Transmission of JPEG2000 Images in an Uplink Cellular Network with UPA and SCFDE: A System Description

Moein Shayegannia
Dept. of Engineering Science
Simon Fraser University
Burnaby, Canada
moeins@sfu.ca

Sami Muhaidat
Khalifa University of Science Technology & Research
Abu Dhabi, UAE
muhaidat@ieee.org

Atousa HajShirMohammadi
Dept. of Engineering Science
Simon Fraser University
Burnaby, Canada
atousah@sfu.ca

***Abstract*—In this paper, we describe a work in progress for transmission of JPEG2000 images using an unequal power allocation algorithm and single carrier frequency domain equalization technique over a block fading frequency selective channel. The optimization algorithm exploits the hierarchical structure of the JPEG2000 images and uses a distortion model along with the channel state information for allocating optimal values of power on each coding pass to minimize the end-to-end distortion. The single carrier frequency domain equalization technique combats the negative impact of inter symbol interference and inter carrier interference in a frequency selective channel. Two antennas at the transmission terminal are utilized to evaluate the performance of our system in a multi input single output scenario using space time block coding scheme. The simulation results present that integration of the unequal power allocation technique with orthogonal frequency division multiplexing yields a higher quality than when single carrier frequency domain equalization is used instead. In addition, the transmit diversity technique enhances the peak signal to noise ratio of the received image for about 2.5 dB. These results prove that our power allocation algorithm is more compatible with orthogonal frequency division multiplexing than single carrier frequency domain equalization, and it yields spacial diversity in a multi transmitter antenna system.**

Keywords- JPEG2000; unequal power allocation; single carrier frequency domain equalization; space time block coding; wireless image transmission.

I. Introduction

Transfer of multimedia streams with high reliability of the received signal, and high data rate over wireless channels is becoming more attractive in the current mobile era. The increasing demand of access to multimedia data and the hostile behavior of wireless medium impose challenges in maintaining the total available bandwidth, the total transmission power, and quality of the transmitted stream. To address these challenges, we need to alleviate the sources of disturbance in wireless channels, such as fading, interference, shadowing, path loss, and multipath, by providing an effective data protection technique.

The inherit redundancy contained within multimedia signals and bandwidth limitation require compression of image and video streams before transmission. JPEG2000 is one of the recent and advanced source coding techniques for image coding. This standard provides some degrees of protection against errors in noisy channels with the help of an error-resilient feature. The error resilient tool is able to detect errors but it can not correct any of them in the code-stream. Once an error is detected, the rest of data is discarded and resynchronization mechanism of the received data is performed [1]. Therefore, the error resilience tool of JPEG2000, by its own, is insufficient for alleviating sever channel impairments. A higher degree of protection is achievable with the aim of the hierarchical structure of JPEG2000 coded bitstream in which some bits hold more important information compared to others. This scalable coded bitstream enables us to provide higher protection over the more important bits. Different techniques such as Unequal Error Protection (UEP) and Unequal Power Allocation (UPA) are introduced in the literature to enhance the transmission of scalable coded bitstreams. The UEP methods apply Forward Error Correction (FEC) coding with different coding rates to different portions of the bitstream, based on the importance of each portion. The UPA techniques distribute the total available power for transmission of an image unequally over the bitstream in such a way that more power is allocated to the more important bits.

Transmission of JPEG2000 images using UEP techniques over slow fading non-frequency selective channels has been widely investigated in [2]-[5]. In [2], UEP is achieved in JPEG2000 code-streams by using Reed Solomon (RS) block codes. In [3], Banister *et al.* make use of Viterbi algorithm to jointly optimize source rate and channel rate for the purpose of UEP. In [4], the authors employ product coded streams which consist of Turbo-codes and RS codes to obtain UEP. In [5], the authors obtain UEP using RS channel coding for the header and convolutional coding for the body of the image bitstream. Protection of JPEG2000 images over slow fading non-frequency selective channels using UPA schemes has been reported in [6] and [7]. Atzori employs an optimized UPA scheme in [6] based on increasing JPEG2000 image quality as well as RS channel coding to protect coded bitstream. In [7], we proposed an optimized UPA scheme based on minimizing the total end to end distortion of JPEG2000 images, which proved its effectiveness in improvement of the Peak Signal to Noise ratio (PSNR) performance and at a lower complexity in comparison with the existing UEP techniques.

Evaluation of UEP for JPEG2000 image transmission over frequency selective channels is investigated in [8]-[11]. Houas *et al.* prove the efficiency of their UEP technique with rate compatible punctured convolutional codes in an OFDM system [8]. In [9], the layer structure of the JPEG2000 is exploited by protecting data in top layer with an FEC code, and the performance is analyzed in an OFDM transmission system. In [10], authors achieve UEP with the means of an optimal joint source-channel coding and consider progressive image transmission over differentially space-time coded OFDM system. Sethakaset *et al.* propose an UEP scheme in the spatial domain through enhanced beamforming algorithms over closed loop multiple input multiple output OFDM system [11]. Despite the extensive reports on the performance evaluation of UEP techniques for image transmission over frequency selective channels, effective performance of an optimized UPA scheme for transmission of JPEG2000 images in frequency selective channels has not been analyzed. To address this issue, we prove the efficiency of our proposed optimized UPA scheme for frequency selective channels in [12] by combining the UPA algorithm with the OFDM technique.

All the literature reports on multimedia data transmission over frequency selective channels, with UEP or UPA, make use of OFDM to combat the negative impact of Inter symbol Interference (ISI) and Inter Carrier Interference (ICI). The multicarrier implementation of OFDM technique leads to several drawbacks including large Peak-to-Average Power Ratio (PAPR) and high sensitivity to carrier frequency offsets [13]. To tackle these issues, OFDM is implemented in the base station of a cellular network for downlink data transmissions, and Single Carrier Frequency Domain Equalization (SCFDE) is adapted at the end user station for uplink data transmissions. SCFDE is comparable with OFDM in terms of complexity, while it avoids the drawbacks associated with OFDM [13]. In this paper, we integrate our proposed UPA scheme with SCFDE to provide protection for uplink transmission of JPEG2000 coded bitstreams in block fading frequency selective channels. Moreover, we obtain full spatial diversity in our transmission by using Alamouti's Space Time Block Coding (STBC) scheme [14]. Continuation of this work includes further investigation on the impact of SCFDE and STBC on the bit budget of the JPEG2000 coded bitstream for the possible amount of conservation on the bandwidth.

The rest of this paper is organized as follows: Section II provides a brief overview of JPEG2000 image coding, Section III presents the system model, the simulation results are presented in Section IV, and Section V concludes the paper.

Notations: $[\cdot]^H$ and $|\cdot|$ denote the Hermitian transpose and the absolute value Operations, respectively.$[\cdot]_{ik}$ refers to the $(i,k)^{th}$ entry of a matrix. $[\cdot]_i$ means the i^{th} entry of a vector. **Q** represents an $N \times N$ FFT matrix whose $(i,k)^{th}$ element is given by $1/\sqrt{N}exp\ (-j2\pi ik/N)$ where $0 \leq i,k \leq N-1$. Bold uppercase letters denote matrices, bold lowercase letters represent vectors and lowercase letters denote scalar variables.

II. Review of JPEG2000 Image Coder

In the JPEG2000 image coder, the first operation is to (optionally) partition a source image into a number of rectangular non-overlapping blocks called tiles. Then Discrete Wavelet Transform (DWT) is applied to the tile which transforms the samples into spacial frequency subbands at different levels of resolution. The first level of decomposition consists of four subbands LL1, LH1, HL1, HH1 [15]. The LL1 subband is the lowest resolution of the tile and is a down-sampled low-resolution representation of the original tile-component. The LL1 subband can be further decomposed by applying DWT. This process can be repeated to obtain different resolution levels. Then, each resolution of each tile component is further partitioned into precincts. Within every subband, each precinct contributes one packet to the code-stream of the image. Precincts are not a partition of image data and do not impact sample data transformation or coding. Precincts are used to reconstruct the resolution [2].

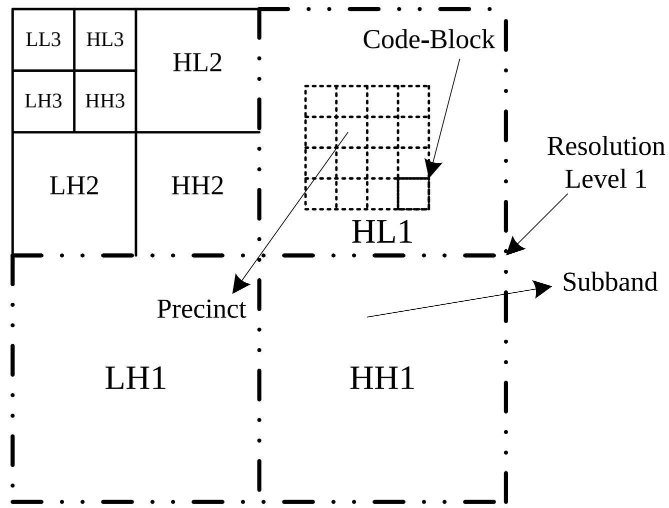


Fig. 1: Components of a JPEG2000 transformed image

Each subband is partitioned into small blocks, called code-blocks, where quantization and bit-plane coding are initiated. The packets furnished by the precincts identify their header and body from the contributions of the code-blocks belonging to the relevant precinct. Starting from the Most Significant Bit (MSB), the coder scans through the bit-planes of each coding pass. Each of the coding passes collects the relevant information about the bit-plane data. Based on the significance of a particular bit location and its neighboring, location of each bit in the coding passes is decided. The encoder uses this information to generate a compressed bitstream or a code-stream [1]. Fig.1 illustrates a 3 layer decomposition of a source image using DWT and its partitioning into four resolution levels, subbands, precincts, and code-blocks.

To increase the robustness of the JPEG2000 bitstream against error propagation along the code-stream, error resilient feature is introduced in the standard. Small size code-blocks are independently coded and included with resynchronization markers. As a result, errors do not propagate beyond the code-block whose bit-stream is corrupted, and the markers keep synchronization between the encoder and decoder in case of occurrence of bit errors. JPEG2000 standard also provides a mechanism to combine all the packet headers within the main header. This adds an advantage to the decoding process of the received data stream, if the main header can be transmitted in an error-free medium. It is necessary to correctly decode the header of a packet in order to extract the code-block contributions to the body of the packet [1], [15].

III. System Model

The overall system block diagram that we are implementing in this study is shown in Fig. 2. We have presented detailed explanations on the functionality of the JPEG2000 encoder, Structure Information Retrieval, UPA optimization, and the Power Adjustment units in [7]. For the sake of completeness, we present a short overview of these units here. The JPEG2000 encoder transforms the format of an input image into JPEG2000 format and generates a scalable coded bitstream. The Structural

 ISBN: 978-1-61208-203-5

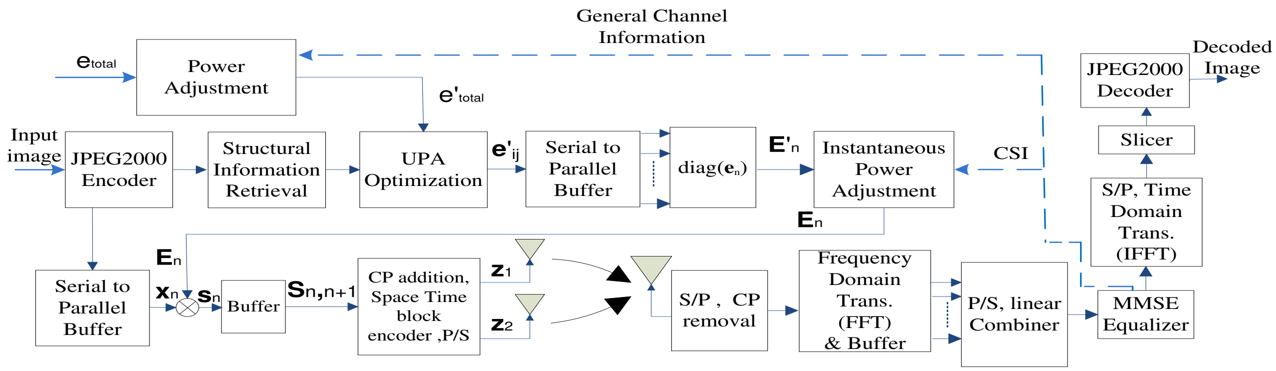


Fig. 2: System block diagram

Information Retrieval unit recovers the required information, such as the number of code-blocks and the number of coding passes within each code-block, from the source coder and passes them to the UPA optimization unit. In the UPA optimization unit runs Simulated Annealing optimization algorithm on the coded bitstream of the JPEG2000 image. This algorithm aims at minimizing the total end to end distortion of the received image by allocating optimal amount of power to each coding pass. During the process of power allocation, the UPA optimization unit obtains the total available power to distribute among the coding passes ($e^{'}_{total}$) from the power adjustment unit. The UPA optimization unit assumes an Additive White Gaussian Noise (AWGN) channel for the transmission medium. The fading impact of the channel is taken into consideration in the Instantaneous Power Adjustment unit by altering the amount of power allocated to each coding pass by the UPA algorithm. In part C, we will describe the functionality of the power adjustment unit. The bitstream and the power assigned to each bit are categorized into N_B blocks. Before the transmission instant, every block of data is appended with cyclic prefix, and two consecutive blocks , n^{th} and $(n+1)^{th}$ where $(n = 1, 2, ..., N_B)$, are passed to the Space Time Block Encoder. The received terminal includes the model of a typical SCFDE receiver.

A. Channel Model

The wireless communication channel is considered to be block fading frequency selective, where two antennas are used at the transmitter side, and one antenna at the receive terminal. First, we will elaborate the transmission model in the case of one transmit antenna, and then we will expand it to two transmit antennas in part D. The channel impulse response for the n^{th} transmission block is given by $\mathbf{h}_n = [h_0\ h_1\ ...\ h_{m-1}]^T$ where m is the channel memory length and $n = 1, 2, ..., N_B$. We append the beginning of each transmitting block of data with a size of $N \times 1$ with the last m samples of the same block to eliminate the impact of Inter Block Interference (IBI). At the receiver side, the first m samples of every block is discarded and only N samples are processed. We can account for the addition and removal of the cyclic prefixes by forming the channel into a circulant matrix for every n^{th} transmission block. Thus, assuming a single transmit antenna, the received signal is given by

$$\mathbf{r}_n = \mathbf{H}_n\sqrt{\mathbf{E}_n}\mathbf{x}_n + \mathbf{v}_n \quad n = 1, 2, ..., N_B \tag{1}$$

where $\mathbf{r}_n$ is the n^{th} received block of data, $\mathbf{H}_n$ is an $N \times N$ circulant matrix for the n^{th} transmission block with entries $[\mathbf{H}_n]_{ik} = [\mathbf{h}_n]_{(i-k)\ mod\ N}$ and $[\mathbf{h}_n]_i = 0$ for $i > m-1$. $\mathbf{v}_n$ is an $N \times 1$ additive white Gaussian noise vector with mean of zero and variance of 1/2 per dimension. Since $\mathbf{H}$ is a circulant matrix, it can be eigen-decomposed to form

$$\mathbf{H}_n = \mathbf{Q}^H\mathbf{\Lambda}_n\mathbf{Q} \tag{2}$$

$\mathbf{\Lambda}_n$ is a diagonal matrix of size $N \times N$ for the n^{th} transmission block, in which the diagonal elements are [16]:

$$[\mathbf{\Lambda}_n]_{ii} = \sqrt{N}\mathbf{q}_i^H\left(\mathbf{h}_n\ \overbrace{0\ 0\ ...\ 0}^{N-m}\right)^T \qquad i = 1, 2, ..., N \tag{3}$$

where $\mathbf{q}_i$ is the i^{th} column of the matrix $\mathbf{Q}$. The channel impulse response varies for every transmission block of data, and so does the diagonal elements of $\mathbf{\Lambda}$. These elements are in fact the eigenvalues of the channel matrix $(\mathbf{H})$.

B. Single Carrier Frequency Domain Equalization Model

In [17], a thorough overview of SCFDE with STBC scheme is presented, and we use this scheme to form our receiver model. At the receiver side, initially a serial to parallel conversion is performed and then the redundant cyclic prefix data are discarded. As known from its name, the equalization of SCFDE is carried on in the frequency domain. Thus, we transform the received time domain block $\mathbf{r}_n$ into frequency domain by applying the FFT

$$\mathbf{Q}\mathbf{r}_n = \mathbf{Q}\mathbf{H}_n\sqrt{\mathbf{E}_n}\mathbf{x}_n + \mathbf{Q}\mathbf{v}_n = \mathbf{\Lambda}_n\sqrt{\mathbf{E}_n}\mathbf{x}_n + \mathbf{Q}\mathbf{v}_n \tag{4}$$

The next step is to equalize the signal using Minimum Mean Square Error (MMSE) estimator. Our MMSE-SCFDE for the n^{th} received block is given by a diagonal matrix of size $N \times N$ with the following elements [17]:

$$[\mathbf{W}_n]_{ii} = \frac{[\mathbf{\Lambda}_n^H]_{ii}}{|[\mathbf{\Lambda}_n]_{ii}|^2 + \frac{1}{SNR}} \tag{5}$$

where SNR is the Signal to Noise Ratio. The output of the MMSE equalizer will be $\mathbf{y}_n = \mathbf{W}_n\mathbf{r}_n$ and can be transferred to time domain by applying the IFFT to recover the original data given by $\hat{\mathbf{x}}_n = \mathbf{Q}^H\mathbf{y}_n$. Then we can apply a hard decision slicer on the recovered data, and pass it to the JPEG2000 decoder to generate the received image.

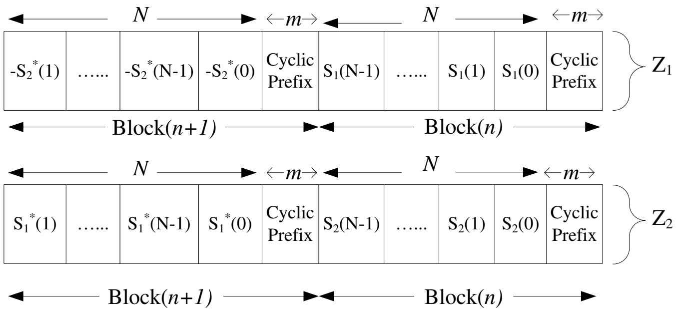


Fig. 3: Transmission block format for SCFDE-STBC [17]

C. Instantaneous Power Adjustment Unit

Our proposed UPA algorithm in [7] assumes an AWGN channel at the time of optimal power allocation to the coding passes. The Instantaneous Power Adjustment unit compensates for the effect of fading by using the instantaneous values of the channel impulse response

$$\mathbf{E}_n = \frac{\mathbf{E}_n^{'}}{\alpha + \left|\sum_{k=0}^{m-1} h_k\right|^2} \tag{6}$$

where h_k is the k^{th} tap channel impulse response for the n^{th} transmission block and m is the channel memory length or the total number of taps. $\mathbf{E}_n^{'}$ is the assigned power to the bits within the n^{th} transmission block and $\mathbf{E}_n$ represents the corresponding power of the bits after the effect of channel fading is taken into consideration. α is small constant value which prevents new zero values in the denominator when the channel is sever and the fading factor is small. In addition, this constant value avoids very large adjusted power to keep the power amplifiers perform in their linear region. For this part, we assume that the Channel State Information (CSI) is available at the receiver side and can be communicated to the transmitter. There are plenty of papers in the literature that report on the estimation of CSI using pilot assisted techniques or blind estimation methods [18], [19].

D. Space Time Block Coding for Transmit Diversity Scheme

In our system design, we employ two antennas at the transmitter side to benefit from spacial diversity. This increases the reliability of the wireless link and improves the quality of the received image. We can also conserve energy by maintain similar received image quality as the single transmit antenna case, however at a lower transmit power. To explain the functionality of the space time block encoder unit and the linear combiner unit in Fig. 2, we follow the proposed transmit diversity methodology in [17]. The two antennas, deployed at the transmitter terminal in Fig. 2, send two transmitting blocks of data ($\mathbf{z}_1$ and $\mathbf{z}_2$) to the channel. Figure 3 presents the structure of these data blocks. In this structure, cyclic prefixes are appended to each block and then discarded at the receiver side in order to eliminate IBI and shape all the channel matrices circulant. An important assumption that we consider in this part for the transmission of the STBC structures is that the channel impulse response remains constant over two consecutive blocks of data. The available power for transmission at any of the two antennas is half of its value in the single transmit case. This helps to keep the total transmit power constant. The linear combiner methodology is detailed in [17] and we will follow the same principle.

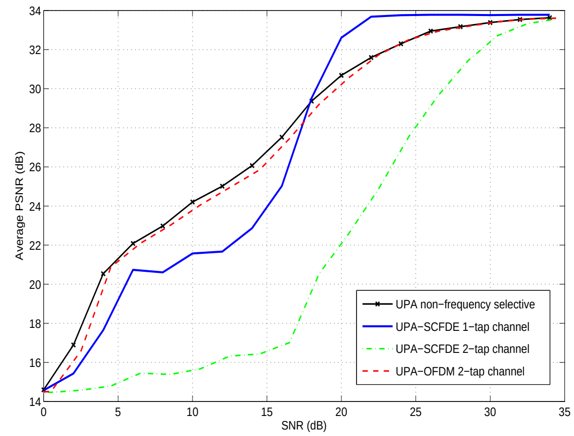


Fig. 4: PSNR performance comparison between combination of the UPA algorithm with SCFDE and OFDM

IV. Simulation Results

We develop our simulation results using Kakadu as the JPEG2000 image coder to encode image of Lena with a size of 512×512 at a rate of 0.25 bit per pixel (bpp). We use Binary Phase Shift Keying as the modulation scheme for the codestream obtained from the codec, and assume that the header information is transmitted error free. Based on our previous experiments in [7], the value of α in (6) is set to be 0.01. We analyze the performance of our proposed UPA scheme with SCFDE technique by calculating the PSNR of the received image transmitted through block fading frequency selective channels. Figure 4 compares the PSNR performance of the system when the UPA algorithm is used alone for image transmission over block fading non-frequency selective channels, and when it is combined with either SCFDE or OFDM to eliminate the effects of ISI and ICI in frequency selective channels. In Fig. 4, a degradation in the PSNR of the received image is noticeable as the number of channel taps increases. For example, at an SNR value of 10 dB, integration of UPA and SCFDE lowers the PSNR of the system in a 2-tap channel for about 6 dB in comparison with the single tap channel. The latter is also lowered by about 2.2 dB compared to the case where only UPA is used for transmission over frequency flat channels. However, this loss in the PSNR performance is not notable when SCFDE is replaced by OFDM. The reason is that our UPA algorithm eliminates the effect of channel to compensate for the instantaneous and average fading. However, SCFDE technique requires the circulant channel structure to obtain multipath diversity and enhance the system performance as the number of channel taps increases. This implies that OFDM is more compatible than SCFDE with our UPA optimization algorithm to combat the negative effect of ISI in frequency selective channels, and maintain high quality of the received image. This figure also suggests that for SNR values greater than 18 dB, the proposed system, which combines UPA and SCFDE, has a superior performance in a single tap channel in comparison to the other scenarios. Figure 5 illustrates the improvement in the PSNR performance when two transmit antennas are employed at the transmitter side using Alamouti's STBC scheme. At an SNR value of 10 dB, this diversity scheme contributes to an increment of about 2.5 dB in the PSNR of the received image transmitted through 2-tap frequency selective channel. Thus, we are able to receive the image with a higher

 ISBN: 978-1-61208-203-5

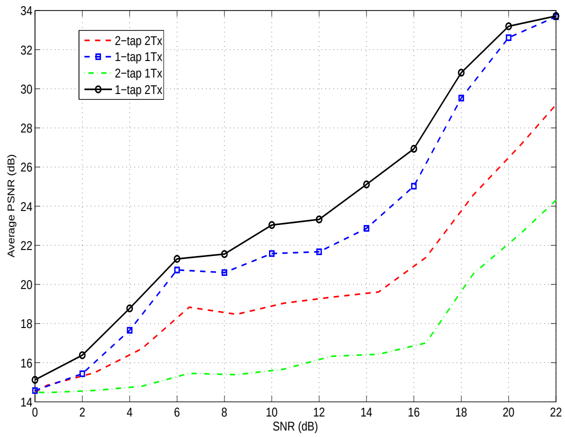
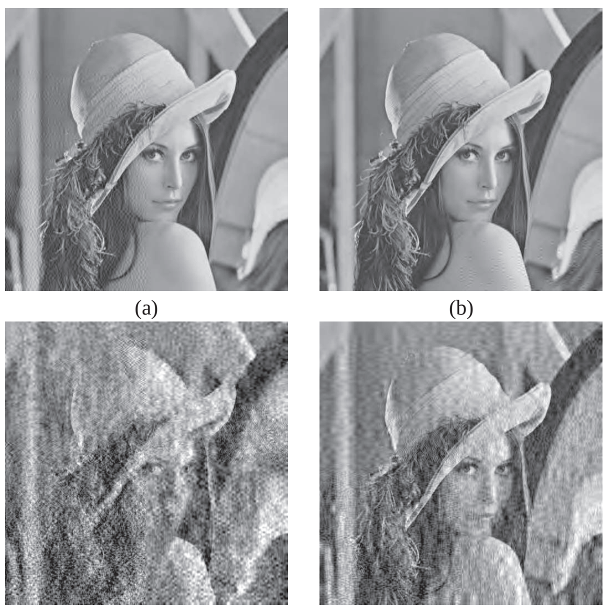


Fig. 5: PSNR performance comparison between different number of transmitter antennas for combination of the UPA algorithm with SCFDE

quality at the receiver, or conserve energy by bounding the quality of the received image.



(a) (b) (c) (d)

Fig.6: Visual comparison of "Lena" at 0.25 bpp, transmitted at SNR=20 dB over Block fading frequency selective channels (a) 1-tap hannel & 1 transmitter antenna, PSNR=32.70 dB (b) 1-tap channel & 2 transmitter antennas, PSNR=33.74 (c) 2-tap channel & 1 transmitter antenna, PSNR=22.10 (d) 2-tap channel & 2 transmitter antennas PSNR=26.47

Figure 6 presents a visual comparison for transmission of "Lena" over block fading frequency selective channel using the UPA algorithm and SCFDE technique. The image is transmitted through a single and 2-tap channels with different number of transmitter antennas. It is clear that the visual quality of the received image is enhanced when the number of transmitter antennas increases. In addition, increasing the number of channel taps lowers the quality of the received image.

V. Conclusion and Future Works

In this paper, JPEG2000 images are transmitted through frequency selective block fading channels using an UPA algorithm and SCFDE technique. The optimization algorithm allocates unequal power to each coding pass based on its contribution to the quality of the received image. The simulation results for the image of Lena imply that combination of the UPA algorithm and the OFDM technique leads to a higher image quality than combining the algorithm with the SCFDE technique, while both methods combat the negative effects of ISI and ICI. In this paper, Alamouti's STBC diversity technique is also incorporated within the proposed system, and the results prove the effectiveness of using two transmit antennas, at the transmitter side, in the PSNR enhancement of the received image. The continuation of this work is to compare the performance of the system at different encoder bit budgets when different number of transmit antennas. This will show us the effectiveness of using two transmit antennas in preserving bandwidth.

References

[1] D.S. Taubman and M.W. Marcellin, *JPEG2000: Image Compression Fundamentals, Standards and Practices*, Kluwer Academic. Publishers, 2002.

[2] A. Natu, D.S. Taubman, "Unequal Protection of JPEG2000 Code-Streams in Wireless Channels,"*IEEE Global Telecom. Conference, GLOBCOM*, vol. 1, pp. 534-538, Nov. 2002.

[3] B.A. Banister, B. Belzer, and T.R. Fischer, "Robust Image Transmission using JPEG2000 and Turbo-codes,"*Proceedings of the 2000 International Conference on Image Processing*, vol. 1, pp. 375-378, Aug. 2004.

[4] N. Thomas, N. V. Boulgouris, and M. G. Strintzis, "Optimized Transmission of JPEG2000 Streams over Wireless Channels,"*IEEE Trans. on Image Proc.*, vol. 15, no. 1, pp. 54-67, 2006.

[5] Y. Wei, Z. Sahinoglu, and A. Vetro, "Energy Efficient JPEG2000 Image Transmission over Wireless Sensor Networks,"*IEEE Global Telecom. Conference, GLOCOM*, vol. 5 , pp. 2738-2743, 2004.

[6] L. Atzori, "Transmission of JPEG2000 Images over Wireless Channels with Unequal Power Distribution," *IEEE Trans. on Consumer Electron.*, vol. 49, no. 4., pp. 883-888, 2003.

[7] M. Torki and A. Hajshirmohammadi, "Unequal Power Allocation for Transmission of JPEG2000 Images over Wireless Channels," *IEEE Global Telecom. Conference, GLOBCOM*, 2009.

[8] H. Houas, I. Fijalkow, and C. Baras, "Resource Allocation for the Transmission of Scalable Image on OFDM Systems,"*IEEE Inter. Conference on Comm., ICC*, 2009.

[9] K. Munadi, M. Kurosaki, K. Nishikawa and H. Kiya, "Robust JPEG2000 Image Transmission over Closed-Loop MIMO-OFDM with Limited Feedback,"*Proceed. of the International Symp. on Circuits and Systems, (ISCAS)*, vol. 2, pp. 432-435, 2003.

[10] Y. Sun, Z. Xiong and X. Wang, "Progressive Image Transmission over Differentially Space-Time Coded OFDM Systems:Research Articles"*Journal of Wireless Communications and Mobile Computing*, vol. 6, no. 8, Dec. 2006.

[11] U. Sethakaset and S. Sumei, "Robust JPEG2000 Image Transmission over Closed-Loop MIMO-OFDM with Limited Feedback,"*IEEE Int. Symp. on Personal, Indoor and Mobile Radio Comm. (PIMRC)*, pp. 1-5, 2008.

[12] M. Shayegannia, A. Hajshirmohammadi, S. Muhaidat and M. Torki, "An OFDM Based System for Transmission of JPEG2000 Images Using Unequal Power Allocation," accepted at *IEEE Wireless Communications and Networking Conference, WCNC*, April 2012.

[13] F. Pancaldi, G. Vitetta, R. Kalbasi, N. Al-Dhahir, M. Uysal and H. Mheidat, "Single-Carrier Frequency Domain Equalization, "*IEEE Signal Processing Magazine*, vol. 25, no. 5, pp. 37-56, 2008.

[14] S. Alamouti, "A Simple Transmit Diversity Technique for Wireless Communication"*IEEE Journal on Selected Areas in Communications*, vol. 16, no. 8, pp. 1451-1548, 1998.

[15] T. Acharya, and P.S. Tsai, *JPEG2000 Standard for Image Compression: Concepts, Algorithems and VLSI Architecture*, John Wiley and Sons, Inc., Hoboken, New Jersey, 2004.

[16] A.H. Sayed, *Adaptive Filters*, Hoboken, New Jersey John & Wiley Sons, Inc., 2008.

[17] N. Al-Dhahir, "Single Carrier Frequency Domain Equalization for Space-Time Block-Coded Transmissions over Frequency-Selective Fading Channels"*IEEE Communications Letters* , vol. 5, no. 7, pp. 304-306, 2001.

[18] R. Negi and J. Cioffi, "Pilot Tone Selection for Channel Estimation in a Mobile OFDM System,"*IEEE Trans. on Consumer Electron.*, vol. 44, no. 3, pp. 112-1128, 1998.

[19] C. Shin, R. W. Heath, and E. J. Powers, "Blind Channel Estimation for MIMO-OFDM Systems," *IEEE Trans. Veh. Tech.*, vol. 56, no. 2, pp. 670-685, Mar. 2007.

[20] J.G. Proakis, *Digital Communications*, Boston McGraw-Hill, 2000.

 ISBN: 978-1-61208-203-5