Cross-Layer Optimization for H.264/AVC Video Transmission Over Space-Frequency (SF) Coded MIMO-OFDM Systems

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Abstract—**Multicarrier communication becomes a natural choice to transmit multimedia content at high data rates. Among multicarrier communication techniques, the combination of Orthogonal Frequency Division Multiplexing (OFDM) technology with Multiple Input Multiple Output (MIMO) systems is very effective for high data rate wireless communication. In this paper, we propose a cross layer optimization technique for transmitting H.264/AVC video data over a MIMO-OFDM wireless channel. A set of fast time-varying and frequency selective fading channels is considered. The channel is assumed to be unchanged for the duration of one OFDM block and change independently from one OFDM block to the other. The number of pilot symbols for each OFDM block is held constant and they are dispersed throughout the block for efficient channel estimation. The video transmission system uses a jointly optimal Space Frequency (SF) code design and pilot placement scheme. Rate Compatible Punctured Convolutional (RCPC) codes are used for channel protection. The problem formulation selects the set of source and channel coding rates along with the optimal pilot placement for a total bit rate constraint. The performance of the optimal power allocation case is compared with the equal power distribution case. At the transmitter, we have developed a method for the estimation of the video distortion at the receiver for given channel conditions. The accuracy of this method is validated using experimental results. Computer simulation results are shown for a 2×2 MIMO-OFDM system but the results can be extended to MIMO-OFDM systems with any number of transmit and receive antennas.**

Index Terms—**Multiple Input Multiple Output (MIMO), Video Coding, Cross-Layer Optimization, Space Frequency (SF) Codes, H.264/AVC.**

I. INTRODUCTION

During the past few years, there has been an increased interest in multimedia communication over different types of channels. In recent days, a significant amount of research has been focused on multimedia transmission over wireless channels. Multicarrier communication becomes a natural choice to transmit multimedia content at high data rates. Among the multicarrier communication techniques, Orthogonal Frequency Division Multiplexing (OFDM) has become a popular technique for multimedia transmission over wireless channels. It converts a frequency selective fading channel into a parallel collection of frequency-flat subchannels. In [1], we optimized a wireless system for video transmission over an OFDM system. In [2], a cross-layer optimization approach is proposed for video transmission over the Media Access Control (MAC) layer. The paper focuses on resource allocation of the source coding rate and channel coding rate with optimal MAC frame length.

On the other hand, in a Multiple Input Multiple Output (MIMO) communication system, multiple antennas can be used at the transmitter and the receiver. A MIMO system can be implemented in a number of ways to achieve diversity gain [3], [4] to account for signal fading or to obtain capacity gain [5], [6], [7]. Hence, the combination of OFDM technology with MIMO systems becomes a natural choice for high data rate wireless communication [8]. However, the performance of such systems depends upon the knowledge of the channel state information at the receiver.

Blind channel estimation techniques, though utilizing the complete bandwidth for data transmission, require the channel to be a slow time-varying one. In practice, however, it would not be reasonable to expect such channel conditions at all times. In fast fading channel environments, blind channel estimation techniques show steep degradation in performance. Non-blind channel estimation techniques at the other end involve transmitting pilot symbols alone over an OFDM block followed by OFDM blocks containing user data symbols. The channel state estimated using the pilot data is assumed to be constant till the next pilot OFDM block arrives at the receiver. Semi-blind channel estimation combines both of the above mentioned techniques by transmitting OFDM blocks which contain a set of pilot symbols and data within the same OFDM block instead of transmitting pilot-only OFDM blocks a priori. Besides providing channel estimation performance that is comparable to non-blind techniques, such a scheme allows for increased data rates for the same power and channel capacity constraints. However, direct implementation of this technique without judicious design and placement of pilot symbols in coordination with data symbols would result in having to perform inversion of matrices of high dimensions. The computational complexity involved in performing such operations is clearly not feasible for estimating the channel in

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fast fading environments [9].

In [10], [11], [12], channel estimation for MIMO-OFDM channels has been studied. In [12], a pilot tone design technique was proposed. The pilot tone design was connected to Space-Frequency (SF) codes utilizing the ideas of simplified channel estimation algorithm in [10], [11]. In this paper, we propose an alternative approach by extending the pilot placement design in [12]. A joint source-channel coding framework is proposed for the transmission of H.264/AVC video over a MIMO-OFDM system with joint pilot placement and SF code design. At the transmitter, we have developed a method for the estimation of the video distortion at the receiver for given channel conditions. Rate Compatible Punctured Convolutional (RCPC) codes are used for channel protection. The problem formulation selects the set of source and channel coding rates for a total bandwidth budget. The performance of the optimal power allocation case is compared with the equal power distribution case.

The rest of the paper is organized as follows. In section II, the basic model for a MIMO-OFDM system along with the signal model are presented. The video transmission system is proposed in Section III. In Section IV, experimental results are presented. Finally, in section V, conclusions are drawn.

II. SYSTEM MODEL

In this section, we provide the signal and channel model for the system. The source data bit stream is channel coded and modulated before being fed to a MIMO Space-Frequency (SF) encoder. The individual bit streams from each of the antennas are then subjected to an adaptive pilot sequence insertion along with optimal power allocation between data and pilots. The bit streams are then fed to OFDM modulators at each of the Tx antennas which perform an inverse FFT (IFFT) operation followed by cyclic prefix (CP) insertion in order to mitigate the effect of Inter Symbol Interference (ISI). The resultant OFDM blocks from the N_t transmit antennas are sent over a time-varying frequency-selective fading channel. At the N_r receive antennas, the inverse operations of those at the transmitters are performed in addition to the channel estimation, which is done using pilot symbols that are extracted from the OFDM blocks. Optimal Maximum Likelihood (ML) detection is then performed in the MIMO SF decoder and the resultant bit-stream is demodulated / channel decoded to obtain the final estimate of the source bit-stream.

A. Channel Model

In our system, the assumption made is that the channel is block fading, i.e. the channel coefficients remain constant over one OFDM block but change from one OFDM block to another. Let us denote $h_l(i,j)$ to be the lth coefficient of the channel impulse response to the jth transmit antenna from the ith receive antenna. From the Discrete Fourier Transform (DFT) relation we have,

$$H_k(i,j) = \sum_{l=0}^{L-1} h_l(i,j) W_N^{kl} \quad l = 0, 1, \ldots, (L-1) \qquad k = 0, 1, \ldots, (N-1) \tag{1}$$

where, $H_k(i,j)$ is the kth tone of the channel frequency response at the jth transmit antenna from the ith receive antenna. Here, N is the length of the OFDM block, also representing the number of FFT/IFFT points, L represents the channel length and $W_N = e^{-j2\pi/N}$. For a $N_r \times N_t$ MIMO-OFDM system, $h = [h_0^T, \ldots, h_{L-1}^T]^T$, $H = [H_0^T, \ldots, H_{N-1}^T]^T$, $\underline{\Im}_N = \Im_N \bigotimes I_{N_r}$ where, $\Im_N$ is a $N \times N$ DFT matrix and $\bigotimes$ denotes the Kronecker product. Also, $(.)^T$ denotes the transpose operation while I_{N_r} is a $N_r \times N_r$ identity matrix.

B. Signal Model

Let us denote the transmitted OFDM block from the ith transmit antenna by $\mathbf{S(i)} = [S_0(i), S_1(i), \ldots, S_{N-1}(i)]$. Also, let us denote the received OFDM block at the jth receive antenna to be $\underline{Y}(j) = [Y_0(j), Y_1(j), \ldots, Y_{N-1}(j)]$. Also, if we denote the Channel Frequency Response (CFR) matrix at the jth receive antenna by

$$\underline{H}(j) = \begin{pmatrix} H_0(j,1) & \cdots & H_0(j,N_t) \\ \vdots & \ddots & \vdots \\ H_{N-1}(j,1) & \cdots & H_{N-1}(j,N_t) \end{pmatrix}, \tag{2}$$

then the received and transmitted OFDM blocks are given by the relation $\underline{Y}(j) = S\underline{H}(j) + \underline{Z}(j)$ where, $S = [diag\{\mathbf{S}(1)\}, \ldots, diag\{\mathbf{S}(\mathbf{N_t})\}]$ and $\underline{Z}(j)$ is the zero mean additive white Gaussian noise at the jth receive antenna.

III. DESIGN OF VIDEO TRANSMISSION OVER MIMO-OFDM SYSTEM

A. H.264/AVC Video Codec

H.264/AVC is the latest video coding standard of ITU-T VCEG and ISO/IEC MPEG [13]. H.264/AVC is organized into two conceptual layers: the Video Coding Layer (VCL) and the Network Abstraction Layer (NAL). The VCL deals with the efficient encoding of the video data while the NAL defines the interface between the encoded video data and the transport media. The primary goals of H.264/AVC are improved coding efficiency and improved network adaptation. The VCL employs techniques like integer transforms, multiple block size motion estimation, multi-frame motion prediction, quarter pixel motion accuracy, different intra encoding modes, Context Adaptive Variable Length Coding (CAVLC), Context Adaptive Binary Arithmetic Coding (CABAC), deblocking filter etc. to achieve high compression efficiency for the same video quality compared to previous standards.

B. Channel Coding

Rate Compatible Punctured Convolutional (RCPC) codes are used for channel coding. RCPC codes are an obtained by puncturing a low rate mother code periodically. For the RCPC codes, fewer bits punctured leads to a lower channel coding rate and more powerful error correction. The convolutional codes are decoded using the Viterbi algorithm, which is a maximum likelihood estimation procedure. The major benefit of the RCPC codes with the same mother code is that they can all be decoded by the same Viterbi decoder [14].

C. Optimal Resource Allocation

In our discrete optimization problem, the total available bit budget is shared between the source and channel coding. Thus, a high source coding rate will allow lesser channel error protection and vice versa. The proposed pilot assisted transmission technique multiplexes known symbols with information-bearing data to estimate the channel. The number of pilot symbols is kept constant for each OFDM block. Hence, the higher the number of inserted pilot symbols, the lower the number of data symbols transmitted. Two pilot-tone designs are considered. The pilot-tone design 1 ($N_t = 2$ design) requires a lesser number of pilot tones to be placed along the sub-carriers of an OFDM block compared to the pilot-tone design 2 ($N_t = 4$ design). This implies that a a larger number of sub-carrier slots can be used to transmit data in design 1 than in design 2.

The power is optimally allocated between the data and pilots within each OFDM block to achieve minimum bit error rate (BER) for a specific SNR. The power is distributed such that, $\frac{1}{N}\sum_{k=1}^{N}(P_k^{(p)} + P_k^{(d)}) = P$ where, N is the length of the OFDM block and $P_k^{(p)}$ and $P_k^{(d)}$ are the power for the pilot and data parts of the symbol respectively. Let R_s be the set of source coding parameters, R_c be the set of channel coding parameters, P_{ratio} is the fraction of the power allocated to the data and pilot symbols in each OFDM block and N_t denotes which joint SF coded pilot placement scheme is used. Mathematically, $R_s = \{R_{s_1}, \ldots, R_{s_M}\} \in S^M$ and $R_c = \{R_{c_1}, \ldots, R_{c_N}\} \in C^N$ and $P_{ratio} = \{P_1, P_2, \ldots, P_t\} \in P^t$, $N_t = \{N_{t_1}, N_{t_2}\} \in N_t^c$. The distortion has two components namely source distortion (D_s), which is deterministic and the channel distortion (D_c) that is stochastic. Hence, the mathematical formulation for the optimal power distribution case can be written as,

$$\min_{R_s,R_c,P_{ratio},N_t} E\{D_{s+c}\} \text{ subject to } R_{s+c} \leq R$$
$$\text{and } \frac{1}{N}\sum_{k=1}^{N}(P_k^{(p)} + P_k^{(d)}) \leq P \qquad (3)$$

where, R_{s+c} is the total number of bits used for source and channel coding, R is the bit rate constraint and $P_{ratio} = P_k^{(p)}/P_k^{(d)}$ is the fraction of the total power allocated to data and pilot symbols in each OFDM block such that $\frac{1}{N}\sum_{k=1}^{N}(P_k^{(p)} + P_k^{(d)}) \leq P$.

The constrained optimization problem in Eq. (3) can be solved in general using the Lagrangian optimization technique and can be written as,

$$\min_{R_s,R_c,P_{ratio},N_t} J(s,c) = \min_{R_s,R_c,P_{ratio},N_t} \{E[D(s,c)] + \lambda \times R(s,c)\} \qquad (4)$$

where λ is selected in order to meet the bit rate constraint.

The D_{s+c} values are calculated using the algorithm in Section III-D to estimate the distortion D_{s+c} at the H.264/AVC encoder. The packet loss rate is calculated as

$$PLR = 1 - (1 - BER(R_c, N_t, M))^{PL} \qquad (5)$$

where, PL is the fixed length of the video packet and BER is the bit error rate calculated from a set of channel parameters, i.e. channel coding rate (R_c), modulation scheme (M) and joint SF code design and pilot placement scheme (N_t).

Our target is to find the optimal bandwidth allocation which requires changing both the source coding rate, channel coding rate, pilot placement scheme and the power allocation between the data and pilots in each OFDM transmission block. It is done in two steps. In the first step, we calculate the probability of error for sending H.264/AVC video data over the MIMO-OFDM wireless channel for discrete sets of channel coding rates (R_c) and the pilot placement scheme (N_t) and power allocation between the data and pilots (P). The effective channel coding rate is depending on the pilot placement scheme. The bit error rate values are used to find the packet loss rates according to Eq. (5). In the next step, we tradeoff the packet loss rate and the source coding rate (R_s) under a total bit rate constraint. The bit rate constraint of the system (R) is chosen as 384 kbps. It is related to the other system parameters as,

$$R = \frac{R_s}{k \times R_c \times \log_2 M} \qquad (6)$$

where R is the total bit rate constraint of the system, R_s is the source coding rate, M is the chosen modulation scheme for the MIMO-OFDM system. $k = \frac{y_d}{y_d + y_p}$ where, y_d is the number of data symbols and y_p is the number of pilot symbols in each transmitted OFDM block. At the transmitter, we use a method for the estimation of the video distortion at the receiver for given channel conditions. The details of the estimation of the distortion at the video decoder can be found in Section. III-D.

D. Estimation of Rate-Distortion Functions

Let f_n^i denote the original ith pixel value at frame n, $\hat{f}_n^i$ denote the corresponding reconstructed pixel at the encoder for the nth frame. The reconstructed pixel at the receiver is denoted by $\tilde{f}_n^i$. The distortion of the ith pixel of frame n at the encoder comes due to quantization error only. The reconstructed pixel at the receiver has error due to quantization, error propagation, packet loss and concealment distortion. The average distortion over all the possible pixels of frame n for different channel realizations can be given by,

$$D_n = E\{(f_n^i - \tilde{f}_n^i)^2\} = (f_n^i)^2 - 2f_n^i E\{\tilde{f}_n^i\} + E\{(\tilde{f}_n^i)^2\} \qquad (7)$$

R_s	R_c	N_t	$PSNR$ (dB)	
			Equal Power	Opt. Power
84000	1/4	4	36.86	37.08
90000	1/4	2	37.09	37.60
112000	1/3	4	38.28	38.52
120000	1/3	2	38.46	39.01
168000	2/3	4	40.3	40.61
180000	2/3	2	40.51	41.13
224000	1/2	4	41.88	42.30
240000	1/2	2	42.04	42.88

TABLE I: Comparison of Equal and Optimal Power allocation scheme for transmission of packet based H.264/AVC video over MIMO-OFDM channels for a $15dB$ channel with the video user of interest transmitting the “foreman” sequence.

R_s	R_c	N_t	$PSNR$ (dB)	
			Equal Power	Opt. Power
84000	1/4	4	40.26	41.04
90000	1/4	2	41.45	41.54
120000	1/3	2	42.84	43.09
180000	2/3	2	44.65	45.33
240000	1/2	2	46.3	46.84

TABLE II: Comparison of Equal and Optimal Power allocation scheme for transmission of packet based H.264/AVC video over MIMO-OFDM channels for a $15dB$ channel with the video user of interest transmitting the “container” sequence.

Calculation of D_n requires the first and second moments of the random variable of the estimated image sequence $\tilde{f}_n^i$. The total average distortion can be decomposed into the distortion due to source coding and the distortion due to channel coding. It can be mathematically written as $D_n = D_{s,n} + D_{c,n}$. where, D_n is the average distortion over all pixels in all frames, $D_{s,n}$ is the distortion due to source coding and $D_{c,n}$ is the channel distortion. In this formulation it is assumed that the video sequence is partitioned into Groups of Pictures (GOPs). The channel distortion $D_{c,n}$ can be mathematically written as $D_{c,n} = PD_{EC,n} + f(\beta_n, P)D_{c,n-1}, \forall n = 1, \ldots, N-1$. where, P is the loss probability, $f(.)$ is the error propagation factor, β_n is the intrarate. $D_{EC,n}$ is the concealment distortion and can be written as $D_{EC,n} = E\{(\tilde{f}_n^i - \hat{f}_n^i)^2\}$ for simple frame copy concealment method [15]. For details on the model used, the reader is referred to [16].

IV. SIMULATION RESULTS

We next present experimental results for the video transmission over MIMO-OFDM channels. The video sequences used are the “foreman” and “container” sequences (176×144, 300 frames). JM 12.2 release of H.264/AVC is used to create the video bitstream. The admissible channel coding rates are $1/4$, $1/3$, $2/3$ and $1/2$ using RCPC codes. The proposed MIMO-OFDM transmission system has two transmitter (N_t) and two receiver (N_r) antennas. The number of sub-carriers, i.e. the length of a OFDM block is chosen to be $N = 64$. The Cyclic Prefix (CP) length, i.e the guard length is chosen to be $G = 11$. This CP is prefixed to each OFDM block before being transmitted over the channel. The channel being simulated is a Jakes' model. The number of channel taps or the channel length $L = 8$. Thus, for the results shown, $L < G$ and ISI does not come into play. However, it can be shown that the trend of the results remains the same even during the presence of ISI. The four channels, namely $h_{11}, h_{12}, h_{21}, h_{22}$ are assumed to be independent from each other and vary from one OFDM block to the next. The OFDM symbol duration is given by $T_s = N \times T_a$ where, T_a is the sampling interval defined as $T_a = 1/B$ where B is the bandwidth. The sampling duration chosen is $t_s = 50ns$, typical for Hyper-LAN applications. The modulation scheme used in the simulation is 4-QAM, which reads and modulates two bits at a time. The noise variance is chosen to be 1. Data and pilot symbols are Space Frequency (SF) coded using Alamouti's design.

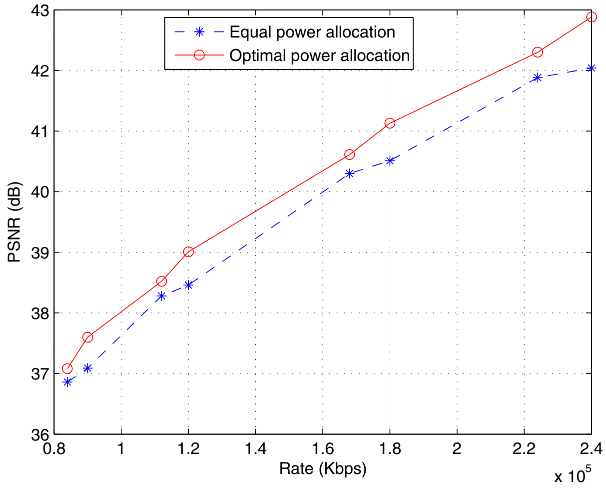

Fig. 1: PSNR comparison for transmission of packet based H.264/AVC video over SF coded wireless MIMO-OFDM channel using equal power distribution and optimal power allocation between the data and pilot symbols for the video user of interest transmitting the “foreman” sequence.

We encode a high motion video sequence viz. “foreman” sequence (176×144, 300 frames) and a low motion video sequence i.e. “container” sequence (176×144, 300 frames) at 30 frames per second. The optimization algorithm selects the set of source coding rates R_s, RCPC channel coding rates (R_c), joint SF code design and pilot placement scheme (N_t) and total power budget (P) for a given rate budget. Rate control is enabled for each specific target source coding rate (R_s). R_s is calculated based on Eq. (6). The total bit budget is $R = 384$ kbps. For a fixed packet loss of 100 bytes, Eq. (5) can be used to calculate the packet loss rate (PLR). The set of admissible source coding rates is $R_s \in \{84, 90, 112, 120, 168, 224, 240\}$ kbps. The set of pilot placement schemes is $N_t \in \{2, 4\}$. The possible channel coding rates are $R_c \in \{1/4, 1/3, 2/3, 1/2\}$. A comparison is drawn between the results of equal power distribution between data and pilots and optimal power distribution between the data and pilots. The results from the optimal problem formulation

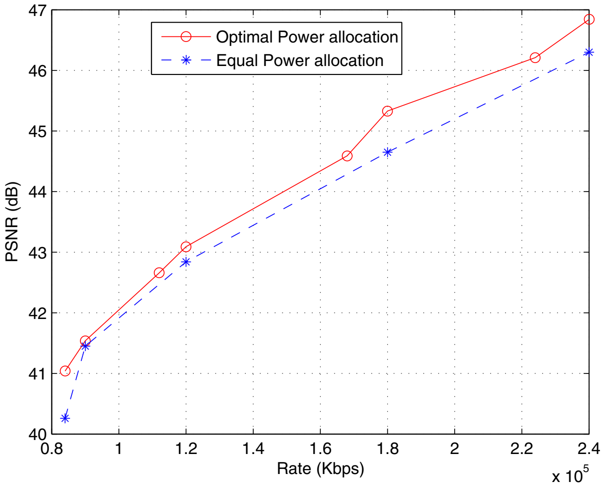

Fig. 2: PSNR comparison for transmission of packet based H.264/AVC video over SF coded wireless MIMO-OFDM channel using equal power distribution and optimal power allocation between the data and pilot symbols for the video user of interest transmitting the "container" sequence.

in Eq. (3) are shown in Tables. I, II and Figs. 1, 2. A subjective comparison for the frames from the "foreman" sequence and the "container" sequences are shown in Figs. 3 and 4 respectively.

For the optimal power allocation case, approach we find the optimal power fraction θ or an average value taken over a number of Monte-Carlo runs such that the value minimizes probability of error or the BER for a given SNR/channel conditions.

The pilot-tone design 1 ($N_t = 2$ design) requires a lesser number of pilot-tones to be placed along sub-carriers of a OFDM block compared to pilot design 2 ($N_t = 4$ design). This implies that a higher number of sub-carrier slots can be used to transmit data in design 1 than in design 2. For example, for the 2×2 system with $L = 8$ and $N = 64$, while design 1 allows 48 sub-carriers for data symbol Tx, design 2 provides just 32 sub-carriers resulting in a 50% decrease in data rate.

V. CONCLUSIONS

We have presented a cross-layer optimization technique for wireless H.264/AVC video transmission over Space-Frequency coded MIMO-OFDM systems. The technique determines the source coding rate, channel coding rate, pilot placement scheme and power allocation between pilot and data symbols. The objective is to minimize the expected distortion at the receiver. Our experimental results demonstrate the importance of optimal power allocation between pilot and data symbols as opposed to equal power allocation.

(a)

(b)

Fig. 3: Frame 84 of the "foreman" sequence. $R_s = 240,000$ bps, $R_c = 1/2$, $N_t = 2$. Comparison is drawn for packet based H.264/AVC video transmission over a 15 dB SF coded wireless MIMO-OFDM channel. (a) "Optimal Power Allocation", (b) "Equal Power Allocation".

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(a)

(b)

Fig. 4: Frame 280 of the “container” sequence. $R_s = 240,000bps$, $R_c = 1/2$, $N_t = 2$. Comparison is drawn for packet based H.264/AVC video transmission over a 15 dB SF coded wireless MIMO-OFDM channel. (a) “Optimal Power Allocation”, (b) “Equal Power Allocation”.

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