An Unequal Modulation Scheme for the Transmission of Compressed Multimedia Data over Adaptive MIMO-OFDM Systems

Tasso Athanasiadis, Kevin H. Lin, and Zahir M. Hussain
School of Electrical and Computer Engineer, RMIT University
124 LaTrobe Street, Melbourne, VIC 3000, Australia
Emails: s8902991@student.rmit.edu.au; kevinhlin@catt.rmit.edu.au; zmhussain@ieee.org

***Abstract*— Modern video/image source coders employ data compression techniques which encode information that are not equally important. Transform based or subband coders, compress data into their respective low-frequency and high-frequency components. In wireless/mobile communication systems, data representing the low-frequency components are more sensitive to the time-varying nature of channel conditions and propagation environments. To deal with this problem, we propose an optimum transceiver structure for a combined source-modulation coded MIMO-OFDM system with adaptive eigen-beamforming. Using an unequal adaptive modulator, we maximize the channel-to-noise ratio (CNR) based on a lookup matrix-adaptive bit and power allocation (LM-ABPA) scheme to sort and allocate subcarriers with the highest SNR to the low-frequency components of the compressed data, and adjusting the signal constellation/modulation type respectively. In comparison to other transmission systems, simulation results based on the application of compressed images showed that the proposed unequal adaptive modulation scheme achieves significant performance gains under a constant data rate load.**

I. Introduction

Over the past decade, there has been an increasing demand for wireless multimedia-equipped devices capable of supporting high data rate transmission. Recent trends in next-generation mobile networks also suggest a significant shift towards multi-carrier (MIMO-OFDM) systems with an emphasis on personalized mobile communications - ubiquitous computing. As a result, wireless multimedia communication has attracted considerable interest by both the research community and industry to address the growing need for new approaches in radio design for the provision of high-speed wireless multimedia services and applications.

To support multimedia communication, however, particularly in the transmission of high-quality digital video/images, one must deal with the bottlenecks commonly associated with the transmission of high-rate multimedia data over wireless systems - limited communication bandwidth, power, and processing resources. Also, in a wireless environment, the time-varying nature of channel conditions and propagation characteristics such as multipath fading, inherently subject wireless signals to intersymbol interference (ISI) leading to high bit-error rates [1]. Moreover, the transmission of wireless data over multipath fading channels cause a degradation in both communication channel performance, system latency, and the acceptable or subjective quality of data received on user terminals.

For transmission through noisy band-limited wireless radio channels, the information must be compressed using source encoders. Key compression technologies to emerge include, JPEG2000 and MPEG [2], which employ transform based techniques such as the Discrete Wavelet Transform (DWT). It is well known, that the data from these type of encoders carry information which can be classified into two main classes: important data, that is, the low-frequency components/approximate coefficients - which are very sensitive to transmission errors; and less important data, that is, the high-frequency components/detail coefficients.

In current wireless (MIMO-OFDM) transmission systems with combined source-channel coders, the data representing the low-frequency information of the compressed signal is encoded and transmitted together with the high-frequency components using a sub-optimal transmit power level, signal constellation size, and modulation type. This can lead to a significant degradation in system performance as a large number of low-frequency components can be subjected to subchannels with a low SNR value, resulting in a loss of signal quality during the reconstruction/decoding process at the receiver. Consequently, for multimedia communication this means degradation in overall system performance, a reduction in data throughput, and a constraint on achieving high data-rate transmission.

To enhance the spectral efficiency and error performance of MIMO-OFDM systems the author in [3] proposes an adaptive modulator based on a *lookup matrix*-adaptive bit and power allocation scheme (LM-ABPA) combined with adaptive transmitter beamforming. In this system, knowledge of the subchannel gain is used to maximize the instantaneous channel-to-noise ratio (CNR) such that an optimal number of antenna beams are selected with a corresponding power splitting ratio. Thus, minimizing the symbol-error-rate (SER) and eliminating the deep fading effect of the entire system.

In this paper, we extend our previous work in [4] on the use of MIMO-OFDM systems with adaptive beamforming for the transmission of compressed digital images, and propose an optimized transceiver structure with a combined source-modulation coded adaptive MIMO-OFDM system using an

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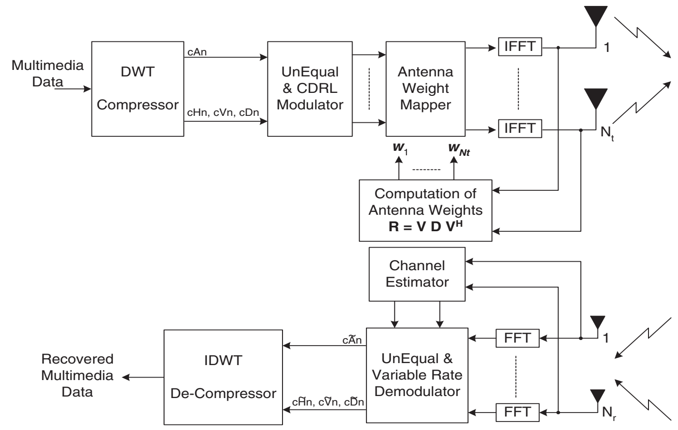

Fig. 1. Transceiver structure of a combined source coder and unequal modulator for adaptive MIMO-OFDM systems with trasmitter beamforming

unequal adaptive modulation scheme. This approach can be extended to study the transmission of other sources of multimedia information such as digital video.

Notation used in this paper includes the following: $(.)^*$, $(.)^T$, and $(.)^H$ are complex conjugation, transposition, and Hermitian transposition respectively. $\|\mathcal{A}\|_F$, $\sqrt{\mathcal{A}}$ and $\det(\mathcal{A})$ denote the Frobenius norm, Hermitian square root, and the determinant of matrix $\mathcal{A}$, respectively. Capital bold letters represent matrices, small underlined are vectors.

II. System Model

The transciever structure proposed in this paper consists of 3 main blocks: data compression using a transform based coder, an unequal adaptive modulator, and a MIMO-OFDM transmission model with adaptive eigen-beamforming. Note, that a channel encoder such as, turbo coding, is not included as we are only interested in the baseline performance of the system. Channel encoding schemes provide error correction capability and only add redundancy to the entropy coded data to achieve a BER close to the shannon limit. A block diagram of the system model is shown in Figure 1. A description of the various processing elements are provided in the following sections.

A. Transform-Based Source Encoder

Referring to Figure 1, multimedia data is compressed using a source coder based on discrete wavelet transformation. In the case of transmitting digital images, a multiresolution 2D-DWT decomposition is performed using biorthogonal wavelets. In wavelet analysis, we represent the low-resolution subband (low-frequency information) by approximation coefficients ($\mathbf{cA_n}$) and high-pass subband spatial-frequency data (high-frequency information) with horizontal, vertical, and diagonal detail coefficients ($\mathbf{cH_n}$, $\mathbf{cV_n}$, $\mathbf{cD_n}$) respectively. For an n-level decomposition, the coefficient matrix $\mathbf{CM}$ consists of the following coefficients

$$\mathbf{CM} = [\mathbf{cA_n}, \mathbf{cH_n}, \mathbf{cV_n}, \mathbf{cD_n}, \cdots, \mathbf{cH_1}, \mathbf{cV_1}, \mathbf{cD_1}] \tag{1}$$

During transmission, transform coefficients (DWTC) are adaptively mapped to a finite set of values using a uniform scalar quantizer. Additional lossless compression is achieved by further removing spatial and statistical redundancy of the DWTC using a combined run-length and entropy encoder. In this paper, we use an improved Huffman coding scheme described in [5]. Unlike other systems, however, the coefficients resulting from the compression stage are not encoded together but are processed separately. That is, the approximate coefficients are transmitted over OFDM subchannels using an optimal transmit power level, constellation size, and modulation type.

B. Unequal Adaptive Modulation

To ensure that the SNR of the multimedia data recovered at the receiver is optimized, sensitive low-frequency data from the compressor is transmitted by making use of a desirable subchannel state. In this work, we maximize the instantaneous channel-to-noise ratio (CNR) based on a lookup matrix-adaptive bit and power allocation (LM-ABPA), and constant data rate loading (CDRL) scheme in [3]. An unequal modulator is employed to first sort subcarrier information from the LM-ABPA process into subchannels with the highest SNR values to the lowest. To achieve a target system SNR level, we allocate subcarriers with the highest SNR values to the approximate coefficients and the remaining data to the detail coefficients, such that, an optimal modulation signal is transmitted with a constellation size determined for the required subchannel SNR and target SER/BER. This process is adapted to the varying channel conditions using the following MIMO-OFDM transmission system.

For a MIMO channel configuration, with N_t transmit and N_r receive antennas, and a wireless fading channel assumed to be frequency-selective (i.e., channel gains for subcarriers are independent) but spatially correlated, the transmit spatial covariance matrix that specifies the spatial correlation between antenna elements is defined as $\mathbf{R}_t$ [6] - assuming that a uniform linear array (ULA) configuration is used for N_t BS antennas. Let $\mathbf{H}_k$ be the channel frequency response matrix. Thus, the correlated channel frequency response is given by $\sqrt{\mathbf{R}_t}\mathbf{H}_k$, where $\sqrt{\boldsymbol{\mathcal{A}}}$ denotes the Hermitian square root of matrix $\boldsymbol{\mathcal{A}}$.

To maximize the transmitted signal power along the dominant multi-paths, eigen-beamforming strategy of [7] is utilized and eigen-decomposition of the spatial covariance matrix is performed. The resultant antenna weights are given by the eigenvector that corresponds to the largest eigenvalue. The eigen-decomposition of $\mathbf{R}_t$ has the form $\mathbf{R}_t = \mathbf{V}\mathbf{D}\mathbf{V}^H$, where $\mathbf{D} := \mathrm{diag}(\mu_1, \mu_2, \cdots, \mu_{N_t})$ is a diagonal matrix with ordered (non-increasing) eigenvalues on the main diagonal and $\mathbf{V} := [\boldsymbol{\nu}_1, \cdots, \boldsymbol{\nu}_{N_t}]$ is a unitary matrix whose columns are the corresponding eigenvectors. Thus, the transmit weight vector $\mathbf{w} = \boldsymbol{\nu}_1$ can be found as the first column of $\mathbf{V}$.

Based on the channel estimation feedback message, a baseband signal constellation size and a transmit power level are computed during the CDRL process and allocated to each subcarrier. Thus, the number of information bits γ_k transmitted from the k^{th} subcarrier may be different from other subcarriers.

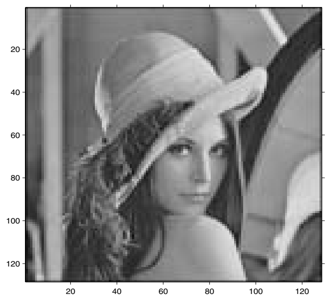

Fig. 2. Original 128x128 Lena source image (8-bit gray scale)

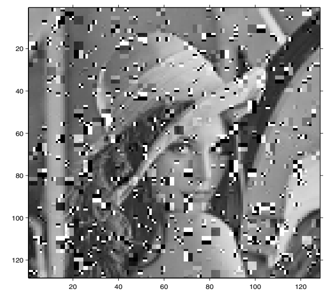

Fig. 3. Received image with non-adaptive modulation (PSNR=11.8dB)

Fig. 4. Received image with unequal adaptive modulation (PSNR=14.9dB)

Let x_k be the CDRL output baseband symbol to be transmitted on the k^{th} subcarrier and ρ_k be the amount of power allocated. At the receiver, DFT is applied to signals received from N_r antennas and the discrete-time baseband equivalent expression for the received signal can be written as

$$\boldsymbol{y}_k = x_k \sqrt{\rho_k} \mathbf{w} \sqrt{\mathbf{R}_t} \mathbf{H}_k + \boldsymbol{\eta}_k \tag{2}$$

where $\boldsymbol{\eta}_k$ is the receiver noise vector with zero mean and σ_k^2 variance. At the receiver, channel estimation is performed by correlating pilot tones embedded in the transmitted signal. This estimate is then fed into the variable rate demodulator (VRD), which consists of a maximum ratio combiner (MRC) and a maximum likelihood detector (MLD).

C. Error Performance Analysis

The receive SNR for the k^{th} subcarrier at the output of MRC can be found from (2) as $\text{SNR}_k = \varepsilon_s \rho_k \mu_1 \|\mathbf{H}_k\|_F^2 / \sigma_k^2$, where $\|\cdot\|_F$ denotes the Frobenius norm and ε_s is the average baseband symbol energy.

Next, we define the instantaneous channel-to-noise ratio (CNR) for the k^{th} frequency tone as $\text{CNR}_k = \mu_1 \|\mathbf{H}_k\|_F^2 / \sigma_k^2$.

For a M-QAM baseband modulated system, the average BER can be approximated as [8], $\text{BER}_{k,M-\text{QAM}} \approx 0.2 \exp[1.6 \cdot \text{SNR}_k / (2^{\gamma_k} - 1)]$ and $\text{BER}_{k,M-\text{PSK}} \approx \text{erfc}(\sqrt{\text{SNR}_k} \sin(\pi / 2^{\rho_k})) / \rho_k$ for M-PSK. Using these BER_k approximation, we can express the required SNR as a function of a target BER (BER_{tar}) for a particular M-QAM constellation size as

$$\text{SNR}_{\text{req},M-\text{QAM}} \approx \frac{(\ln(\frac{\text{BER}_{\text{tar}}}{0.2}))(1-M)}{1.6}. \tag{3}$$

and M-QAM constellation size as

$$\text{SNR}_{\text{req},M-\text{PSK}} \approx \frac{-\ln(2 \cdot \text{BER}_{\text{tar}})}{\sin^2(\frac{\pi}{M})} . \tag{4}$$

D. Constant Data Rate Loading

As the unequal modulator is configured for a constant data rate load, mathematically, the constrained optimization problem can be written as

$$\begin{aligned} \textbf{minimize} \quad & \text{BER}_k \ , \quad \forall\ k = 1, \cdots, N_c \\ \textbf{subject to} \quad & \text{C1.} \quad \sum_{k=1}^{N_c} \log_2 M_k = \mathcal{R}_{\text{T,tar}} \quad \text{and} \\ & \text{C2.} \quad \sum_{k=1}^{N_c} \rho_k = P_{\text{T}}, \end{aligned} \tag{5}$$

where $\mathcal{R}_{\text{T,tar}}$ is the target system data rate. The CDRL algorithm is divided into two major stages. Details of the loading techniques can be found in [3].

III. Simulation Results

The performance of the proposed transmission structure was evaluated using the application of compressed images. A resized (128x128) version of the standard 512x512 gray scale Lena image was used for processing, and is shown in Figure 2. This was compressed using biorthogonal wavelets and a level 4 decomposition. The system model was configured for M-ary PSK modulation and simulated using a ULA with $N_t = 4$ and $N_r = 2$ (with a spacing of 0.5λ employed at the transmitter), over a correlated fading channel with a system SNR of 15dB. Also, the source encoder was configured for a compression ratio (CR) of 40.6 using a global DWTC threshold of 10.

In order to determine the effectiveness of the proposed unequal modulator scheme, the system was simulated and compared to a MIMO-OFDM system with a typical adaptive modulator. The resulting images and PSNR values obtained are shown in the accompanying Figures 3 and 4. As expected, visual inspection (subjective quality) of the images simulated, show quite clearly that a significant gain in system performance is achieved for a combined source-modulation coded adaptive MIMO-OFDM system using an unequal adaptive modulator.

IV. CONCLUSION

In this paper, we have introduced an unequal modulation scheme for adaptive MIMO-OFDM systems with eigenbeamforming for the application of multimedia data over wireless/mobile channels. Simulation results based on the transmission of digital still images, show significant performance gains when compared to general adaptive OFDM systems. Currently, we are working on an extension of this study, which aims to further improve the overall performance of diversity-coded OFDM systems by combining an adaptive multiwavelet compression system with the unequal modulator proposed in this paper.

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