Multimedia Transmission over Wireless Space-Time-Frequency coded OFDM Systems with Adaptive Beamforming

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Abstract

The transmission of multimedia data over wireless systems generally require network devices designed with a high communication bandwidth, power, and processing resources. To deal with these bottlenecks commonly associated with multimedia transmission, various diversity coding schemes have been proposed. We have previously shown that wireless OFDM systems based on space-time block-coding with adaptive beamforming (STBC-OFDM-AB) are well suited to multimedia communication. Recent studies have shown further performance gains in systems utilizing space-time-frequency (STF) coding. In this paper, we introduce a transmission system which combines STF coding with adaptive beamforming (STF-OFDM-AB). Simulation results based on the transmission of compressed images showed that the performance improvements introduced by STF-OFDM-AB can be readily observed.

1. Introduction

Recent trends in wireless/mobile networks have shown an increased demand for modern communication products that are capable of the transmission and processing of high-speed multimedia applications (high-quality digital video, images, and audio). This suggests a significant paradigm shift towards digital communication systems designed to support wireless multimedia-equipped devices capable of high data-rate transmission. As a result, wireless multimedia communication has attracted considerable interest by both the research community and industry to address the growing need for high-speed multimedia services over wireless networks such as 3G mobile communication systems.

In designing communication devices for next-generation (NG) wireless networks, one must however deal with the bottlenecks commonly associated with the transmission of high-rate multimedia data over existing wireless systems - limited communication bandwidth, power, and processing capabilities. 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 (BER) [1]. Moreover, the transmission of wireless data over band-limited multipath fading channels cause a degradation in both communication channel performance, system latency, and the acceptable or subjective quality of data received on wireless terminals/devices.

To support multimedia transmission through noisy wireless radio environments various key technologies have emerged: compression systems such as, JPEG2000, MPEG, H.263/L [2]; 'adaptive' channel coding techniques [5],[6]; and transmit diversity schemes such as, space-time block coding (STBC) [3],[4]. However, any improvements in the error performance and capacity of wireless OFDM systems can be mainly attributed to the recent developments in adaptive transmit diversity coding techniques [7],[8].

In [9] and [10], we have shown that the use of space-time coded OFDM with an adaptive beamforming scheme (STBC-OFDM-AB) is well suited to the application of multimedia data, and that a significant performance gain readily facilitates the transmission of high-quality/high data-rate multimedia signals. More recently, however, the authors in [11]-[13] have shown that additional diversity branches in broadband multipath channels can be exploited using space-frequency (SF) and space-time-frequency coding (STF). Providing significant improvements over other space-time coded OFDM systems. This can be seen in Figure 1, which shows the resulting error performance curves in bit-error-rate (BER) and symbol-error-rate (SER) for OFDM systems that are STBC and STF coded respectively.

In this paper, we present a transmission system for the application of compressed images over wireless channels using a combined source coding and STF-OFDM-AB scheme. This method can be extended to study the transmission of other sources of multimedia information such

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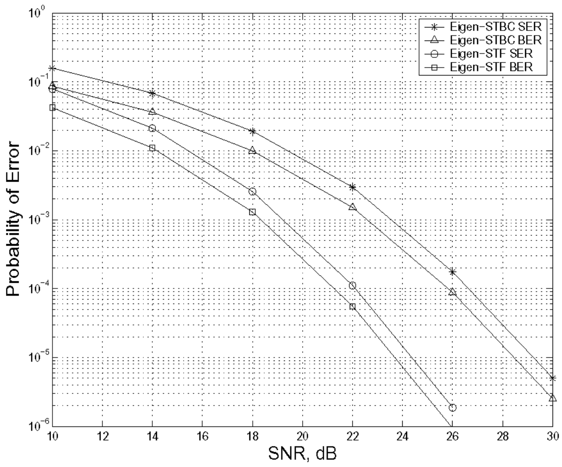

Figure 1. Error performance curves of STBC-OFDM-AB and STF-OFDM-AB systems in correlated fading channels.

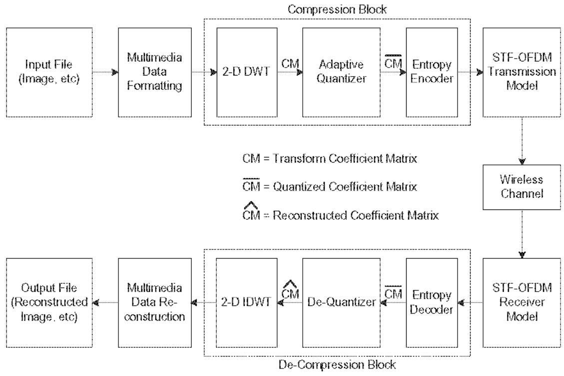

Figure 2. Block diagram of the multimedia transmission system with STF-OFDM-AB.

as digital audio and video data. Notation used throughout the paper include the following: $(.)^*$, $(.)^T$, and $(.)^H$ are 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.

2. System Model

The transmission system proposed in this paper consists of 3 main blocks: multimedia data formatting, data compression, and an adaptive STF-OFDM model. Note, that a channel encoder such as, turbo coding, is not required 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 shanon limit. A block diagram of the system model is shown in Figure 2. This is based on the STBC-OFDM-AB simulation scheme previously outlined in [10]. A description of the various processing elements are provided in the following sections.

2.1. Preprocessing of Multimedia Data

To enable the simulation of multimedia data over the adaptive STF-OFDM-AB transmission scheme, multimedia signals from various data sources (which may be stored on a PC) are converted to a suitable format which can be further processed by the compression block. In the case of monochrome digital still images (with 8-bit/pixel resolution), the source data is converted into a matrix array $(M \times N)$ containing 8-bit integer values which directly correspond to the intensity information of the image.

The output of the compression block provides a vector array of integers representing the bitstream required for conversion to a vector array of baseband modulated data symbols $\{s(n)\}_{n=0}^{N_s-1}$, as specified by the STF-OFDM model. In the receiver path, the reverse operation is performed on the modified data symbols $\{\hat{s}(n)\}$ produced by the STF decoder.

2.2. Data Compression

Referring to Figure 2, signal compression of image data consists of wavelet transformation and entropy coding. 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 by approximation coefficients $(\mathbf{cA_n})$ and high-pass subband spatial-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

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

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 [14].

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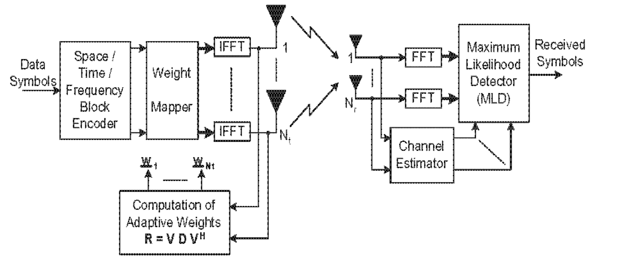

Figure 3. General structure of the adaptive STF-OFDM model. Bold arrows represent multi-line signals.

2.3. The Adaptive Space-Time-Frequency OFDM Model

The general structure of the MIMO-OFDM system employing the proposed adaptive STF transmission structure can be found in Fig. 3. We assume that the OFDM system uses N_c frequency tones with N_t transmit and N_r receive antennas, and that the channel is frequency-selective.

At the BS, STF encoding is performed by formatting the compressed multimedia data symbols into a codeword matrix $\mathcal{C} := [\mathbf{C}_1, \cdots, \mathbf{C}_k, \cdots, \mathbf{C}_{N_c}] \in \mathbb{C}^{N_t \times pN_c}$, where $\mathbf{C}_k$ is a $N_t \times p$ sub-matrix (which spans across p OFDM-symbol intervals and N_t transmit antennas) to be transmitted on the k^{th} subcarrier. Because the number of baseband constellation points is finite, there is a limited number of possible STF codeword matrices and we denote this finite set as $\Upsilon \ni \mathcal{C}$. Details of the design criteria and the formatting of STF codewords can be found in [11] and [12].

Assuming that a uniform linear array (ULA) configuration is used for N_t BS antennas with a spacing of d meters, the normalized spatial covariance matrix that specifies the spatial correlation between antenna elements is defined as [15]

$$\mathbf{R}_t = \frac{1}{L} \sum_{\ell=1}^{L} \underline{a}(\phi_\ell) \underline{a}^H(\phi_\ell) \, , \tag{2}$$

where L denotes the number of dominant resolvable paths, $\underline{a}(\phi_\ell) := [1, e^{j\beta}, e^{j2\beta}, \cdots, e^{j(N_t-1)\beta}]^T$ is the array propagation vector for the ℓ^{th} tap with an AoA of ϕ_ℓ, and $\beta = [2\pi \cdot d \cdot \sin(\phi_\ell)]/\lambda$ with λ being the carrier frequency wavelength. In general, $\mathbf{R}_t$ is a nonnegative-definite Hermitian matrix and its eigenvalue-decomposition (EVD) can be expressed as $\mathbf{R}_t = \mathbf{V}\mathbf{D}\mathbf{V}^H$, where $\mathbf{V} = [\underline{v}_1, \cdots, \underline{v}_{N_t}]$ is a unitary matrix with columns that are the eigenvectors of $\mathbf{R}_t$ and $\mathbf{D} = \text{diag}\{\mu_1, \mu_2, \cdots, \mu_{N_t}\}$ contains the corresponding eigenvalues. Define $\underline{g}_{i,j} = [g_{i,j}(0), \cdots, g_{i,j}(L-1)]$ as the L-tap channel impulse response vector for the $(i,j)^{\text{th}}$ receive-transmit antenna pair. The channel frequency response matrix can be expressed as $\mathbf{H}_k$ with its $(i,j)^{\text{th}}$ entry $h_{i,j,k} = \underline{g}_{i,j} \underline{f}_k$ where $\underline{f}_k = [1, e^{-j2\pi(k-1)/N_c}, \cdots, e^{-j2\pi(k-1)\tau_{L-1}/N_c}]^T$ is the corresponding discrete Fourier transform coefficients and τ_ℓ is the integer delay of the ℓ^{th} tap. The correlated channel frequency response can then be given as $\mathbf{H}_k \sqrt{\mathbf{R}_t}$. We assume that the spatial correlation is the same for all subcarriers.

To facilitate STF codeword transmission in the eigenmodes of the correlation matrix, eigen-weight mapping is performed across the space dimension of the STF codeword, $\{\mathbf{C}_k\}_{k=1}^{N_c}$, prior to transmission. Mathematically, it can be expressed as $\mathbf{W}^H \mathbf{C}_k$, where $\mathbf{W} = [\underline{w}_1, \cdots, \underline{w}_{N_t}]$ is the eigen-weight mapping matrix and $\underline{w}_j = \underline{v}_j$. Signal transmission on different eigenvectors of, $\mathbf{R}_t$, amounts for transmitting N_t orthonormal beams in the direction of the dominant multipaths seen by the BS. In the case when $\mathbf{R}_t$ is not the same for all subcarriers, beamforming should be performed individually for groups of subcarriers with one coherent bandwidth apart.

At the receiver, discrete Fourier transformation (DFT) is applied to the received signals from N_r antennas. The discrete time baseband equivalent expression of the received signal has the form

$$\mathbf{Y}_k = \mathbf{H}_k \sqrt{\mathbf{R}_t} \mathbf{W}^H \mathbf{C}_k + \mathbf{E}_k \, , \tag{3}$$

where $\mathbf{E}_k$ is the receiver noise matrix and its elements are modeled as uncorrelated white Gaussian random variables having $\mathcal{N}(0, \sigma_n^2)$. At the receiver, channel estimation is performed by correlating pilot tones embedded in the transmitted signal. The result is then fed into the MLD for STF decoding of the multimedia data symbols by evaluating the decision matrix as follows

$$\widehat{\mathcal{C}} = \arg\min_{\mathcal{C} \in \Upsilon} \sum_{k=1}^{N_c} \| \mathbf{Y}_k - \mathbf{H}_k \sqrt{\mathbf{R}_t} \mathbf{W}^H \mathbf{C}_k \|_F^2 \, . \tag{4}$$

3. Simulation Results

The performance of the overall transmission system was evaluated using the application of compressed images. A resized (128x128) version of the standard 512x512 gray scale Lena image, with 8 bits/pixel resolution, is used as the multimedia source data. The Lena image used for processing is shown in Figure 4. This was compressed using biorthogonal wavelets and a level 4 decomposition.

The STF-OFDM-AB scheme was configured for QPSK baseband modulation and simulated using a maximum Doppler frequency of 100Hz and 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

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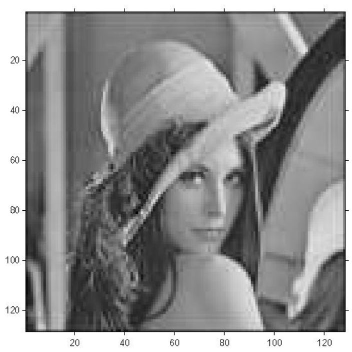

Figure 4. Original Lena source image (8-bit gray scale) resized to 128x128.

of 0dB. Also, the source coder was configured for a compression ratio (CR) of 32.2 using a global DWTC threshold of 5. In order to determine the effectiveness of the STF-OFDM-AB system, this was simulated and compared to the STBC-OFDM-AB scheme presented in [10]. The resulting images obtained are shown in the accompanying Figures 5 and 6.

As expected, analysis of the performance curves and visual inspection (comparison of subjective fidelity measures) of the images simulated, show quite clearly that significant improvements in system performance are achieved with an OFDM system using STF coding and adaptive beamforming.

4. Conclusions

In this paper, we have introduced a transmission system for the application of multimedia data over wireless channels using a combined source coding and STF-OFDM-AB scheme. Simulation results based on the application of digital still images, show a good match between between performance curves obtained through numerical studies and subjective fidelity measures (human visual perception). Finally, this study confirms that wireless communication systems based on adaptive STF-OFDM are better suited to multimedia communication when compared to other diversity-coded OFDM systems.

Currently, we are working on an extension of this research study, which aims to further improve the overall performance of diversity-coded OFDM systems by combining an adaptive wavelet compression and adaptive modulation scheme for the optimization of various transmission parameters towards the system SNR/BER.

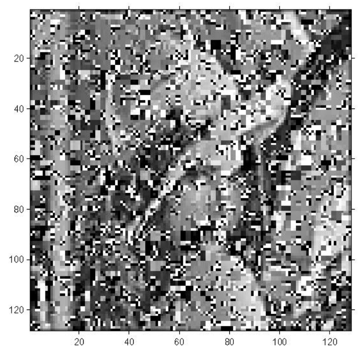

Figure 5. Reconstructed Lena image from the STBC-OFDM system with adaptive beamforming: SNR=0dB.

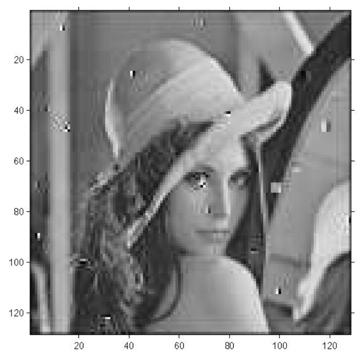

Figure 6. Reconstructed Lena image from the STF-OFDM system with adaptive beamforming: SNR=0dB.

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