Energy-Efficient Transmission of DWT Image over OFDM fading Channel

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***Abstract*—In many applications retransmission of lost packets are not permitted. In an OFDM system, due to channel fading, only a subset of carriers are usable for successful data transmission. If the channel state information is available at the transmitter, it is possible to take a proactive decision of mapping the descriptions optimally onto the good subcarriers and discard at the transmitter itself the remaining descriptions, which would have been otherwise dropped at the receiver due to unacceptably high channel errors.**

In this paper we present a energy saving approach to transmission of discrete wavelet transformation based compressed image frames over the OFDM channels. Based on one-bit channel state information at the transmitter, the descriptions in order of descending priority are assigned to the currently good channels. In order to reduce the system power consumption, the mapped descriptions onto the bad subchannels are dropped at the transmitter. Via analysis, supported by MATLAB simulations, we demonstrate the usefulness of our proposed scheme in terms of system energy saving without compromising the received quality in terms of peak signal-noise ratio.

***Index Terms*—DWT-OFDM system, fading broadcast channel, channel state feedback, energy saving**

I. Introduction and motivation

It is always desired to increase the data rate over wireless channels. But high rate data communication is significantly limited by Inter Symbol Interference (ISI) and frequency selective fading nature of the channel. Rayleigh fading channel is an example of frequency selective and time varying channel. Multi-carrier modulation is used for such channels to mitigate the effect of ISI. OFDM is a multi-carrier modulation scheme having excellent performance which allows overlapping in frequency domain. In OFDM, individual subchannels are affected by flat fading, so for a period of time, condition of the subchannels may be good, or they might be deeply faded. The packets which are transmitted through these faded subchannels are highly prone to be lost at the receiver due to non-acceptable errors. OFDM system provides an opportunity to exploit the diversity in frequency domain by providing a number of subcarriers, which can work as multiple channels for applications having multiple bit streams.

There are three types of source coding techniques: *non progressive coding*, which is designed purely for compression efficiency but it requires retransmissions; *progressive coding*, which also requires retransmissions but it offers scalability; and *multiple description coding* (MDC), where no retransmission is required but it sacrifices some compression efficiency.

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For still image transmission, most common way is progressive (or layered) encoding technique. State-of-the-art image or video compression techniques, such as JPEG2000 [1] (which uses Discrete Wavelet Transform DWT), layered coding is performed. In this technique, layers should reach in a predefined order for processing the data and reconstructing the image at the receiver. Lost layers are retransmitted to complete the processing at the receiver. This process introduces unpredictable latency, thereby restricting the performance of the system. Layered coding produces data of unequal importance and hence one has to put a higher protection for more important data. Scalability property of the layered coding approach allows that a fewer layers can be transmitted to reconstruct the image frame of an acceptable quality. However those layers should be received perfectly, which leads to the need for retransmissions. Thus, although progressive coding works well in loss-less transmission system, in the event of errors reconstruction of image can be stalled due to retransmission of lost coefficients, which is not acceptable in real time content delivery applications.

MDC [2] is used for the applications which do not allow latency in the reception. In MDC, source contents, such as DWT coefficients, are divided into multiple bit streams (called descriptions) which are transmitted through different channels. MDC receiver is able to decode with a low but acceptable quality even if a fewer descriptions are received. In comparison with the layered coding with no error protection in both, MDC always outperforms in delay sensitive applications [3]. This is because, MDC gives an opportunity to estimate the lost descriptions from the correctly received descriptions without the need for retransmissions. However, if some channel state information (CSI) (e.g, binary indication, like 'good' or 'bad') is available at the transmitter, then MDC performance in the delay sensitive applications is no more superior with respect to the layered coding. Since MDC distributes the importance equally among all the coefficients, it works against its recovery quality when CSI is known. It can be explained by the fact that, for a limited correlation among the descriptions produced by MDC, the distortion for even one description loss is more than the minimum variance of the input data streams [4]. So, rather than unnecessarily increasing complexity by using MDC, the DWT compressed data could be directly transmitted over the error-prone subchannels, with the coefficients having lower variances (i.e., with lower importance levels, high pass coefficients) mapped onto 'bad' subchannels. Thus, the more important coefficients are protected from likely losses in the transmission process. The lost coefficients in DWT image would still introduce lesser distortion than what it would have been in the MDC scheme.

A key observation is that, the unequal importance level of the compressed image coefficients can be combined intelligently with the binary channel state feedback to achieve an improved transmission performance in delay-sensitive applications. This feedback can also be used further for energy saving in the transmission process with little or no trade-off in transmission performance.

In this paper, we explore the possibility of transmitting JPEG2000 compressed (DWT) image frames through the block fading OFDM channels with *binary channel state feedback*, where, unlike in conventional layered coded frame transmission, retransmission of lost packets are not allowed. Depending on the binary channel feedback and a predefined acceptable received power threshold, the 'good' and 'bad' (deeply faded) channels are sorted, and the coefficients in order of their importance levels are mapped to the subchannels belonging to the good ones. As an *energy saving measure*, if a coefficient is mapped onto a 'bad' subchannel, we propose that, it is discarded at the transmitter itself. Since our mapping scheme ensures that the discarded coefficients are of rather lesser importance, in most cases the transmitted frame could be reconstructed at the receiver with some distortion, without needing retransmissions. An application scenario of our proposed scheme could be real-time image/video transmission in peer-to-peer broadband communication systems.

Prior work on DWT-OFDM system in [5] studied the transmission of DWT compressed still image over OFDM multipath channels. In that approach, the high pass coefficients were simply discarded before transmission. In contrast, in our approach, we consider the possibility of transmitting the low pass as well as high pass coefficients. We also explore the possibility of energy saving in transmission process over fading channel environment by discarding the coefficients of lower importance level through an informed decision process.

Note that, as an alternative approach, adaptive modulation and coding (AMC) [6] may prove to be a good solution for the OFDM system with *full channel feedback*. But it has a higher complexity in terms of optimization, and full channel feedback information is also less reliable in fast-changing environment due channel estimation error. On the contrary, under such fast fading channel conditions, the binary channel state information at the transmitter could be available more reliably and at a much lower overhead. This is because, in our approach, binary feed back corresponds to the comparison of the received signal strength with the threshold without resorting to any channel estimation technique.

In our proof of concept study, we generate four coefficients, after the first level DWT. Each coefficient in the form of a data vector is mapped on to a subchannel. We compare the energy saving and reception quality performance, by sending all coefficients over the mapped subchannels versus discarding the ones that are mapped on to the bad channels. Our results show that, up to 60% energy saving is possible at the low fading margins with a considerably high gain in the quality (PSNR) of the received image.

Rest of the paper is organized as follows. Section II describes the DWT-OFDM system model, followed by our proposed mapping and energy saving scheme. Section III presents the analysis of distortion and energy saving in our proposed approach. Section IV contains the simulation and analytical results and discussions. The paper is concluded in Section V.

II. SYSTEM MODEL

In our system model, an image frame is compressed using DWT, and the compressed data is arranged in data vectors, each with equal number of coefficients. These vectors are quantized and binary coded to get the bit steams, which are then packetized and intelligently mapped to the OFDM system, such that poorer subchannels can only affect the lesser important data vectors. We consider only one-bit channel state information available at the transmitter, informing only about the subchannels to be 'good' or 'bad'. For a good subchannel, instantaneous received power should be greater than a threshold P_{th}. Otherwise, the subchannel is in fading state and considered 'bad' for that batch of coefficients. Note that the data transmitted through deeply faded subchannels are highly prone to error and are likely to be discarded at the receiver.* Thus, the binary channel state information gives an opportunity to map the bit streams intelligently and to save a reasonable amount of power. Below, we described the DWT-OFDM system model in details.

A. DWT-OFDM system:

The proposed model is for transmission of DWT compressed data over OFDM channels in fading environment and illustrated in Fig. 1. The steps involved are as follows:

1) DWT is applied on an image frame of original size $S_1 \times S_2$ pixels, producing four sub-images: HL, LH, HH, and LL, each of the size $\frac{S_1}{2} \times \frac{S_2}{2}$ pixels.

2) From these sub-images four coefficient vectors are generated, each of length $\frac{S_1 \cdot S_2}{2}$.

3) The coefficient vectors are uniformly quantized and binary coded with L bits/coefficient to form four bit streams.

4) The bit streams are packetized and mapped on the OFDM system.

B. Packetizing and mapping onto the OFDM system:

As described in Fig. 1, bit streams are packetized by chopping them into bit vectors of size N' bits. Four such vectors are contained in a packet. Training bits are added at the front of each bit vector to estimate the SNR of the

*In fading environment, channel noise (say, AWGN) can lead to wrongly declaring a 'good' (respectively, 'bad') channel as 'bad' (respectively, 'good'), especially when the received signal power lies near the threshold. In our current study, the boundary cases are ignored because of their low probability of occurrence.

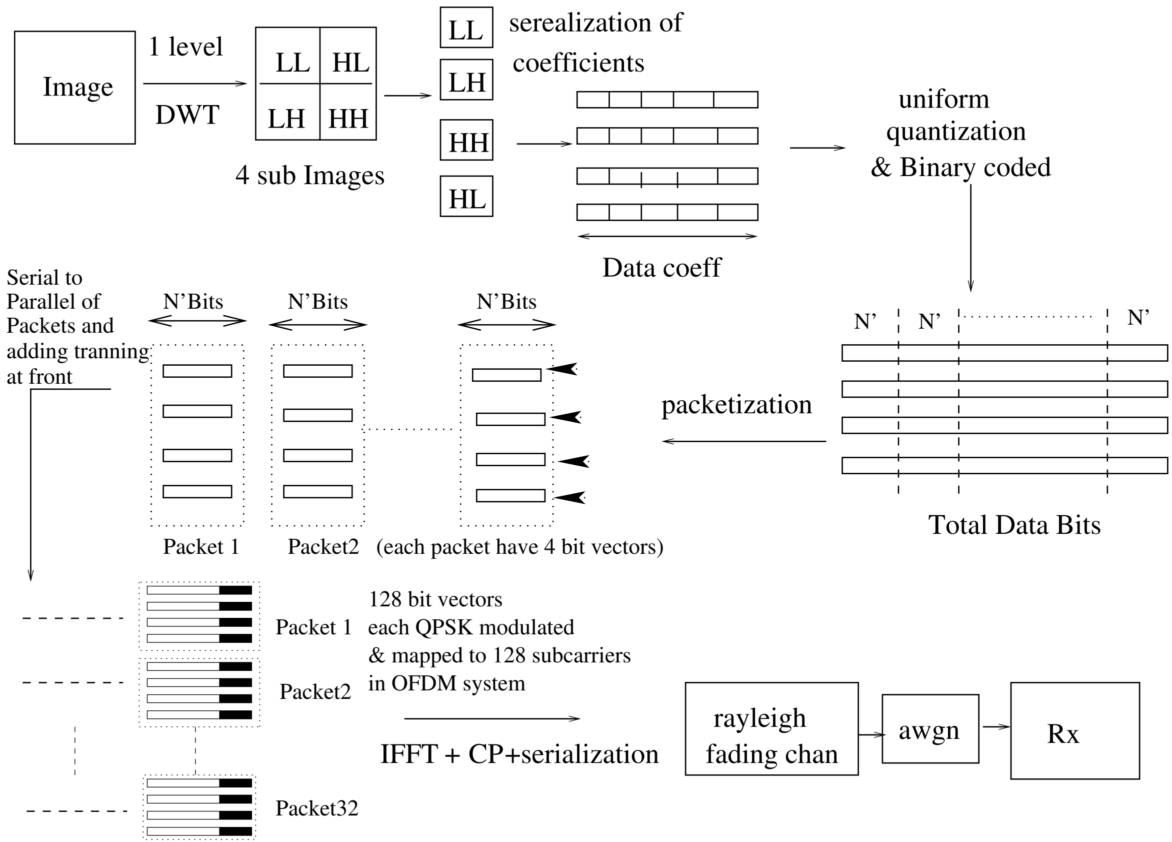

Fig. 1. DWT-OFDM system.

subchannels at the receiver [7]. We illustrate the system by taking an example of OFDM system with IFFT size 128. For this system 32 packets are arranged in parallel to get 128 bit streams (see Fig. 1).[†] Each bit vector in a packet is m-ary modulated, and 32 packets are simultaneously transmitted through different subchannels set. Here we use the feedback to decide the subchannel condition ('good' or 'bad'), and accordingly re-arrange the data vectors to map them to the IFFT module. We propose a mapping scheme, which is proved to be efficient in terms of quality reception as well as energy savings. Packets are sent through frequency selective, slowly varying fading channel. The reverse process is done at the receiver with suitable treatments due to the discarded or lost data vectors.

1) Proposed Mapping scheme : For intelligent mapping of the data vectors, subchannel states are fed back to the transmitter in binary form (i.e, one-bit per subcarrier: 'good' (1) or 'bad' (0)). This simple feedback approach also has very less complexity, as it involves only comparison of received signal power with a predefined threshold P_{th}. In a slow fading scenario, a 'bad' channel feedback implies the data sent through that subchannel would have been below an acceptable

[†]Note that, all subcarriers in the entire OFDM channel are used for the point-to-point content delivery purpose, and hence a subchannel implies the frequency band corresponding to a given subcarrier. Thus, in our current context, the number of subchannels is equal to the number of subcarriers.

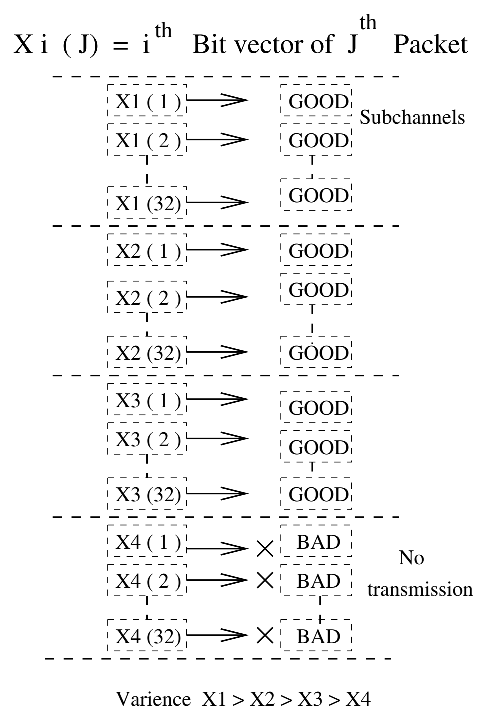

Fig. 2. Packet mapping based on channel state DWT-OFDM system.

quality. Accordingly, in our energy saving transmission policy, those data mapped on to the bad subchannels are discarded at the transmitter. Additionally, at the receiver, to discard a data vector, the receiver checks if the received power of a data vector is below an acceptable threshold. Retransmission of discarded coefficients are avoided. Instead, the discarded coefficients at the receiver are replaced by the average coefficient values of their respective sub-images, which introduces some distortion.

To reduce the distortion due to discarding some data, we propose a mapping scheme which takes care of the importance level of the mapped data such that the less important data (i.e., in general for DWT image, low pass filtered components are more important: the ones with lower variance levels) are mapped to the bad subchannels. As described in Fig. 2, we arrange the bit vectors from all 32 packets such that they are spaced as apart as possible in frequency domain. The subchannels are grouped in to good and bad categories, as depicted in Fig. 2. For this group formation we scan all the subchannels and collect the bad subchannels in order, while maintaining the order of the good ones.

The average distortion per coefficient in a packet produced by this scheme is denoted by $\overline{D}$ for the analysis purpose. The chosen threshold value P_{th} affects the selection of data vectors that are to be discarded at the transmitter. Thus, the quality of reception and the amount of power saved are also changed. It may be mentioned here that the chosen P_{th} corresponds to a particular fading margin.

C. Channel model:

In this study we use block fading channel model as in [8]. The channel model is illustrated in Fig. 3, where M is the coherence bandwidth in terms of number of subchannels. In a block fading environment, M consecutive subchannels will simultaneously be either bad or good. Each such set consisting M subchannels is called a 'sub-band'. We denote total number of such sub-bands in the OFDM system as N. Thus, the total number of subchannels in the system is $N \times M$. All sub-bands are independently faded with Rayleigh-distributed envelop, which corresponds to the block fading approximation in frequency domain [9], [10]. Our proposed mapping scheme generates a situation of subcarrier assignment for each data vector in a packet. Analysis of this environment is presented in Section III.

III. Formulation and Analysis

We now formulate the average distortion and energy savings in our proposed transmission scheme. We measure the system performance by probabilistic analysis of the average distortion in a block fading environment.

A. Distortion involved for various loss events

As described in section II-B1, in the proposed scheme we arrange the data vectors and subchannels in such a way that only the specific loss events can take place. For example, it is unlikely to happen that the data vector with higher importance is transmitted through a bad subchannel, resulting in a loss, while the lesser important data is mapped to a good subchannel and received correctly.

Thus, the proposed mapping scheme gives an opportunity to reduce the distortion as much as possible for a given channel condition. Observe that, only a few loss events can take place. Let x_1, x_2, x_3, and x_4 are the data vectors corresponding to the four sub-images obtained from original frame using DWT compression. Also, let $\sigma^2_{x_1}$,$\sigma^2_{x_2}$,$\sigma^2_{x_3}$, and $\sigma^2_{x_4}$ are the respective variances. Without any loss of generality, assume that the variances $\sigma^2_{x_1}$ to $\sigma^2_{x_4}$ are in descending order of magnitude. Thus, the corresponding importance levels are also in descending order. These data vectors are mapped over different subchannels in such a way that only a few specific loss events are possible. The corresponding likelihood of loss events would be: only x_4 is lost; x_3 and x_4 are lost; x_2, x_3, and x_4 are lost; and all x_1, x_2, x_3, and x_4 are lost. Thus, according to our mapping strategy only four combinations of the loss events are possible. The respective distortion associated would be as follows.

The distortion when no data coefficients are lost or discarded is given by:

$$D_{1111} \equiv D_4 = \frac{4\Delta^2}{12},$$

where Δ is the step size of the quantizer and $\frac{4\Delta^2}{12}$ is the total quantization noise. The distortion when only x_4 is lost or discarded is given by:

$$D_{1110} \equiv D_3 = \sigma^2_{x_4} + \frac{3\Delta^2}{12}.$$

Similarly, the distortion when x_3, and x_4 are lost or discarded is given by:

$$D_{1100} \equiv D_2 = \sigma^2_{x_3} + \sigma^2_{x_4} + \frac{2\Delta^2}{12},$$

the distortion when x_2, x_3, and x_4 are lost or discarded is given by:

$$D_{1000} \equiv D_1 = \sigma^2_{x_2} + \sigma^2_{x_3} + \sigma^2_{x_4} + \frac{\Delta^2}{12},$$

and, the distortion when x_1, x_2, x_3, and x_4 are lost or discarded is given by:

$$D_{0000} \equiv D_0 = \sigma^2_{x_1} + \sigma^2_{x_2} + \sigma^2_{x_3} + \sigma^2_{x_4},$$

where D_i = distortion when only i number of data vectors out of the four are received in a packet ($i = 0, 1, 2, 3, 4$). In general, we can write:

$$D_i = \begin{cases} \frac{i\Delta^2}{12}, & \text{if } i = 4, \\ \sum_{i+1}^{4} \sigma^2_{x_i} + \frac{i\Delta^2}{12}, & \text{otherwise.} \end{cases} \quad (1)$$

B. Block fading channel behavior

The performance of the proposed scheme depends on probability of the loss events. In this section, the probabilities of loss events are determined with respect to the channel fading parameter. As mentioned in section II-B1, the packets are mapped in such a way that the channel fading can be

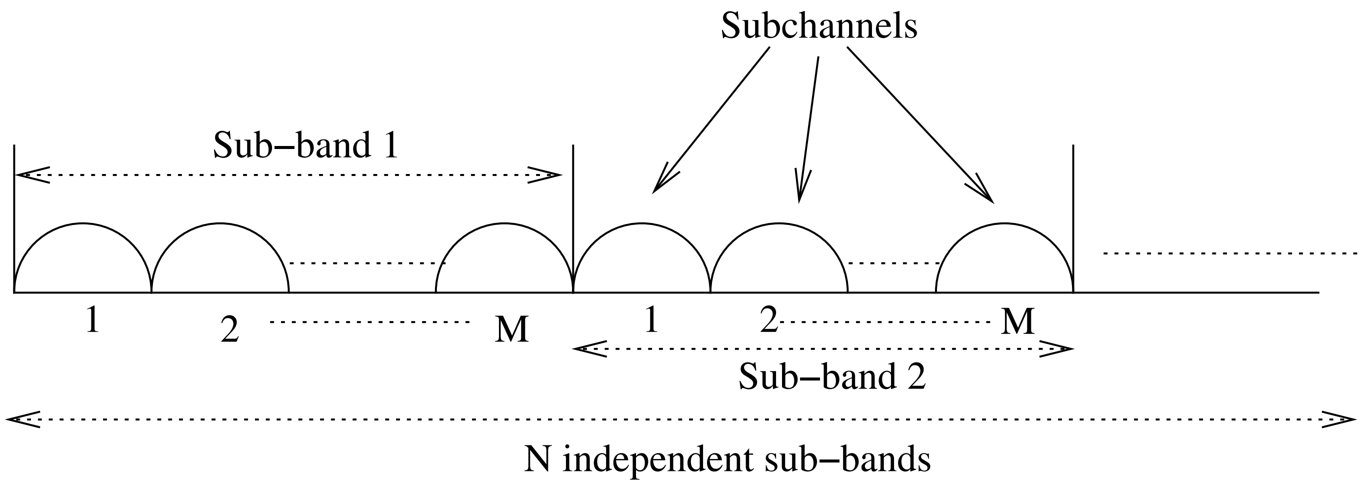

Fig. 3. The concept of block fading channels in OFDM system.

considered independent for all the four data vectors in any packet. For Rayleigh fading channel, the received power P is exponentially distributed with probability density function (pdf) given by:

$$f_P(a) = \frac{1}{\overline{P}} exp\left(-\frac{a}{\overline{P}}\right), \tag{2}$$

where $\overline{P}$ be the average received power. If F is the fading margin, it is related to the receiver threshold sensitivity P_{th} as:

$$F = \frac{\overline{P}}{P_{th}}. \tag{3}$$

Let p be the probability that a sub-band is in deep fade. Using (2), p can be expressed as:

$$p = \int_0^{P_{th}} f_P(a)\, da = 1 - exp\left(-\frac{1}{F}\right). \tag{4}$$

In our interleaved coefficient mapping scheme, all the four subchannels per group of four coefficients are from different sub-bands. Thus, p will also be the probability of a subchannel to be bad. Let P_i = probability associated with the loss event i, for $i = 0, 1, 2, 3, 4$, which produces distortion D_i. Thus, for an arbitrary received packet we can write:

$$P_i = \binom{4}{i} p^{4-i} (1-p)^i. \tag{5}$$

Then, the average distortion of the proposed scheme can be written as:

$$\overline{D} = \sum_{i=0}^{4} D_i P_i, \tag{6}$$

where D_i and P_i can be obtained from (1) and (5), respectively.

C. Energy saving measure:

In the proposed scheme the less important data vectors are discarded at the transmitter to save power if corresponding subchannel is in fading state. Denoting the percentage of data not transmitted in a packet as a measure of the percentage of energy saving, using (5) we can write energy saving expression as:

$$\%\ energy\ saved = 100 \times \sum_{i=0}^{4} iP_i/4. \tag{7}$$

IV. Results and discussion

The analytical results from the formulation in Section III as well as the simulation results to validate the analysis are presented here. For simulations we transmitted standard 'Lena' image of size 256 × 256 pixels. We simulated the OFDM system with $N \times M = 128$ subcarriers. In this way, 32 packets can be transmitted simultaneously through the OFDM system. Packets are distributed in time and frequency domain as described before, but the packets which are transmitted back to back through same group of 4 subchannel are corrupted due to slowly time varying nature of fading. We maintain coherence time to be more than that of the packet transmission time through a subchannel, and the channel condition is fed back for each packet. We simulated block fading channel with number of sub-bands $N = 4$ and the coherence bandwidth equivalent to 32 subcarriers ($M = 32$). QPSK is used as modulation scheme. Thus, 128×2 bits per OFDM symbol are transmitted through a subchannel.

The variances of data vectors obtained for 'Lena' image provide the conditional distortion values associated with different loss events given by (1). The conditional distortions are plotted against the loss events in Fig. 4. We can observe the effective distortion variation according to the importance of the data vectors. The probabilities of loss events are determined from (5) with respect to the channel fading parameter and are plotted against the P_{th} in Fig. 5. For low values of P_{th} (high fading margin) effective distortion probabilities are observed to be decreased. But gives less opportunity to save power.

Analytically obtained distortion measure and percentage energy saving, given by (6) and (7), respectively, are plotted against the P_{th} in Fig. 6, where the analyzed results are supported by simulated values. Note that, to show the effect

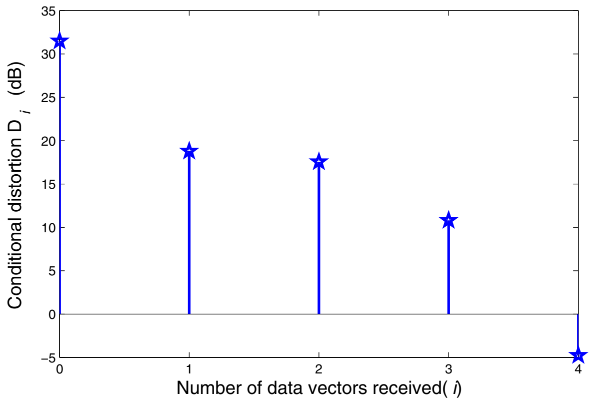

Fig. 4. Conditional distortions for Lena image.

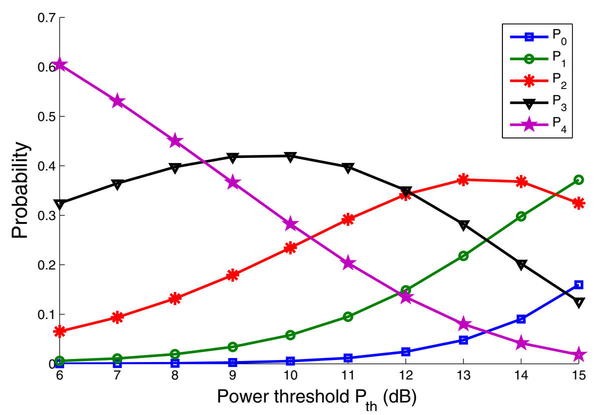

Fig. 5. Data vector loss probabilities for proposed scheme in block fading channel.

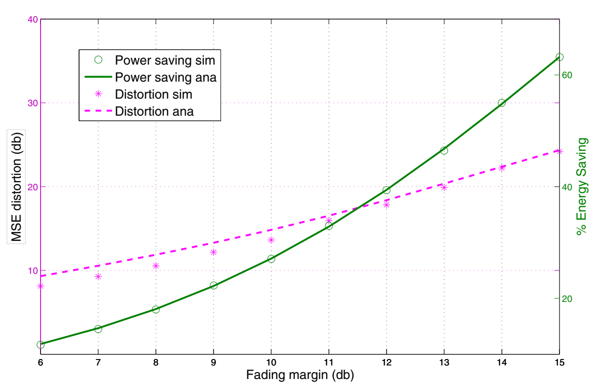

Fig. 6. Simulation and analytical results for distortion and % power saved

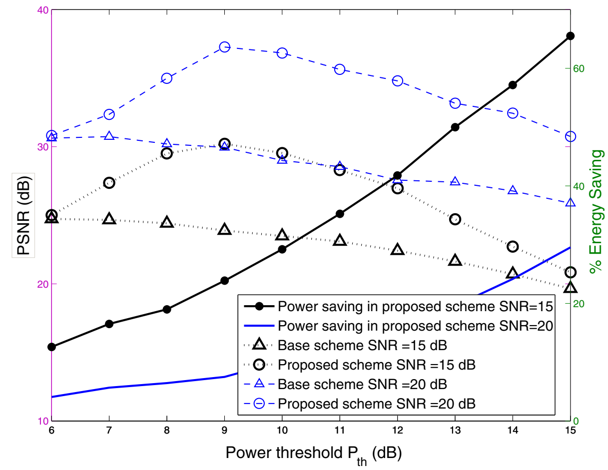

Fig. 7. Trade-off between energy savings and reception

of fading we have neglected here the AWGN in simulation as well as in analysis. From Fig. 6, it can be concluded that the distortion in reception process increases with power threshold P_{th}. But this increase is not high, as the data having lower importance have a higher probability of transmission through the bad subchannel. It follows from the figure that the energy saving is also increasing by restricting lesser important data from transmission through bad subchannels. In the worst case, it follows that we can save more than 60 percent power.

Transmission of Lena image through the OFDM system provides simulation data, showing PSNR and energy saving variations (quality) in Fig. 7, which also include the effect of AWGN. Here, for a fair comparison with our proposed scheme we have also simulated the base scheme. The base scheme corresponds to the technique where subchannel state information in binary form is available at the transmitter to use intelligent mapping like our proposed mapping scheme, but the data vectors are not discarded at the transmitter. Rather, the receiver rejects a coefficient for which the instantaneous SNR is below an acceptable threshold. It can be noted from Fig. 7, that our proposed mapping scheme with energy saving always outperforms than the base scheme. From the figure we also get the optimal value of P_{th} is about 9 dB, where the reception quality is maximum. For lower values of P_{th} AWGN dominates, producing a higher distortion even if the coefficients are accepted at the receiver due to a low P_{th}. Also, in this case a lesser number of subchannels will be considered in deep fade, providing a lesser energy saving. For higher values of P_{th}, i.e., at $P_{th} > 9$ dB, the effect of AWGN diminishes. But, as more subchannels are considered in fading state the quality suffers while providing a higher energy saving.

It can be further noted that, we restrict the transmission depending upon the instantaneous received power of the subchannels, and a decision is made based on the value P_{th}. Thus, the amount of power saved and the corresponding degradation

(a) Original image

(b) PSNR = 38 dB

(c) PSNR = 28 dB

(d) PSNR = 21 dB

Fig. 8. Transmitted Lena image and its received versions at different PSNRs.

in quality for a higher P_{th} can be controlled. It would be user dependent to choose between the reception quality and energy saving, as both are controlled by the parameter P_{th}.

Fig. 8 shows the received Lena images with different PSNR. Note that, PSNR $=$ 21 dB corresponds to a reasonably poor image quality. Thus, at a given channel SNR, an arbitrary choice of P_{th} may lead to an unacceptably poor reception quality.

V. Conclusions

To conclude, we present a case of DWT compressed image transmission over OFDM channels where binary channel state information is available at the transmitter, but retransmission is not allowed. We propose a energy saving approach, where the compressed coefficients are arranged in descending order of priority and mapped over the channels starting with the good ones. The coefficients with lower importance level, which are likely mapped over the bad channels are discarded at the transmitter to save power without significant loss of reception quality. Our analytic observations on reception quality and energy saving performance are validated by extensive MATLAB simulations.

As a future work, we plan to extend the current study with CSI adaptive channel rate as well as power control to find a more generalized trade-off between transmission rate and energy saving in image as well as video transmission applications.

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