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# Robust Wireless Image Transmission using Jointly-Optimized Modulation and Source Coding

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**Abstract** - An Orthogonal Frequency Division Multiplexing (OFDM) system is an effective technique for high data rate transmission over wideband multipath fading channels. In this paper a robust image transmission system is proposed, based on a Reed-Solomon (RS) coded 16-QAM OFDM scheme. This system comprises a Vector Quantization (VQ) source encoder with a compression rate of 16. The data is encoded using a Reed-Solomon block code and mapped onto a 16-QAM constellation. The parameters of the codebook have been optimized for 16-QAM. It is shown, through simulations, that the combination of OFDM and Reed-Solomon coding makes the system robust to errors. Results indicate that the joint optimization of source coding and QAM minimizes the visual artifacts that result from channel induced errors.

## I. INTRODUCTION

Recently, there has been an increasing interest in multimedia communications such as the transmission of video, images, data, and high quality audio over wideband wireless channels [1]. Highly compressed data are extremely sensitive to the bursty errors that are commonly encountered in wireless channels [1]. At high data rates, radio channels introduce distortions such as multipath fading, which results from a signal taking multiple paths from the transmitter to the receiver [2,3].

OFDM is one of the most effective radio techniques for high bit rate applications such as digital audio broadcasting (DAB) [6], digital video broadcasting (DVB) [7], and wireless LANs [5]. OFDM can mitigate intersymbol interference (ISI) caused by multipath fading. The European Telecommunications Standards Institute (ETSI) has specified OFDM for its new 5GHz indoor mobile communication standard HIPERLAN/2 [4,5]. In an OFDM system, the entire channel is divided into many narrow sub-bands, each of which suffers frequency flat fading [8,9,10,11].

In this paper the combination of source coding and QAM modulation in an RS coded OFDM system is discussed in order to reduce the impairments introduced by the wireless channel. VQ is used for the compression of images with the codebook design performed using Kohonen's Self-Organizing Feature Map [12]. This approach was chosen because of the organized nature of the generated codebook [14]. The codeword index is then RS encoded and mapped onto

a 16-QAM OFDM constellation.

This paper is organized as follows. In Section II the transmission system is described. Simulation results are given in Section III, which show examples of the received images along with BER and PSNR performances achieved with the proposed method. Section IV discusses the proposed method and concludes the paper.

## II. SYSTEM MODEL

The elements of the transmission system, whose block diagram is shown in Figure 1, are described in the following sections.

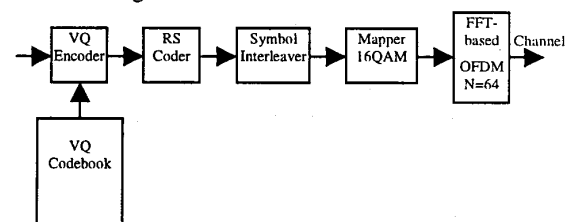


Figure 1. Image transmission system block diagram.

### A. Vector Quantization

Vector Quantization (VQ) image coding can provide fixed length code words, which are useful for error resilient coding applications since channel errors can not propagate between codewords [1]. VQ exploits the statistical redundancy between pixels to reduce the bit rate. The input data are divided into blocks and then tested against a set of codevectors to find the best match. The index of the corresponding codevector is transmitted, and the receiver uses this index to extract the codevector from a local copy of the codebook [13,15]. The codebook design in this study is performed using Kohonen's Self-Organizing Feature Map (SOFM) [12,16]. This approach was chosen to achieve the joint optimization of the source coding and QAM hard decision process [14]. Self-organizing maps learn to recognize groups of similar input vectors in such a way that neurons physically close together in the neuron layer respond to similar input vectors. The ordered nature of the generated codebook, corresponding to the topology-preserving feature of the SOFM, means that adjacent indexes have similar codewords [14]. This important property will be exploited later in the design of the coded modulation schemes.

## B. Orthogonal Frequency Division Multiplexing (OFDM)

OFDM is used to combat frequency selective fading and to randomize the burst errors caused by Rayleigh fading [9]. In OFDM, the data stream is distributed over  $N$  closely spaced individual carriers. These carriers are made orthogonal by choosing the frequency spacing between them to be equal to the reciprocal of the OFDM symbol period [8]. The major advantage of OFDM is that each sub-channel can now have a bandwidth within the coherence bandwidth of the channel, and so the channel can be considered narrowband. Since each sub-channel covers only a small fraction of the original bandwidth, equalization is far simpler than a serial system [10]. The total signaling interval is spread out, thereby the system has less sensitivity to delay spread.  $N$  symbols of duration  $T_s$  are collected to form a group of symbols with duration  $T=N*T_s$ , which is the duration of the OFDM symbol. The system has the ability to degrade gracefully in increasing dispersion, interference and noise. One way to prevent ISI is to create a cyclically extended guard interval, where each OFDM symbol is preceded by a periodic extension of the signal itself. The total OFDM symbol duration is  $T_{total}=T_g+T$  where  $T_g$  is the guard interval and  $T$  is the useful symbol duration. When the guard interval is longer than the channel multipath delay, the ISI can be eliminated [8].

In our system the number of subcarriers per OFDM symbol is  $N=64$  resulting in a subcarrier spacing of  $1/(N*T_s)=312.5$  kHz for a bandwidth of 20MHz at 5.2GHz. This leads to a row symbol duration  $T=3.2\mu s$ . After  $1/2$  rate RS encoding and including guard interval ( $T_g=T/4$ ) the data rate for this OFDM system is approximately 32Mbps. These values were used since they are compatible with HIPERLAN/2 IEEE 802.11 and MMAC standards.

## C. Channel Model

In a wireless communication system, the signal arriving at the receiver consists of several multipath components. A fading multipath channel is generally characterized as a linear, time-varying system having an impulse response  $c(t)$  given by:

$$c(t) = \sum_{n=1}^L A_n(t) e^{i\theta_n(t)} \delta(t - \tau_n) \quad (1)$$

where  $A_n(t)$ ,  $\theta_n(t)$ ,  $\tau_n(t)$ , represent the time varying gain, phase and time delay of the  $n^{th}$  path.  $A_n(t)$  is modeled as Rayleigh fading and  $L$  denotes the number of resolvable multipath components.

The model employed for these simulations uses a wideband multipath Rayleigh channel with the mean impulse response following an exponentially decaying power delay profile. Each path is faded independently according to Rayleigh statistics with a

Doppler frequency  $f_d$  of 175 Hz. This corresponds to a worst-case indoor speed of 10m/s at 5.2GHz. The RMS delay spread was chosen to be 60ns, which is typical for a non line of sight office channel [2,5].

The fading is assumed quasi-static, i.e., it remains constant during the transmission of an OFDM frame and only changes from one frame to another. This is a reasonable assumption because of the large coherence time of the channel compared to the duration of a single frame. Furthermore, the noise is modelled as a complex-valued white Gaussian random process with zero mean and power spectral density  $N_0$ . In this paper perfect channel state information is assumed to be available at the decoder.

## D. Joint Source Coding/Modulation

The modulation scheme considered in this paper is 16-QAM (Quadrature Amplitude Modulation). Grey mapping is used to ensure that the majority of symbol errors contain just a single bit error. The joint optimization of source coding and modulation is performed using Kohonen's SOFM neural network algorithm (performing vector quantization) as the source-coding scheme. The ordered nature of the codebook means that adjacent indexes have similar codewords and so an error in the QAM constellation leads to a similar codeword (Figure 2) [14].

Consider a 4x4 2D SOFM leading to 16 codewords. If each codeword is associated to one point in the constellation diagram (QAM-Gray mapping) a perfect mapping between the codebook indexes and the constellation points is realized (for example 16 indexes for 16-QAM). However for a larger codebook (256 codewords) the 8-bit binary representation of each index is split into two 4-bit binary coordinates. In this case, a 4D(4x4x4x4) SOFM scheme must be used [14].

Hence, the combination of OFDM and channel coding will make the system robust to errors introduced by the wireless channel and the joint optimization of source coding and QAM will ensure that most errors lead to a similar codeword, thus reducing the impact of visual artifacts.

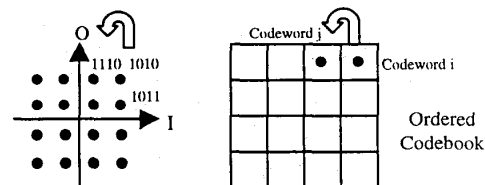


Figure 2. A transmission error in the Gray mapped QAM (1010  $\rightarrow$  1110) leads to a similar codeword since adjacent indexes have similar codewords.

## E. Channel Coding

In our system, a rate  $1/2$  Reed-Solomon code over  $GF(2^8)$  (i.e. 8-bit symbols) is employed to encode the

symbols across the frequency domain. This means that one RS symbol is mapped onto two 16-QAM symbols. The convolutional  $G=[133_{oct}, 171_{oct}]$  code used in the HIPERLAN/2 standard was not employed in this scheme because a systematic code was needed to preserve the joint optimization of source coding and QAM. Symbol interleaving is used to minimize the effect of burst errors, with interleaving depth of 8 or 16. The interleaving width is equal to the number of information sub-carriers in the OFDM frame. Automatic Repeat Request (ARQ) protocols could also be used to correct errors at the expense of bandwidth, capacity and delay in a unicast transmission.

### III. SIMULATION RESULTS

In this section, simulation results are given to illustrate the concepts developed in this paper. First, the 8-bit/pixel monochrome test image "Lena" is divided into  $4 \times 4$  dimension blocks. The Kohonen method is applied for the design of a 4-dimensional  $(4 \times 4 \times 4 \times 4) = 256$  codebook optimized for 16-QAM. The compression rate is 16, corresponding to a transmission rate of 0.5 bit/pixel. Figure 3 shows the VQ-coded image of "Lena". The peak signal to noise ratio (PSNR) of an image is a measure of the distortion of an image relative to a reference image. It can be used to measure the distortion of an image due to compression or transmission errors, compared with the original image. PSNR is defined as:

$$PSNR(dB) = 10 \log_{10} \frac{(2^n - 1)^2}{MSE} \quad (2)$$

where  $n$  is the number of bits required to represent each pixel in the original image ( $n=8$ ) and  $MSE$  is the mean squared error between the distorted and the original image [13]. The PSNR in our example is 28.3 dB but higher PSNRs (above 30dB) can be achieved for transmission rates of 0.9-1 bit/pixel.



Figure 3. VQ-coded image "Lena" (compression rate=0.5 bit/pixel, PSNR=28.3).

The systematic  $\frac{1}{2}$  rate RS codes over  $GF(2^8)$  (i.e. 8-bit symbols), RS(64,32,16) and RS(32,16,8) are

employed for error correction. A 16-QAM-OFDM with  $N=64$  subchannels is used and all other assumptions are as described in Section II.

The BER versus  $E_b/N_0$  of the uncoded OFDM and the RS(64,32,16) and RS(32,16,8) coded OFDM systems are shown in Figures 4 and 5 respectively. As can be seen the performance of the uncoded system in the frequency selective channels is improved after RS coding and as the interleaver depth increases. The RS(64,32,16) has a better performance than the RS(32,16,8) because of the better correction capability of the code (but it introduces longer delays). The interleaver and deinterleaver end-to-end delay is  $(2WD-2W+2)$  symbols where  $W$  and  $D$  are the interleaver width and depth respectively.

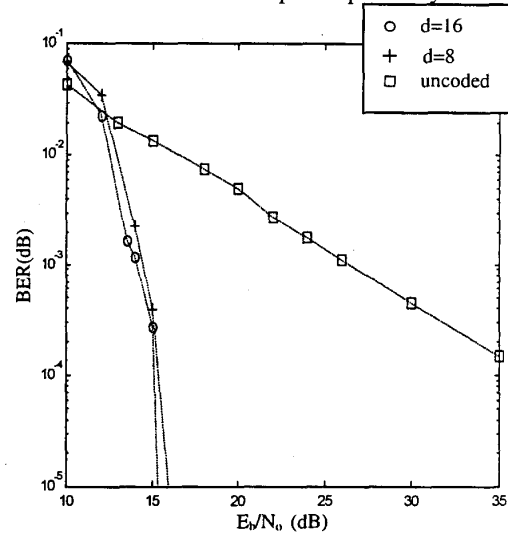


Figure 4. BER performance after the RS(64,32) code with interleaving depth  $d=8$  and 16.

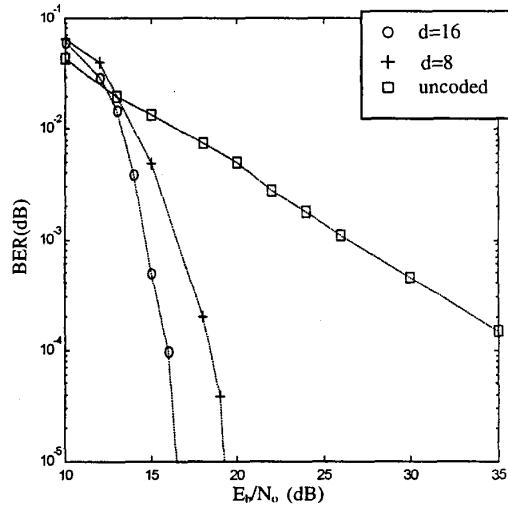


Figure 5. BER performance after the RS(32,16) code with interleaving depth  $d=8$  and 16.

Figure 6 and 7 show the PSNR performance of the system against the channel SNR for RS(64,32,16) and RS(32,16,8) respectively. From Figures 6 and 8

we observe a PSNR of 28.25dB (PSNR of transmitted image =28.3 dB) at SNR=18dB (BER=3x10<sup>-4</sup>) over the wideband channel. Table 1 summarizes the system performance in terms of the required channel SNR in order to maintain less than 1dB PSNR image degradation.

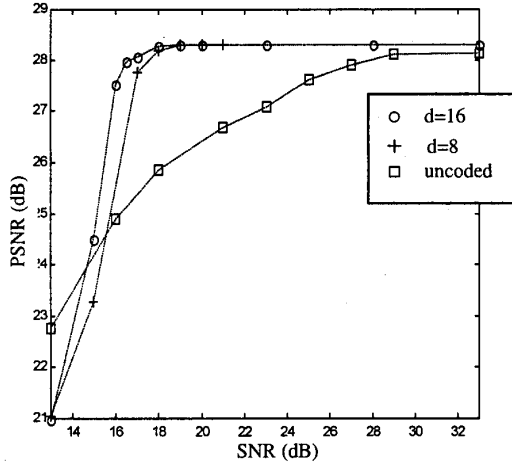


Figure 6. Received image PSNR performance against channel SNR with the RS(64,32) code.

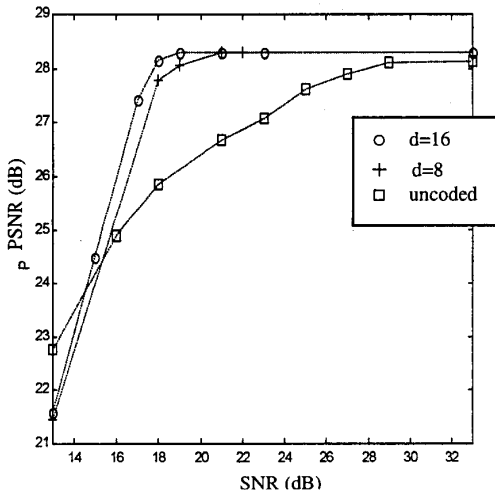


Figure 7. Received image PSNR performance against channel SNR with the RS(32,16) code.

Mod.	Code	SNR	E <sub>b</sub> /N <sub>0</sub>	BER
16QAM	RS(64,32)	16	13	0.0027
16QAM	RS(32,16)	17	14	0.0039

Table 1. Summary of results over wideband channels assuming PSNR degradation of 1dB.

Figures 8 and 9, show examples of the received images. Given the channel characteristics, the images present a good subjective quality. Note that the ordered codebook of the VQ coder reduces the visual artifacts. From Figure 8(c) we can observe that even for high BER (2x10<sup>-3</sup>) the quality of the image remains largely acceptable with a PSNR of 28 dB

(which is a negligible loss of 0.3dB). These results show that the proposed transmission system is very robust to the transmission errors introduced by the wideband Rayleigh fading channel.



(a) Without channel coding; BER=0.015 PSNR=25.3



(b) After RS coding; BER= 3x10<sup>-4</sup>; PSNR=28.25



(c) SNR=16.5dB; BER=2x10<sup>-3</sup>; PSNR=28

Figure 8. (a),(b) Received image with and without channel coding (RS(64,32)) over wideband channel with channel SNR=18dB. (c) With SNR=16.5dB

#### IV. CONCLUSIONS

In this paper, a new OFDM image transmission system based on joint modulation and source coding is proposed and investigated in a wideband channel. Simulation results were presented for an RS coded

16QAM OFDM system and these showed that the proposed scheme is capable of reliable transmission at relatively low SNRs (Table 1). Furthermore, the ability of OFDM to degrade gracefully in increasing dispersion, interference and noise and the joint optimization of the source encoder with 16QAM results in the gradual degradation of the image quality as the SNR is decreased (Figure 9), similar to an analog system. The proposed system ensures robust image transmission in a highly dispersive Rayleigh-fading environment even at speeds of 10m/s, requiring channel SNRs of only around 18 dB for near-unimpaired image transmission.

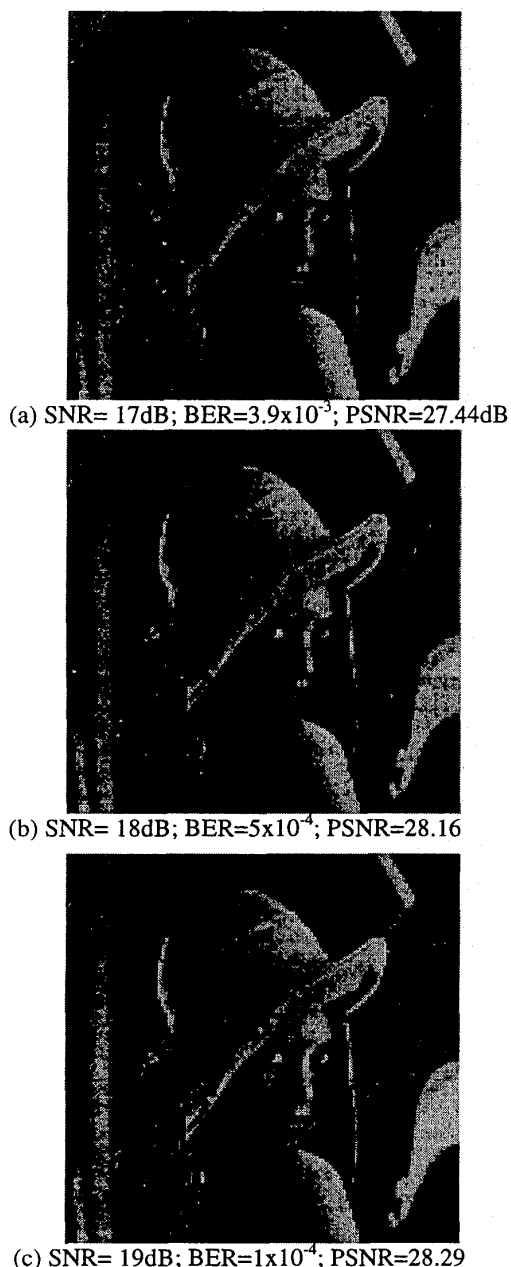


Figure 9. Examples of received images with the RS(32,16) code.

## V. ACKNOWLEDGEMENT

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