unequal error protection (UEP) for binary symmetric channels (BSC) and showed that the performance of the two are very close for the BSC and fixed block length. The optimal EEP minimizes Equation 2 while finding the best parity allocation under the constraint that the parity allocation for all blocks are equal. Despite the slight performance loss in PSNR, the optimal EEP has some advantages over the optimal UEP. First, it does not require any extra header information pertaining to the D-R estimation for the receiver. For the optimal UEP, there exist two options for the receiver to have the necessary header information. Option one is to code and transmit the parity allocation per block. This can potentially be a large amount of information at high transmission rates. Option two entails sending the side information that is needed to calculate $\hat{D}(R)$ at the receiver. This is the number of total bits and sign bits at the end of each SPIHT pass. Considering that without the header information the decoding of the image can not correctly occur, the header information must be extremely well protected. On the other hand, for the optimal EEP the receiver just needs to know a single number that achieves the optimal EEP for a large group of blocks. The second advantage of the optimal EEP is that it does not require optimization techniques like those that employ gradient based methods or dynamic programming to obtain the optimal or near optimal UEP. For real time applications, the time delay to run such programs for every image or video sequence may be intolerable. For systems with power constraints like mobile phones, the use of an optimization program for every image or image sequences could potentially be an obstacle for the system designer. A third advantage of the optimal EEP is that the probability of decoding failure of all transmitted blocks is lower relative to the optimal UEP. Finally the optimal EEP is simpler to implement since the code rate is the same for each block over a large group of blocks whereas for an UEP scheme the parity per each block may vary.

Like the paper in [8], we employ Reed Solomon(RS)[4] codes which are a popular type of forward error correction (FEC) employed in fading channel environments. Their wide usage is due to their burst error correction capabilities. FEC is a technique that enhances channel reliability by adding parity symbols to the information message that is to be transmitted. The RS codeword that we use are of block size of $N_{code} = 255$ code symbols. Each code symbol is a 8 bit binary sequence. Denote the probability of code symbol error by $P_{cs}$. We assume that the probability of code symbol error for each code symbol is independent of other code symbols in each RS block. If the channel has memory then we may use interleaving to make sure that the code symbol errors are independent. Then $B(N_{code}, P_{cs})$, the number of symbol errors in a block, is a binomial random variable with parameters $N_{code}$ and $P_{cs}$. Then $P$, the probability of more than $t$ symbol errors, is given by [4]

$$P(t) = \Pr(B(N_{code}, P_{cs}) \geq t+1) = \sum_{i=t+1}^{N_{code}} \binom{N_{code}}{i} P_{cs}^{i}(1-P_{cs})^{N_{code}-i} \qquad (3)$$

In Figure 1 we have used optimal EEP scheme on the Lena image with a BPSK system and AWGN channel. The total transmission rate is $0.5$ bpp. The solid curve represent the optimum EEP for each $E_b/N_o$ . The dotted curve represents the optimal EEP at only 4.77 dB. The parity allocation used for $4.77$ dB is sub-optimal for all other rates. At the $E_b/N_o$ of 3 dB, there is a $17.31$ dB difference in PSNR between the optimal allocation and the mismatch allocation. At the $E_b/N_o$ of 7 dB there is only a $0.9$ difference in PSNR between the optimal allocation and the mismatch. Ideally we would like to be at the optimal matching point where there is no mismatch, but in case of a mismatch, it is preferable to use more parity symbols beyond the optimal parity allocation. In Figure 2 we have plotted the number of parity bytes ber block for the corresponding $E_b/N_o$.

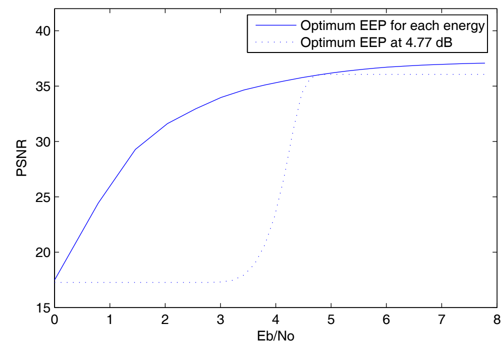


**Fig. 1**. Mismatch EEP for Lena.

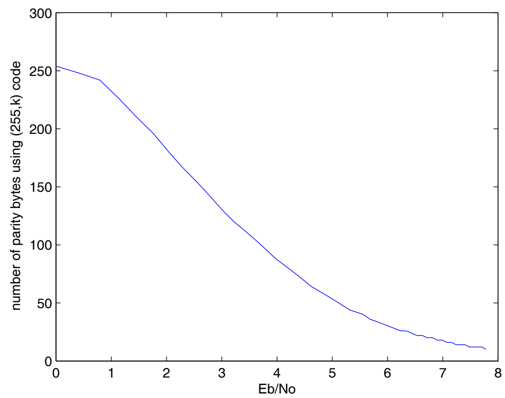


**Fig. 2**. Number of parity bytes allocated at each $E_b/N_o$

## 3. MIMO OFDM USING OSTBC

One of the advantages of OFDM is that the signal period of a sub-carrier is extended relative to a single carrier system. With the addition of small guardband, ISI is eliminated. Since our focus is on JSCC, we assume perfect carrier synchronization, perfect channel estimation of each of the gains of the sub-carriers and perfect suppression of multipath by the guard interval. The time-varying nature of this multipath channel is another obstacle that causes random fluctuation of the signal. This time variation arises because either the transmitter or the receiver or both are moving and therefore the location of the reflectors which cause the multipath will change over time. MIMO communication is a relatively new area in communications. MIMO systems have been shown to be robust against the fading channel. In a MIMO communications system the transmit and receive antennas are used in order to extract a substantial space diversity gain relative to the SISO (single-input single-output) system[11] [14] [10]. Antenna diversity provides the receiver with multiple samples of the same transmitted signal. Increasing the number of antennas, the probability that the fading gain of each antenna is small reduces sharply. Thus the spatial diversity of the MIMO system stabilizes the wireless link relative to a SISO system.

Figure 3 shows our generic MIMO OFDM STBC system. The R-S coder is used to combat fading and AWGN noise. The CRC is used for this purpose so that decoding may be stopped after first uncorrectable block error. The source and channel coder work together under our JSCC scheme so that the minimum receiver MSE is obtained at the receiver. Extra interleaving spreads possible burst errors over several RS code-words. The OFDM is used to combat ISI. Although not indicated in the diagram, we assumed that the OFDM guard-band is sufficiently long enough so that ISI is suppressed completely. The Alamouti encoder is used to obtain maximal antenna transmit diversity. The decoding process at the receiver is essentially the reverse of the transmission process, except for the ML decoding procedure described in [9].

Let us denote the channel impulse response between the $i$th receive antenna $(i = 1, 2,...M_r)$ where $M_r$ is the number of receive antennas and the $j$th transmit antenna $(j = 1, 2)$ as $g_{i,j}[l]$ $(l = 0, 1, 2, ..L - 1)$ , where $L$ is the maximum channel length among all the individual antennas. Let us denote a matrix $G[l]$, whose ij$th$ element is given by $g_{i,j}[l]$. Throughout this work, we assume that every $g_{i,j}[l]$ is zero mean circularly symmetric complex Gaussian distributed and the variance of $g_{i,j}[l]$ is equal to $1/L$ for $l = 0, 1, 2, ..L - 1$.

For the MIMO OFDM OSTBC system using the Alamouti code, the discrete baseband symbol at subcarrier index $k$, can be represented in the following notation[11]:

$$\mathbf{y}[k] = \mathbf{H}[k]\mathbf{s}[k] + \mathbf{n}[k] \tag{4}$$

where $\mathbf{H}$ is a matrix of dimension $M_r \times 2$, $\mathbf{y}[k]$ is the $M_r \times 1$ received vector, $\mathbf{s}[k]$ is the transmit signal vector with dimension $2 \times 1$, and $\mathbf{n}[k]$ is zero mean circularly symmetric complex Gaussian noise vector with variance $N_o$ of dimension $M_r \times 1$. The matrix $\mathbf{H}$ is related to the matrix $G$ by:

$$\mathbf{H}[k] = \sum_{l=0}^{L-1} G[l] \exp(-\frac{j2\pi kl}{N_s}) \tag{5}$$

where $N_s$ is the number of sub-carriers. Using the Alamouti scheme in the OFDM context, we assume that channel remains relatively constant over consecutive sub-channels. That is $\mathbf{H}[k] \approx \mathbf{H}[k+1]$. So the data symbols $s_1$ and $s_2$ are transmitted over sub-channel $k$ on antenna 1 and and antenna 2 respectively and the data symbols $-s_2^*$ and $s_1^*$ are transmitted over antennas 1 and 2 respectively over sub-channel $k + 1$. Alternatively one can use spatial diversity across each OFDM symbol, but this requires that the channel remains constant over two OFDM symbol period. This alternative method was used in [8].

## 4. ANALYTICAL SIMULATION FOR MIMO OFDM OSTBC

Alamouti and Tarokh *et al.* [9][10] have show that a $(M_t,M_r)$ MIMO system using STBC achieves the same diversity gain as an equivalent $(1, M_rM_t)$ RAKE receiver using maximal ratio combining (MRC). The bit error rate (BER) performance of 4-QAM with a diversity order $m$ using MRC with independent and identically distributed Rayleigh fading coefficients is given by[15](pg 542):

$$BER = p^m \sum_{k=0}^{m-1} \binom{m-1+k}{k} (1-p)^k \tag{6}$$

where $p$ is given by:

$$p = \frac{1}{2} - \frac{1}{2}(1 + \frac{1}{E_b/N_o})^{-\frac{1}{2}} \tag{7}$$

A two channel receiver scheme has a gain of 3dB over the Alamouti diversity scheme due to the array gain. So the $E_b/N_o$ needs to be halved in Equation 7 for the Alamouti scheme[15] (pg 553). We can use Equations 6 and 3 in Equation 2 to obtain the optimal EEP and the MSE performance of the MIMO OFDM STBC system. In Figure 4 we have plotted the PSNR performance under an optimal EEP scheme for Lena at a rate of 0.5. The results were obtained for a SISO system using 4-QAM, a MIMO system of (2,1) and a MIMO system of (2,2). In comparison with the results of [8], our (2,1) Alamouti scheme using average probability of error outperforms their (2,2) and (2,4) system by over 8 dB in PSNR at the $E_b/N_o$ of 5 dB. Similarly our (2,2) system at the $E_b/N_o$ of 5 outperforms their system by 12 dB. It should be mention that in our (2,2) system we have used the array gain at the receiver. The large difference between our results and their result is due to the fact that we designed our JSCC based on average probability of error whereas their scheme is based on the outage probability. We have also used longer RS codewords in our JSCC scheme and also used an accurate D-R function. Similarly for the same PSNR of 35 dB, our (2,2) scheme saves about 12 dB in $E_b/N_o$ relative to a SISO system. In Figure 5 we have obtained the optimum EEP PSNR for the first 16 frames of the luminance component of the Susie image sequence at the rates of 0.1. It should be noted again that our D-R estimator can be used for both image and image sequences.

## 5. MONTE CARLO SIMULATION FOR MIMO OFDM

We now consider Monte Carlo simulation for the MIMO OFDM system. We consider a system that transmits 512 kilo-symbols/s on a carrier frequency of 2 GHz. The system uses 512 4-QAM sub-carriers. A two ray channel model with delay

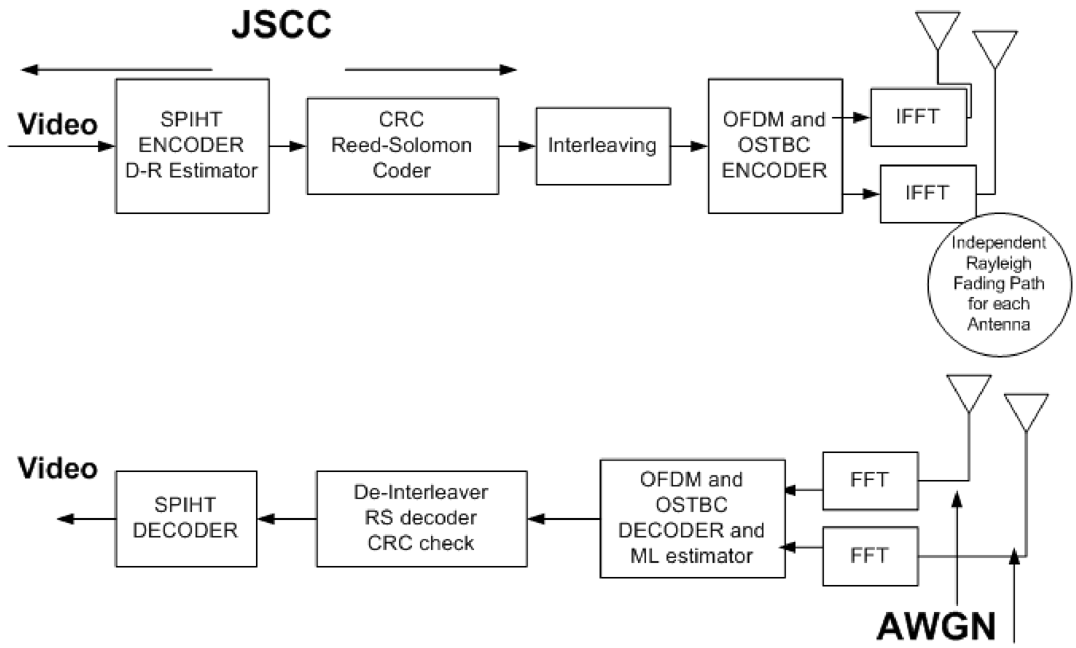


**Fig. 3**. A generic model of the MIMO OFDM system

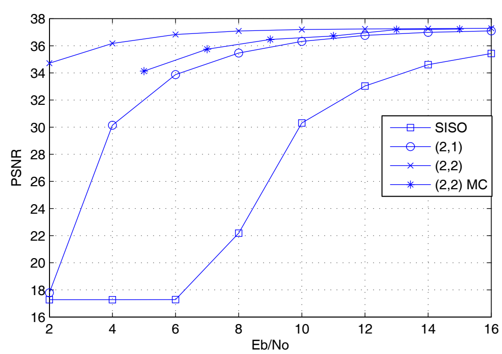


**Fig. 4**. Analytic simulation results for optimum EEP for Lena at 0.5 bpp in MIMO

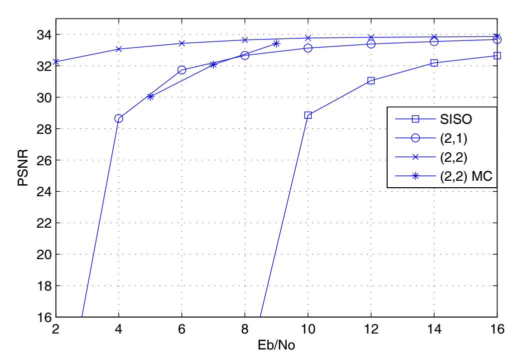


**Fig. 5**. Analytic simulation results for optimum EEP for Susie at 0.1 bpp in MIMO

spread from 0 to 100 $\mu$s is used in our simulation. To completely remove the ISI, 104 of the sub-carriers will be used as guard tones which provides a maximum tolerance of about 200 micro-second to the delay spread. The duration of each OFDM symbol is 1 milli-second. The system model is the one described in Section 2. The channel coefficients are drawn according to the model [16] which is modified from that of Jakes[12]. The modification of Jakes' approach uses orthogonal Walsh-Hadamard codewords to decorrelate the multiple fading coefficients. The steps of the JSCC are simple. First we estimate the D-R function according to Equation 1. Then given the assigned energy and rate constraints, we plug Equations 1, 3 and 6 to obtain the optimum EEP from Equation 2 . Due to the large amount of simulations, and due to emphasis on MIMO systems, we have simulated all runs for the (2,2) MIMO system. We have run the simulations for the mobile speed of 120 km/sec. Each point was simulated 200 times. Both time interleaving of delay 15 millisecond and frequency interleaving over the sub-carriers are used to spread out the fading. The frequency interleaving does not cause any delays. In Figure 4 we have plotted the $E_b/N_o$ vs PSNR. At an $E_b/N_o$ of 5 dB our results are 34.12 dB in PSNR. Relative to the results of [8], this is about 10 dB improvement in PSNR for Lena at the rate of 0.5 bpp. In Figure 5 we ran the simulator for Susie at a rate 0.1 bpp. The Monte Carlo results are indicated by the legend MC. The results are slightly lower than the analytical simulation results predicted in Section 3. This could be due to the more realistic channel model used in the simulator [16] and the fact that the interleaving was not sufficient to make the symbol error probabilities independent as required by Equation 3. Since the symbol error probabilities were not completely independent, the actual probability of block error was slightly higher than that predicted by the analytical equations. Nevertheless, the results suggest that using the average probability error instead of the outage probability, a closer match to the optimal matching of the channel characteristics and the source characteristics is obtained.

## 6. CONCLUSION

In this paper we presented a new real-time JSCC framework for the transmission of image and video sequences over MIMO OFDM systems. The real-time JSCC scheme was designed for fixed transmission energy and a fixed transmission rate. The OFDM was used in order to suppress ISI and the SBTC code was used to obtain spatial diversity in order to reduce the effect of fading. Further time and frequency interleaving was used to spread out deep fades. Because of the fast D-R estimator and the usage of optimal EEP, the JSCC framework presented is suitable for real-time applications. The major result of the paper suggests that for the same energy and rate, using average probability of error to model the channel characerteristics and matching it to the source produces a much higher PSNR than using the outage probability method in [8]. The other major result of the paper is that (2,2) system obtains an almost 12 dB gain in PSNR for the same transmission energy expended.

## 7. REFERENCES


[1] A. Said and W. A. Pearlman. "A new, fast, and efficient image coded based on set partitioning in hierarchical trees." *IEEE Transactions on Circuits and Systems for Video Technology,* 6(3):243-250, June 1996.

[2] A. Nosratinia.; Jin Lu; B. Aazhang, "Source-channel rate allocation for progressive transmission of images," *IEEE Transactions on Communications.*, Volume: 51 Issue: 2 , Feb. 2003 .

[3] Athanasios Papoulis,"'Probability, Random Variables and Stochastic Processes," McGraw-Hill, 3rd Ed., 1991.

[4] S. B. Wicker, *Error Control Systems.* New Jersey: Prentice Hall, 1995.

[5] Masoud Farchchian, Sungdae Cho & William A. Pearlman, "Robust Image and Video Transmission Using Unequal Error Protection Algorithm and OFDM ", IEEE Transactions on Signal Processing Letters, vol. 11, no. 10, pp. 780-783, 2004

[6] T. S. Rappaport, Wireless Communications: Principles and Practices, Prentice Hall, 2001.

[7] B-J. Kim and W.A. Pearlman, "An Embedded Wavelet Video Coder Using Three-Dimensional Set Partitioning in Hierarchical Trees," *IEEE Data Compression Conference*, pp. 251-260, March 1997

[8] J. Song and K. J. R. Liu, "Robust progressive image transmission over OFDM systems using space-time block code", *IEEE Transactions on Multimedia.*, vol. 4, pp. 394-406, september 2002.

[9] Alamouti, S.M. (1998). A simple transmit diversity technique for wireless communications. *IEEE Journal on Selected Areas in Communications*, 16:(8):1451-1458

[10] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space-time block codes from orthogonal designs," *IEEE Transactions on Information Theory,* vol. 45, pp. 1456-1467, Jul. 1999.

[11] Paulraj, A., Nabar, R., and Gore, D. (2003). *Introduction to space-time communications.* Cambridge University Press, Cambridge, UK.

[12] W. C. Jakes, *Microwave Mobile Communications*, Wiley, 1974.

[13] T. S. Rappaport, *Wireless Communications: Principles and Practices*, Prentice Hall, 1996.

[14] Erik G. Larsson and Petre Stoica, *Space-Time Block Coding for Wireless Communications*, Cambridge University Press, 2004

[15] Barry, J.R, Lee, E.A, and Messerschmitt, D.G, *Digital Communications*, Kluwer Academic Publishers, 2004

[16] P. Dent, G. Bottomley and T. Croft, "Jakes fading model revisited," IEE Electronics Letters, vol 29, no 13, pp. 1162-1163, June, 1993