UNEQUAL POWER ALLOCATION FOR JPEG TRANSMISSION OVER MIMO SYSTEMS

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ABSTRACT

With the introduction of multiple transmit and receive antennas in the next generation wireless standards, real-time image and video communication is expected to become more common. New joint transmission and coding schemes are expected to be developed combining advantages of multiple antenna systems with source statistics. Based on this idea, we present an unequal power allocation scheme for transmission of JPEG compressed images over multiple-input multiple-output systems employing spatial multiplexing. The JPEG compressed image is divided into different quality layers and different layers are transmitted simultaneously from different transmit antennas using unequal transmit power, with a constraint on the total transmit power during any symbol period. Results show that our unequal power allocation scheme provides significant image quality improvement as compared to different equal power allocations schemes, with the peak-signal-to-noise-ratio gain as high as 15 dB at low signal to noise ratios.

1. INTRODUCTION

Real-time image and video communication are becoming very common in wireless cellular systems. During the past few years, a large proportion of research related to image and video communication has focussed on developing efficient joint source-channel coding (JSCC) schemes, since these sources require large amounts of bandwidth. The main essence of all JSCC schemes is that the distribution of available resources such as source and channel coding bits, and/or transmission power between different parts of the source is optimized in such a way that the distortion in the transmitted image or video is minimized at the receiver [1, 2].

Multiple-input multiple-output (MIMO) systems can be used to increase system capacity as well as data reliability in wireless communication systems [3, 4]. Over the past few years a large amount of research has been devoted in developing advanced coding schemes commonly known as space-time codes for transmission over MIMO systems. Where these codes provide tremendous increase in capacity while improving data reliability, they assume that all the data bits are equally important for the receiver. However, it is well known that for images and videos coded using most of the current standards, different parts of the bitstream have different importance. Therefore, distortion in the received images and videos can be reduced if more important parts of these sources are transmitted with higher reliability at the expense of lesser reliability for less important parts. This trade-off can be achieved by designing codes that take into account the characteristics of the source.

One such method is to transmit different parts of the image or video using unequal power. Where a large amount of work has been done for unequal power allocation (UPA) for single-input single-output (SISO) wireless systems, there is virtually no published work to date in UPA for image and video communication for MIMO systems. In this paper, we present an UPA scheme for transmission of JPEG compressed images over MIMO systems. The image is divided in different quality streams, and these different streams are transmitted on separate antennas simultaneously with unequal power. Transmit power is allocated between different layers with the goal of minimizing the overall distortion in the received image. The total transmit power from all the transmit antennas during any symbol period is kept constant. In Sec. 2, we present our system model. Sec. 3 formulates our UPA problem, and provides a sub-optimal solution. Sec. 4 provides simulation details with Sec. 5 discussing our results. We conclude the paper in Sec. 6.

2. SYSTEM MODEL

A block diagram of our system model is shown in Fig. 1, with a description of different components given below.

2.1. The Source Coding Model

We used a progressive discrete cosine transform (DCT) based JPEG coder with spectral selection mode of operation [5]. The encoder encodes the image in 64 different quality layers (a DC layer and 63 AC layers), where each layer contains

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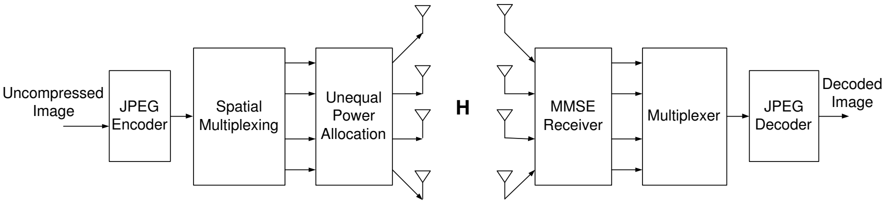

Fig. 1. System model for UPA based MIMO system for JPEG image transmission.

all the DCT coefficients of a particular subband from the entire image. Within each layer, RST (reset) markers are introduced to prevent error propagation between different parts of the bitstream. The encoded data between two consecutive RST markers in a layer is called a 'segment'. More details on this source coder can be found in [6]. After coding the image in 64 layers, headers and markers are separated from the bitstream, and they are assumed to be transmitted error free since they only constitute a small portion of the bitstream [6]. At the receiver, headers and markers are re-inserted at their appropriate locations before decoding.

2.2. Spatial Multiplexing

After the removal of headers and markers, the raw data bitstream is then passed to the spatial multiplexing (SM) block. The SM block divides this bitstream into 4 equal length streams corresponding to the number of transmit antennas, and passes these streams to the power optimization block. At the receiver, the multiplexer combines these streams into a single received bitstream.

2.3. The Channel Model

We used 4 transmit and 4 receive antennas for transmitting the JPEG compressed bitstream. We assumed that the channel is Rayleigh flat fading with a slow fading model. The channel matrix $\mathbf{H}$ is a 4×4 matrix whose entries form an i.i.d. Gaussian collection with zero-mean, independent real and imaginary parts, each with variance $1/2$. We assume that the channel $\mathbf{H}$ is perfectly known both to the transmitter and the receiver. We use 4-quadrature amplitude modulation (4-QAM) for modulating the bitstream.

2.4. Power Optimization

The power optimization (PO) block divides the 4 streams into non-overlapping blocks of lengths $4 \times 2T$, where T is the number of symbols for which we assume the channel to be constant, and 2 is the number of bits per symbol for 4-QAM modulation. Note that we will use the term block in this paper to refer to this block (containing 4 streams) of symbols over which the channel is constant. The power optimization algorithm then runs on each of these blocks independently to allocate the power between different streams such that the overall distortion due to each block is minimized. The total transmit power from all the antennas during each symbol period is kept constant at any given instant. The PO block is also responsible for modulation and allocating different streams to different antennas.

2.5. MMSE Receiver

We used a minimum mean-squared error (MMSE) receiver to decode the spatially multiplexed bitstream. The MMSE receiver is a linear receiver, i.e. it separates the transmitted data streams and then independently decodes each stream. More details on the MMSE receiver for spatial multiplexing systems can be found in [7].

3. UNEQUAL POWER ALLOCATION

The main goal of our unequal power allocation scheme is to transmit different streams from different antennas with unequal power such that the overall distortion due to each block in the transmitted image is minimized. The total transmit power over all the antennas is kept constant during each symbol period. Without loss of generality, we assume that the symbol period is 1, and the noise covariance matrix is $\mathbf{I}_4$, hence the transmit power at any given instant is equal to signal-to-noise ratio (SNR) per symbol E_s/N_0 during any symbol period. If the total number of blocks to be transmitted is N, let $\mathbf{x_n} = [x_{1,n}\ x_{2,n}\ x_{3,n}\ x_{4,n}]^T$ be the transmit power corresponding to streams 1 to 4 respectively of block number n. Let $\mathbf{X}_n$ be a diagonal matrix with the k^{th} element of $\mathbf{x}_n$ as the $(k,k)^{th}$ entry of $\mathbf{X}_n$. Similarly, let $\mathbf{X}'_n$ be a diagonal matrix containing the square root of the entries of $\mathbf{X_n}$. Then, we can write our received signal vector as $\mathbf{y} = \mathbf{X}'_n\mathbf{Hs} + \mathbf{n}$, where $\mathbf{y}$ is the received 4×1 signal vector, $\mathbf{s}$ is the 4×1 transmit signal, and $\mathbf{n}$ is the 4×1 zero mean circularly symmetric complex Gaussian noise matrix with covariance matrix $\mathbf{I}_4$. Our goal is to find the optimal $\mathbf{x}_n$ that minimizes the distortion in the image due to block number n. We formulate the UPA problem as a constrained minimization, where the objective is to minimize the mean squared error (MSE) in the received image due to block n, with an equality constraint on transmit power. This minimization is carried out over all the blocks independently.

The total MSE in the image is the sum of MSE due to all the blocks, given as $MSE_T = \sum_{n=1}^{N} MSE_n(\mathbf{x}_n)$, where N is the total number of blocks. Since the MSE due to individual layers and segments is additive [6], the MSE due to the individual streams is also additive. Hence, the MSE in the image due to block n can be written as

$$MSE_n(\mathbf{x}_n) \quad = \quad \sum_{k=1}^{4} MSE_{k,n}(x_{k,n}), \qquad (1)$$

where $MSE_{k,n}(x_{k,n})$ is the MSE due to the k^{th} stream in the n^{th} block. We attempt to minimize MSE for each block independently due to the additivity of MSE from individual blocks. Hence for block n our optimization problem can be stated as

$$\underset{\mathbf{x}_n}{min}\; MSE_n(\mathbf{x}_n), \qquad (2)$$

with the equality constraint

$$g(\mathbf{x}_n) = \sum_{k=1}^{4} x_{k,n} = P_{TOT}, \qquad (3)$$

where P_{TOT} is the total transmit power from all the antennas at any given instant. Note that $E_s = P_{TOT}$ in our case since symbol period is 1. Once a value of $x_{k,n}$ is obtained, the entire k^{th} stream in the n^{th} block is transmitted with power $x_{k,n}$.

A part of the problem is to find $MSE_{k,n}(x_{k,n})$ for different values of $x_{k,n}$ in real-time during the optimization procedure, without being computationally intensive. In our previous work in [6], we developed a distortion model for predicting MSE as a function of source coding rate and channel bit error rate (BER) over a set of images. For the work presented in this paper, we modified our distortion model slightly to work on a per-image basis, and used it to predict MSE in the image due to individual streams and blocks. Each stream can consist of one or more full or partial non-overlapping segments. The MSE due to these segments is additive and the MSE expressions as functions of source coding rate and channel BER can be found in [6], with different variances now corresponding to segments of a particular image rather than a set of images. We do not include these MSE expressions here due to lack of space.

The MSE expressions in [6] are expressed as a function of instantaneous BER. We need to represent these MSE expression as functions of transmit power (or equivalently SNR). These expressions can be easily derived for MMSE receiver by modifying the signal to interference and noise ratio (SINR) for the equal power case [7]. Thus, for unequal power, we can write the SINR $\eta_{k,n}$ for the k^{th} stream of the n^{th} block as

$$\eta_{k,n} = \frac{1}{[(\mathbf{X}_n\mathbf{H}^H\mathbf{H} + \mathbf{I}_4)^{-1}]_{k,k}} - 1.$$

This SINR can be easily related to instantaneous BER for 4-QAM using the following expression [8]

$$BER_{k,n} = \frac{1}{2}[1 - (1 - Q(\sqrt{\eta_{n,k}}))^2],$$

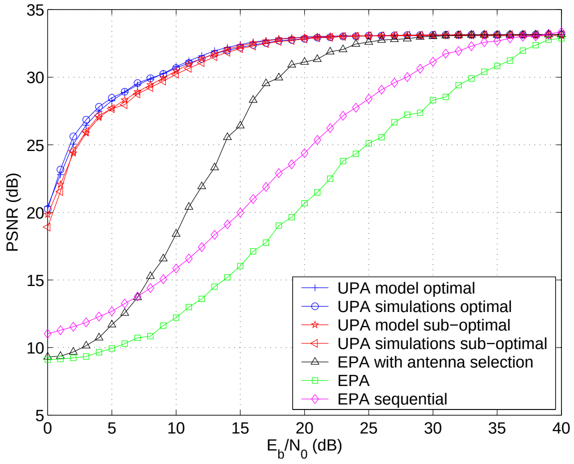

Fig. 2. PSNR curves for UPA and EPA schemes.

where $Q(\cdot)$ is the Q function. Using these relations between SINR, BER, $\mathbf{X}_n$ and $\mathbf{x}_n$, we can easily express MSE as a function of $\mathbf{x}_n$. Using these expressions for MSE, unequal power allocation can be performed in real-time using well developed optimization techniques. We use MATLAB's 'fmincon' function to numerically solve this optimization problem, since a closed form solution is not tractable. Before performing power optimization, we select the best antenna in terms of SINR to transmit the most important stream, the second best antenna to transmit the second most important stream and so on. To perform this antenna selection at any channel instantiation, we first find the 4 SINRs in the case of equal power allocation. We then select the transmit antenna corresponding to the highest SINR to transmit the most important stream, the transmit antenna with the second highest SINR to transmit the second most important stream and so on. Power optimization is performed after this antenna selection. This makes sense intuitively since lesser power will be required by the most important layer if it is being transmitted from the best antenna as compared to that of a random antenna. Hence more power can be allocated to less important layers resulting in further reduction of overall distortion. This does not create any problem at the receiver since the receiver computes the received SINR for each stream and associates the highest SINR decoded stream to the most important stream and so on. The optimizations for UPA are computationally intensive in real-time. To reduce the number of computations performed, we present a very simple sub-optimal power allocation method in the following sub-section.

3.1. A Sub-optimal Power Allocation Algorithm

After performing antenna selection for different streams, the main goal is to allocate the power to the different streams in a computationally non-intensive manner. We present a very simple algorithm for this purpose. We quantize the range of transmit power for each stream in M_k ($k = 1..4$, $M_4 = M_3$) levels, where $k = 1$ corresponds to the most important stream and so on. This algorithm is summarized below.

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Initialize:  $k = 1$, $m = 1$, $E_A = 0$, $MSE_{min} = \infty$,
             $\Delta_1 = \frac{E_s}{M_1}$
Step 1:      Do
                 $x_{k,n} = E_s - m(4-k)\Delta_k - E_A$,
                 $x_{k+1,n} = .... = x_{4,n} = m\Delta_k$.
                 Find $MSE(\mathbf{x}_n)$.
                 If $MSE(\mathbf{x}_n) < MSE_{min}$,
                 then $MSE_{min} = MSE(\mathbf{x}_n)$, $x_{min} = x_{k,n}$.
                 $m = m + 1$.
             While $m < \lceil \frac{M_k}{4-k} \rceil$ AND
             $\eta_{k,n} \geq \eta_{k+1,n} \cdots \eta_{4,n}$
Step 2:      $x_{k,n} = x_{min}$, $E_A = E_A + x_{k,n}$,
             $k = k + 1$, $m = 1$, $\Delta_k = \frac{E_s - E_A}{M_k}$
             If $k < 4$ then goto Step 1,
             else $MSE_{min}$ has the minimum value of
             MSE, and $\mathbf{x}_n$ has the corresponding transmit
             power for different streams.
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This algorithm uses the fact that the received SINR for a more important stream needs to be greater than the received SINR for a less important stream to minimize the distortion. Using this fact, this algorithm does not need not to compute the distortion at all the quantized power levels. Note that after finding the best suited power for a stream, this algorithm does not vary the power for that stream during iterations for the remaining streams.

4. SIMULATIONS DETAILS

We used a database of 50 grayscale 512 x 512 randomly selected natural grayscale images for our simulations. 1.25 bits per pixel source coding rate was used for all the images. We assumed that the channel is constant for 250 symbols, corresponding to 500 bits for 4-QAM modulation. Unequal power allocation was performed using our distortion model [6] to predict the MSE for both the optimal and the sub-optimal case, and the resulting power distribution was used to transmit different streams simultaneously on different antennas. We also computed the actual MSE the receiver using the original unquantized image and the distorted image to compare how closely the model predicts the actual distortion obtained via simulations. We converted MSE to PSNR using the simple relation $\mathrm{PSNR} = 10\log_{10}\frac{255^2}{\mathrm{MSE}}$, and plotted curves for PSNR vs. average channel SNR. Fig. 2 shows PSNR vs. SNR curves for unequal power allocation using the optimization method of MATLAB and our sub-optimal algorithm. Our distortion model was used to predict MSE in real-time for these optimization procedures. The PSNR curves obtained via simulations when the image is transmitted using the power obtained using these optimization procedures are also shown. For comparison purposes, we also show PSNR curves for three different equal power allocation methods. In one of these methods, the best transmit antenna during any channel instantiation is used to transmit the most important stream and so on. We called this scheme ‘EPA with antenna selection’. In the scheme labelled ‘EPA’ in Fig. 2 no antenna selection was performed and streams were transmitted from fixed allocated antennas. We used the same progressive JPEG coder for these two schemes. In the third scheme labelled ‘EPA sequential’, we used a sequential (also called baseline) JPEG coder so that the subbands are distributed uniformly in all the streams and a fair comparison is observed. Equal number of RST markers and same source coding rate was used as that of progressive JPEG. Fig. 3 shows the BER curves for different streams for UPA and EPA schemes. Results for UPA and EPA schemes for the ‘dog’ image at 10 dB SNR are shown Fig. 4.

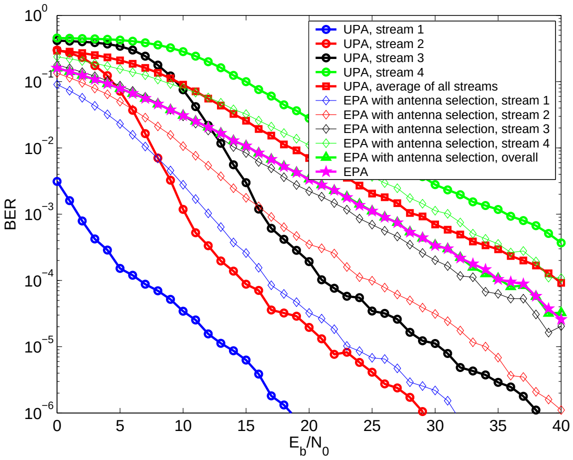
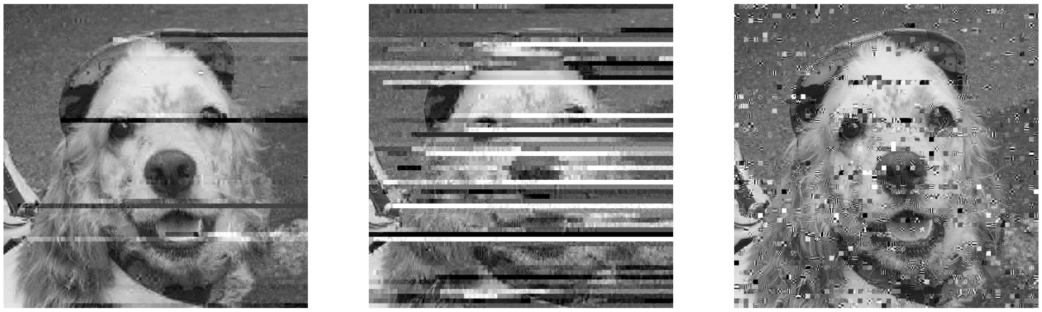


Fig. 3. BER curves for UPA and EPA schemes.

5. RESULTS AND DISCUSSION

As can be seen from Fig. 2, our UPA scheme performs significantly better in terms of PSNR than all the other 3 schemes. Also, our sub-optimal power allocation method performs very close to the optimal power allocation scheme. On the average for each block, the optimal power allocation scheme took 350 MSE evaluations to converge to these values, whereas our sub-optimal method evaluated MSE 26 times on average, reducing the computational complexity by approximately 13 times. Also, as can be seen from this figure, the distortion predicted by our modified distortion model is very close to the actual distortion obtained via simulations. BER curves for different UPA and EPA schemes are shown in Fig. 3. An interesting thing to notice is that though the overall BER for UPA is higher than all the other schemes, the BER for the most important stream is much lower than any other BER curve. It is primarily this stream that is responsible for the large PSNR gains at low SNRs. This shows that even though the total

(a) Original unquantized image (b) UPA, optimal allocation (c) UPA, sub-optimal method



(d) EPA with antenna selection (e) EPA (no antenna selection) (f) EPA with sequential JPEG

Fig. 4. Dog image results for different power allocation schemes.

BER for UPA is higher than EPA schemes, by intelligently allocating power between different streams of unequal importance, significant quality improvements can be obtained. The quality gain by UPA is also evident from the images shown in 4. Also, note that the performance and quality for EPA with antenna selection is much better than EPA without antenna selection.

Similar performance gains were obtained for all the other images, but we showed results for one image only due to lack of space. These results are very encouraging because they show that by using the image statistics for power allocation in MIMO systems, significant quality improvements can be obtained.

6. CONCLUSION

In this paper we presented an unequal power allocation scheme for transmission of JPEG compressed images over MIMO systems employing spatial multiplexing. Different quality streams were transmitted using different antennas, and with unequal power with the goal of minimizing the distortion in the transmitted image. The overall transmit power is kept constant during all symbol periods. We also presented a sub-optimal power allocation method as a solution to the unequal power allocation problem. Results show that our unequal power allocation scheme provides significant gains in terms of PSNR over different equal power allocation schemes. This gain is as high as 15 dB at low SNRs. Furthermore, our sub-optimal algorithm performs very closely to that of optimal power allocation. To the best of our knowledge no unequal power allocation scheme exists for image transmission over MIMO systems. We plan to extend this work to different video coding schemes and advanced space-time coding techniques.

7. REFERENCES

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