Error-resilient Image Transmission System using COTCQ and Space-Time Coded FS-OFDM

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***Abstract*— We present and evaluate a novel robust image transmission system for frequency selective fading channels. The system combines a wavelet image coder and space-time block codes (STBC) in conjunction with Fractional Sampling OFDM (FS-OFDM). Specifically, we employ an image coder based on channel optimized trellis coded quantization (COTCQ), which has not been previously studied for frequency selective fading channels. We demonstrate that our COTCQ coder based system both with (i) (2,2) STBC OFDM without fractional sampling, and (ii) (2,1) STBC with fractional sampling significantly outperforms a system employing trellis coded quantization (TCQ) and set partitioning in hierarchical trees (SPIHT) image coding in conjunction with (2,2) STBC OFDM at low channel signal-to-noise ratios (SNR). The usage of STBC over FS-OFDM systems improves the capacity and diversity achievable over the frequency selective fading channels. For a channel SNR of 9 dB, for instance, the peak signal-to-noise ratio (PSNR) of the Lenna image is over 2–4dB higher with our system. Importantly, the results demonstrate that the diversity gain obtained with a (2,1) STBC FS-OFDM system with low-complexity maximum ratio combining at the receiver can be translated into significant quality gains (in PSNR) in received images.**

I. Introduction

The growing demand for multimedia communications over wireless channels creates a need for reliable transmission of visual data. This challenging task requires a robust and efficient image compression technique along with a error resilient transmission scheme to deal with frequency selective fading channels.

We use a low bit rate wavelet coding scheme, namely *channel optimized trellis coded quantization* (COTCQ) that is designed to optimize image coding based on wireless channel characteristics. Most of the image coders such as SPIHT do not perform well at low SNRs and in error prone and very constrained bandwidth channels. The COTCQ, on the other hand, is error resilient at low SNRs and performs well in bandwidth constrained channels and also for wide variety of channel conditions. Earlier work on COTCQ [1] focuses on the image transmission over the binary symmetric channel (BSC) which has a constant bit error rate. In this paper, we concentrate on image transmission in wireless frequency selective fading channels.

Space-time coding has gained considerable attention in recent years as it uses transmit antenna diversity and provides coding gains and increases the channel capacity. In order to cope with the frequency selective fading conditions over wireless channels, space-time coding is used in conjunction with orthogonal frequency division multiplexing (OFDM) for robust data transmission. In this paper we consider multiple transmit and single receiver antenna systems employing blind schemes which do not require feedback or feedforward information.

OFDM is a multicarrier transmission scheme that has been adopted for digital audio/video broadcasting in Europe, and has been used in local area networks incorporating IEEE 802.11a and HIPERLAN/2 standards. In OFDM, a single datastream is transmitted over a number of lower rate subcarriers which increases the symbol duration thereby reducing the relative dispersion in time for the symbols. Also due to the addition of a guard interval, (wherein the OFDM symbol is cyclically extended), there is a reduction in the intersymbol interference. In addition, OFDM converts a frequency selective fading channel into a set of parallel flat fading channels, facilitating low complexity channel estimation and equalization. Sun et al. [2] have proposed a scalable image transmission system over differential space-time coded systems and Song and Liu [3] study progressive image transmission over space-time coded OFDM systems. Both these works are based on the SPIHT image coder.

In order to exploit the multipath diversity in OFDM, Tepedelenlioğlu and Challagulla [4] propose a low complexity diversity combining scheme through *fractional sampling* (FS) at the receiver. It is shown that by sampling at a rate higher than the symbol rate, known as FS, one can improve the channel capacity and diversity that the wireless channel can provide in an OFDM system. Also, a low complexity maximum ratio combining (MRC) scheme is employed to replace the computationally complex maximum likelihood (ML) receiver. The advantage of using FS at the receiver is that it converts a single input single output (SISO) channel into a single input multiple output (SIMO) channel with the help of multiple receptions and thus increases the achievable diversity and capacity.

As we mentioned, we use COTCQ as an optimal source coder and combine space-time coding with FS-OFDM for error resilient image transmission in frequency selective fading channels. The STBC FS-OFDM combination enhances the

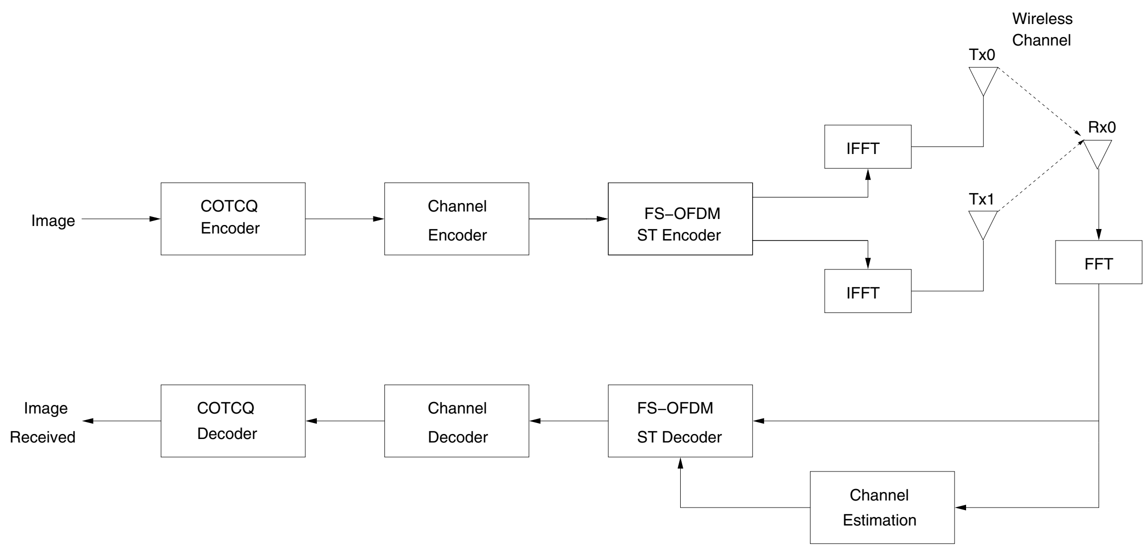

Fig. 1. System structure for image transmission over FS-OFDM system using (2,1) STBC

outage capacity and the diversity offered by the wireless channel and thus reduces the bit error rate. We show that a system using COTCQ and (2,1) STBC FS-OFDM has better performance than a system comprising of TCQ or SPHIT encoder in conjunction with (i) (2,1) STBC FS-OFDM and (ii) (2,2) STBC OFDM respectively. Thus with fewer receive antennas and by employing low complexity MRC, our system performs very well at low SNRs, reducing the receiver load and replacing the computationally complex ML detector used in [3].

This paper is organized as follows. In Section II, we introduce the system structure and describe the COTCQ coder and space-time coding for FS-OFDM. In Section III we provide simulation results and we conclude in Section IV.

II. System Description

The proposed system structure is shown in Fig. 1. The image coding algorithm used is a Channel Optimized TCQ [1] stage that is designed to optimize the image coding based on wireless channel characteristics. The encoded bitstream from the COTCQ stage thus obtained, $s(k'), (k' = 0, 1, \ldots, 2N, \ldots, 2M)$, is first coded into two sub-streams of space-time codes, $s_1(k)$ and $s_2(k), (k = 0, 1, \ldots, N, \ldots, M)$. These two substreams and pilot symbols are mapped onto the corresponding OFDM subcarriers resulting in a set of OFDM symbols each of size N (N is also the number of subcarriers). After performing an inverse fast fourier transform (IFFT), the two OFDM symbol substreams (coded as STBC) pass through a pulse shaping filter and are transmitted via two antennas *Tx0* and *Tx1*. The receiver consists of a single antenna with a matched filter and fractional sampling is employed and a low complexity maximum ratio combining scheme is used for decoding the encoded image bits.

A. COTCQ Wavelet Image Coder

We have used a wavelet based image coder, a COTCQ stage [1] as shown in Fig. 2, that has been designed to optimize the image coding based on wireless channel characteristics. The COTCQ encoder stage consists of a wavelet decomposition stage which decomposes the image into 22 subbands. The mean and variance of the individual subbands are normalized and the calculated statistics are used by the rate allocation scheme to choose an optimal and fixed rate codebook. The normalized subbands are then encoded by the COTCQ encoder that considers the bit error rate of the channel and rate of transmission as the input quantities and codes the image data and then calculates the transition probability matrix for correctly decoding the image bits. The coded bitstream and the side information consisting of calculated statistics (mean and variance) are given as input to the next stage of the image transmission system. The encoder transmits the mean of the lowest frequency subband and the standard deviations of all 22 subbands as side information. Since the side information is small, a simple repetition code is used so that the side information is received without errors. The decoder performs the inverse operations and consists of a COTCQ decoder and a wavelet reconstruction stage for decoding the image.

B. OFDM with STBC

In this paper we use a simple transmit antenna diversity for FS-OFDM system with two transmit antennas and one receive antenna, a (2,1) STBC scheme. In order to compare the performance of the COTCQ image coder with the SPIHT image coder we also use a (2,2) STBC OFDM system without fractional sampling.

Here we discuss the system using a (2,1) STBC and OFDM alone and in the next section we discuss fractional sampling in OFDM. We use an information bearing sequence, $s_n[k]$ where $k = 0, 1, \ldots, N-1$, to denote a single OFDM block. For OFDM transmission we need to take the IFFT of the

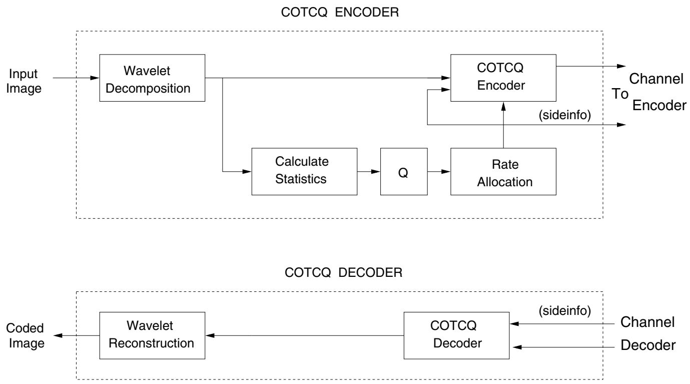

Fig. 2. Block diagram of COTCQ encoder and decoder.

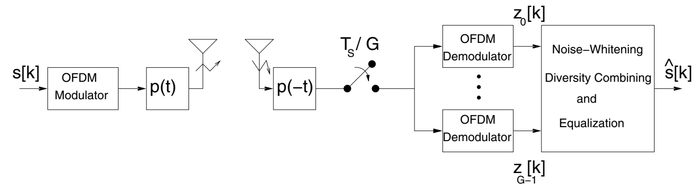

Fig. 3. Block diagram of FS-OFDM system.

information symbols $\mathbf{s_n}$ and append a cyclic prefix to obtain $\mathbf{u_n}$,

$$u_n[k] = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} s_n[k] e^{\frac{j2\pi nk}{N}}, \tag{1}$$

where $n = 0, \ldots, P-1$, and N is the IFFT length, $P := N+\bar{L}$ and $\bar{L}$ is the length of cyclic prefix.

Assuming two transmit antennas, two consecutive OFDM coded blocks $\mathbf{u_n}$ and $\mathbf{u_{n+1}}$ are STBC coded. Thus [$\mathbf{u_n}$ $-\mathbf{u^*_{n+1}}$] is transmitted through antenna $Tx0$ at time instants t and $t+1$ respectively, and [$\mathbf{u_{n+1}}$ $\mathbf{u_n}^*$] is transmitted through antenna $Tx1$ at time instants t and $t+1$.

Let $\mathbf{H_1}$ and $\mathbf{H_2}$ denote the channel coefficient matrices for the two OFDM blocks transmitted via $Tx0$ and $Tx1$ respectively and let $\mathbf{v_1}$,$\mathbf{v_2}$ denote the additive Gaussian noise matrices with zero mean and variance σ^2 associated with the wireless channel. All these matrices $\mathbf{H_1}$,$\mathbf{H_2}$ and $\mathbf{v_1}$,$\mathbf{v_2}$ are of dimension $P \times 1$.

At the receiver, the cyclic prefix is removed and an N pt. FFT is performed. Thus, the channel coefficient matrices are diagonalized [5], giving rise to $\mathbf{\Lambda_1}$ and $\mathbf{\Lambda_2}$ of size $N \times N$ where, $\mathbf{\Lambda_1} = diag(H_1(0), \ldots, H_1(N-1))$, and similarly for $\mathbf{\Lambda_2}$ and $\mathbf{H_2}$. Thus the consecutive received signals are,

$$\mathbf{z_n} = \mathbf{\Lambda_1 s_n} + \mathbf{\Lambda_2 s_{n+1}} + \mathbf{w_1} \tag{2}$$

$$\mathbf{z_{n+1}} = -\mathbf{\Lambda_1 s^*_{n+1}} + \mathbf{\Lambda_2 s^*_n} + \mathbf{w_2}, \tag{3}$$

where $\mathbf{s_n}$ and $\mathbf{s_{n+1}}$ are two consecutive information symbols of size $N \times 1$ and $\mathbf{w_1} = FFT\{\mathbf{v_1}\}$, similarily, $\mathbf{w_2} = FFT\{\mathbf{v_2}\}$.

After combining the outputs of two consecutive received symbols $\mathbf{z_n}$ and $\mathbf{z_{n+1}}$ via the single receive antenna $Rx0$, we have the estimation of transmitted symbols as,

$$\mathbf{\hat{s}_n} = (|\mathbf{\Lambda_1}|^2 + |\mathbf{\Lambda_2}|^2)\mathbf{s_n} + \mathbf{\Lambda^*_1 w_1} + \mathbf{\Lambda_2 w^*_2} \tag{4}$$

$$\mathbf{\hat{s}_{n+1}} = (|\mathbf{\Lambda_1}|^2 + |\mathbf{\Lambda_2}|^2)\mathbf{s_{n+1}} + \mathbf{\Lambda^*_2 w_1} - \mathbf{\Lambda_1 w^*_2}. \tag{5}$$

These combined signals are sent through a maximum likelihood (ML) detector in order to obtain the information symbols.

C. Fractional Sampling in OFDM

The information sequence $\mathbf{s_n}$, to be transmitted using OFDM, is converted to a sequence $\mathbf{u_n}$ by using the IFFT and appending a cyclic prefix (CP) as mentioned earlier. For the case of a system using fractional sampling (FS) [4], a pulse shaping filter is used with an impulse response $p(t)$ to obtain a continuous signal in baseband form, $x(t) = \sum_{r=0}^{P-1} u_n[r]p(t - rT_s)$ with $1/T_s$ as the symbol rate, to be transmitted in the wireless channel.

At the receiver, a matched filter is used (to capture $x(t)$) to obtain, $y(t) = \sum_{r=0}^{P-1} u_n[r] \cdot h(t - nT_s) + v(t)$, where $v(t)$ is the additive Gaussian noise. The output of the matched filter is sampled at rate G/T_s to obtain the polyphase components,

$$y_g[n] = \sum_{l=0}^{P-1} u[l] \cdot h_g[n-l] + v_g[n], \; g = 0, \ldots, G-1, \tag{6}$$

where $y_g[n] = y(nT_s + gT_s/G)$, $h_g[n] = h(nT_s + gT_s/G)$, and $v_g[n] = v(nT_s + gT_s/G)$.

Thus, after the removal of cyclic prefix and performing the FFT at the receiver for each g, we obtain,

$$\mathbf{z}[k] = \mathbf{H}[k] \cdot s_n[k] + \mathbf{w}[k], \; k = 0, \ldots, N-1, \tag{7}$$

where $\mathbf{z}[k] = [z_0[k]...z_{G-1}[k]]^T$ with $z_g[k] = FFT\{y_g[k]\}$, similarly for $w_g[n]$ and $v_g[n]$ and, $H_g[k]\{= [\mathbf{H}[k]]_g\}$ and $h_g[k]$.

The colored noise covariance matrix at the kth subcarrier is $\mathbf{R}_w[k] = E[\mathbf{w}[k]\mathbf{w}^H[k]]$. The transmitted bits are estimated using a low complexity maximum ratio combining (MRC) scheme assuming perfect channel knowledge at the receiver. Thus $\hat{s}_n[k]$, the estimate of $s_n[k]$, is given by

$$\hat{s}_n[k] = \frac{\mathbf{H}^H[k]\mathbf{R}_w^{-1}[k]\mathbf{z}[k]}{\mathbf{H}^H[k]\mathbf{R}_w^{-1}[k]\mathbf{H}[k]}. \tag{8}$$

When transmit antenna diversity is employed for the FS-OFDM system, the diversity order achievable is multiplied by the factor G, due to the multiple receptions made possible by using FS at the receiver. Thus, for the case of (2,1) STBC and G = 2 we obtain a diversity order of 4 using the FS-OFDM system as compared to the system with (2,1) STBC OFDM without FS which has a diversity order of 2 only.

III. Results

In this paper we have evaluated three different image transmission systems namely COTCQ, TCQ, and SPIHT with channel coding. Also the performance of the COTCQ and TCQ image coders were evaluated for the case of no channel coding or forward error correction, and it was found that for SNR values ranging from 5–50dB the COTCQ/TCQ algorithms could not decode the received image data due to large amounts of channel errors. This demonstrates the importance of channel coding for wireless frequency selective fading channels when using the COTCQ/TCQ image coders. Taking into account the advantages of COTCQ as an optimal source coder, we used a moderate channel coding scheme, such as space time block codes, to evaluate the performance at low SNR values.

We performed two sets of simulations to evaluate the image transmission system described in the preceding section. One set of simulations for a 1/2 rate convolutionally coded (2,2) STBC OFDM system without FS and the other set of simulations for a (2,1) STBC FS-OFDM system. For both sets of simulations, we used the COTCQ and TCQ image coders to compress the 512×512 Lenna image encoded at 0.5 bpp at various SNRs.

For the case of the (2,2) STBC scheme, a 128 subcarrier OFDM system is used wherein, a packet of 50 bits of encoded data obtained from the COTCQ coder is fed into a (5,7) convolutional coder to obtain a block of 100 bits and a 128 bit OFDM block is formed with this data using zero padding. In order to simulate the wireless channel we use a three ray channel model with the taps as [0.85 0.15 0.05] to simulate a frequency selective fading channel. The delay spread used is $20\mu s$ and the doppler frequency used is 50Hz. QPSK modulation and coherent estimation are used, assuming perfect channel information at the receivers. At the receiver, a Viterbi decoder along with ML decoding is employed to detect the encoded bits.

For the case of the (2,1) STBC using the FS-OFDM system, as in [4], we use a fractional sampling factor $G = 2$, a set of 64 bit OFDM blocks with cyclic prefix of $\bar{L} = 16$ were formed from the data obtained from the COTCQ coder. Also, a channel delay spread of $\tau_{\max} = 8T_s$ was employed with $N_m = 3$ multipath components. A truncated sinc pulse was assumed for the pulse shaping filter $p_2(t)$. The image PSNR vs. channel SNR performance curves are shown in Fig. 4 for both the cases. The first set of simulations shows the effectiveness of COTCQ as a image coder as compared to the SPHIT coder. The second set of simulations demonstrates the enhancement in performance by using FS along with OFDM at the receiver with a reduced number of receive antennas.

In Figure 4, the plots of the average image PSNR as a function of the average channel SNR show the performance of our COTCQ system as compared to the TCQ and SPHIT coder systems for the cases of (2,1) STBC with FS-OFDM and (2,2) STBC with OFDM alone. It can be inferred from the plots that the COTCQ algorithm performs extremely well at low SNR values of 7dB and 9dB respectively as compared to the TCQ algorithm. This can be intuitively reasoned as COTCQ designs its codebooks based on the channel bit error rate and as a result the combination of the COTCQ algorithm with the (2,1) STBC FS-OFDM gives rise to a robust image transmission system that adds on to itself the advantage of using FS-OFDM system for the frequency selective fading channel. Also the

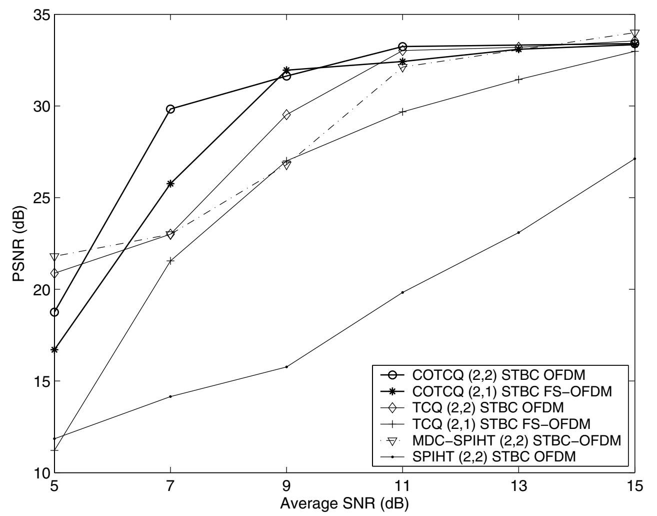

Fig. 4. Image PSNR as a function of channel SNR for COTCQ and TCQ with (2,1) STBC FS-OFDM and with (2,2) STBC OFDM, compared with MDC-SPIHT and SPHIT with (2,2) STBC OFDM for Lenna image at 0.5bpp.

performance of the COTCQ system in the PSNR sense is very good compared to the SPIHT system.

We also tested the (2,1) STBC over FS-OFDM system with the 512×512 Goldhill and Peppers images at 0.5 bpp. Table I shows the average received image PSNR (dB) for the Lenna, Goldhill, and Peppers images which demonstrates the consistency of performance of the system for different images with various intensity levels. Also is shown in Table II the lower and upper bounds of the 95% confidence intervals for the PSNR values obtained using our system. In order to compare the performance of the proposed system, a system with SPIHT coding and (2,2) STBC-OFDM was simulated and Tables III and IV show the average image PSNR and the 95% confidence intervals for the SPIHT encoded system. It is evident from the tables that the COTCQ (2,1) STBC FS-OFDM system performs very well in the average image PSNR sense as compared to the SPIHT (2,2) STBC OFDM system. Though the confidence intervals for the 5dB and 7dB SNR values for the COTCQ system are fairly wide, they become very narrow for the SNR values 9dB, 11dB, 13dB, and 15dB respectively, as compared to the SPIHT system which has a moderate confidence interval gap (about Avg. PSNR $\pm$ 20–25%) for all the SNR values. The PSNR values were tabulated after averaging the PSNRs obtained using 25 stochastically independent image transmissions for each of the input SNR values of 5dB, 7dB, and 9dB respectively and for the higher SNRs, an average of 6 image transmissions were considered for the COTCQ and SPIHT system and an average of 5 transmissions were considered for the case of TCQ system.

IV. CONCLUSION

We have presented an error-resilient image transmission system for frequency selective fading channels employing the COTCQ coder in conjunction with OFDM (both with and without fractional sampling) and space-time block codes. We have demonstrate that both (i) COTCQ in conjunction

TABLE I

AVG. IMAGE PSNR(dB) USING COTCQ AND (2,1) STBC FS-OFDM SCHEME FOR VARIOUS CHANNEL SNR VALUES

Image	5 dB	7 dB	9 dB	11 dB	13 dB	15 dB
Lenna	17.97	24.00	31.95	32.42	33.09	33.34
Goldhill	18.01	23.41	31.54	31.31	31.99	32.91
Peppers	17.55	25.75	29.72	34.15	35.52	35.81

TABLE II

95% CONFIDENCE INTERVALS (LOWER AND UPPER BOUNDS) FOR IMAGE PSNR(dB) FOR COTCQ AND (2,1) STBC FS-OFDM

Image	5 dB	7 dB	9 dB	11 dB	13 dB	15 dB
Lenna	12.6	18.24	31.38	31.79	33.03	33.24
	23.35	29.76	32.51	33.05	33.14	33.43
Goldhill	12.47	16.68	30.76	29.36	30.42	31.70
	23.55	30.13	32.33	33.26	33.57	34.12
Peppers	10.92	18.72	24.07	32.30	35.39	35.69
	24.2	32.78	35.36	35.97	35.65	35.93

with (2,2) STBC OFDM without fractional sampling, and (ii) COTCQ in conjunction with (2,1) STBC FS-OFDM significantly outperform TCQ and SPIHT in conjunction with (2,2) STBC OFDM at low SNR levels. For an SNR of 9dB, for instance, using a single receive antenna our COTCQ system gives over 2dB and 4dB larger image PSNR than the TCQ and SPIHT systems with two receive antennas, respectively. The COTCQ image transmission system with (2,1) STBC FS-OFDM combines the advantages of the COTCQ image coder as optimal image coder for wireless channels and the fractional sampling at the receiver to reduce the complexity by using a low complexity MRC scheme and a single receiver. Thus, the resulting system gives rise to a very robust image transmission scheme with lower bit errors and with increased outage capacity and diversity gain. The results show that the diversity gain obtained using our (2,1) STBC FS-OFDM system can be translated into quality gains (in PSNR) in the transmitted images.

TABLE III

AVG. IMAGE PSNR(dB) USING SPIHT AND (2,2) STBC OFDM SCHEME FOR VARIOUS CHANNEL SNR VALUES

Image	5 dB	7 dB	9 dB	11 dB	13 dB	15 dB
Lenna	11.85	14.14	15.76	19.83	23.09	27.12
Goldhill	15.44	16.45	19.01	19.86	21.61	26.28
Peppers	11.90	13.96	16.24	20.25	23.28	24.47

TABLE IV

95% CONFIDENCE INTERVALS FOR IMAGE PSNR(dB) FOR SPIHT AND (2,2) STBC OFDM

Image	5 dB	7 dB	9 dB	11 dB	13 dB	15 dB
Lenna	9.09	11.69	12.32	16.55	20.03	21.87
	14.60	16.60	19.21	23.10	26.15	32.37
Goldhill	12.22	12.93	16.06	16.40	18.97	23.66
	18.67	19.97	21.95	23.33	24.25	28.90
Peppers	9.82	10.91	12.31	16.15	19.08	19.80
	13.98	17.01	20.18	24.36	27.47	29.14

(a) PSNR = 31.95 dB.

(b) PSNR = 31.84 dB.

(c) PSNR = 27.00 dB.

(d) PSNR = 29.52 dB.

Fig. 5. Received Lenna images at avg. channel SNR = 9dB with (a) COTCQ with (2,1) STBC and FS-OFDM, (b) COTCQ with (2,2) STBC and OFDM alone, (c) TCQ with (2,1) STBC FS-OFDM (d) TCQ with (2,2) STBC and OFDM at 0.5bpp.

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