Combined Source-Channel Coding for the Transmission of Still Images over a Code Division Multiple Access (CDMA) Channel*

E. V. H. Iun, and A. K. Khandani
Dept. of Elec. and Comp. Eng., University of Waterloo, Waterloo, Ont., N2L 3G1

Abstract: This work considers a combined source-channel coding scheme for image transmission over the uplink of a wireless IS-95 CDMA channel using Discrete Cosine Transform. By adjusting the dimension of the orthogonal signaling scheme, we trade the system error-correction capability for a faster bit rate. The increase in channel error is relieved by employing a set of quantizers which are designed using a joint source-channel optimization algorithm. The bit allocation problem of the quantizer array is solved by using a new approach based on the integer programming technique. Without bandwidth expansion, our proposed scheme results in a substantial improvement in the reconstructed image quality, especially for good channel condition.

1 Introduction

In most of the traditional coding schemes, the quantizer and the channel coder are selected independently. Some fundamental results of information theory indicate that such an independent selection scenario can achieve the optimum performance, but only in the limit of an arbitrarily long delay and complicated encoder/decoder structure. In contrast, in many practical systems, one can improve the performance by jointly selecting the quantization and the channel coding schemes. Such a joint design involves: (*i*) selecting the quantizer to have some degree of tolerance to channel errors, and/or, (*ii*) trading the quantization accuracy versus the error correction capability of the channel coder.

This work studies the use of a combined source-channel coding scheme for the transmission of still images over the uplink[1] of the IS-95 cellular radio CDMA system using Discrete-Cosine-Transform (DCT). We make use of a channel optimized quantization scheme, and sacrifice error-protecting redundancy in the channel coding for more accurate quantization (by lowering the dimension of the orthogonal signal set used in the IS-95). We consider an enhanced version of the IS-95 as used in [1]-[2]. This is very close to the IS-95 standard except for replacing the bit-by-bit interleaver with a symbol-by-symbol interleaver.

Kurtenbach and Wintz studied the transmission of PCM data over a noisy channel, ignoring the code assignment problem [3]. Rydbeck and Sundberg, without considering the quantizer design problem, have shown that the code assignment plays an important role in determining the system performance [4]. References [5] and [6] consider the problem of combined source-channel coding for the transmission of still images. In [7], Farvardin and Vaishampayan provide an algorithm for minimizing total distortion caused by the quantization and channel noise. Later, the same researchers present a method for the joint source-channel coding of a scheme based on the 2-dimensional block cosine transform for a Gaussian source over a memoryless binary symmetric channel [8]. More recently, the combined source-channel coding in vector quantization has been studied by Farvardin, who gives an algorithm based on simulated annealing for assigning binary code-words to the vector quantizer code-vectors [9].

The present article is organized as follows: Section 2 gives an overview of the system under consideration. Section 3 describes the combined source-channel coding algorithm. The bit allocation method is explained in Section 4. Section 5 presents some numerical results. Finally, Section 6 is devoted to concluding remarks. A detailed description of this work can be found in [10].

2 System Overview

The block diagram of the system under consideration is depicted in figure 1. The "8×8" blocks of the image are transformed using a 2-dimensional (2-D) DCT. The transformed coefficients are quantized by a set of "8×8" quantizer banks. The quantizer outputs are labeled using the Natural Binary Code (NBC) independent of each other. The output of the source encoder is coded by a rate 1/3 convolutional code. The convolutional encoder has a constraint length of 9, with the generating functions { 557, 663, 711 } octal as adopted by the IS-95

*This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Information Technology Research Centre (ITRC).

[1]Uplink (or reverse link) refers to the transmission from a mobile to the base station.

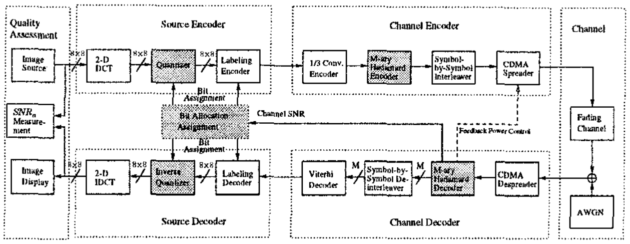

Figure 1: System Overview.

standard. The output bits of the convolutional encoder are mapped to the points of an M-dimensional orthogonal signal set based on the Hadamard code-words. The IS-95 standard specifies M to be 64 which means that every signaling waveform contains 6 coded bits. The constituent bit rate of each Hadamard code-word is fixed at 307.2 kbps. This gives the 64-ary signaling of the IS-95 system the required bit rate of 9.6 kbps.

The proposed combined source-channel coding involves: (i) changing the value M in orthogonal signaling (to trade-off the performance of the channel coder for a better source coder), (ii) optimizing the quantizer thresholds and the reconstruction values (to incorporate the effect of the channel errors), and (iii) generating a bit assignment (which incorporates the effect of the channel errors) using a new method based on integer programming. We assume that M is a power of 2, i.e., $M = 2^n$, where n is the number of bits represented by each of the orthogonal signals. We select $M = \{2, 4, 8, 16, 32, 64\}$, corresponding to $n = \{1, 2, 3, 4, 5, 6\}$, respectively.

Microcellular applications at a carrier frequency of 2 GHz are of interest in this work. We consider slowly fading channels with a Doppler frequency of 2 Hz, which corresponds approximately to a portable speed of 1 km/hr [11].Given that the Doppler shift is much smaller than both the carrier frequency and the bit rate, we have a flat fading channel. Hence, we select a popular Rayleigh flat fading channel as our model. Also, we have selected the widely popular Jakes' model as given in [12] to define the power spectrum of the channel.

We assume that the base station employs a two-antenna diversity. With uncorrelated received signals, our setup represents the mobile radio channel as two independent Rayleigh flat fading paths. The combined effect of the other channel imperfections is modeled by an additive-white-Gaussian-noise (AWGN) source.

The M-ary waveforms are symbol-by-symbol interleaved to combat channel fading.Our 64-ary system has an interleaver span of (16×6), which translates to a time span of 20 ms [13]. We fix the span of the interleaver regardless of the size M of the Hadamard code-word selected. This results in an interleaver span of: $\{16 \times 6, 16 \times 12, 16 \times 24, 16 \times 48, 16 \times 96, 16 \times 192\}$ at a Hadamard code-word of size {64, 32, 16, 8, 4, 2}, respectively. The interleaver output bits are spread and transmitted through the radio channel. The chip rate chosen is 1.2288×10^6 chips/second. This means that each constituent bit of the Hadamard code-words is spread by 4 chips as used in [11].

At the receiver, the signal received is first despread and then correlated with each of the M possible orthogonal waveforms. The output of the Hadamard correlators from the two diversity branches are square-law combined (weighted with equal gains). These M correlation results are de-interleaved and used as the metric to a soft decision Viterbi decoder.

In the process of changing M, it may happen that $\log_2 M$ is not a multiple of 3. This situation results in a mismatch with the rate 1/3 convolutional encoder in which case the trellis decoding becomes nontrivial. We illustrate how the Viterbi decoding is applied to M-ary orthogonal signaling by a simple example shown in figure 2. Assume that the rate 1/3 convolutional encoder has 8 nodes. Each of these nodes has 4 outward edges, each of which is labeled by 3 output bits. Also, assume that we want to use 4-ary signaling for this system. This becomes possible if we merge two subsequent trellis stages together. In this case, each stage of the new trellis corresponds to two information bits and six output bits (or three 4-ary signaling waveforms).

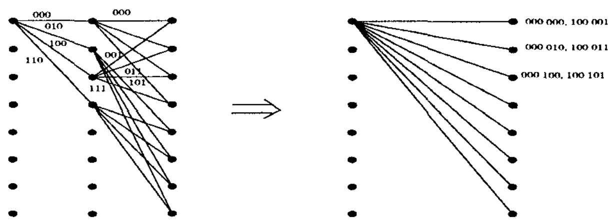

Figure 2: Merging of trellis stages.

The low-rate return downlink [2] serves as a feedback in the close-loop power control. We assume that this channel has a cross-over probability of 5×10^{-3}.

Fixing the bit rate of the 64-ary scheme at 9.6 kbps, we obtain a time duration of 2/9600=0.208 ms for each 64-ary block[3]. During this time interval, a system of dimension {32, 16, 8, 4, 2} can transmit {10, 16, 24, 32, 32} coded bits, respectively. Table 1 summarizes the bit rates corresponding to different values of M. We assume that an "8 × 8" DCT subframe is transmitted in 3.125 ms (corresponding to 30 bits in a conventional 64-ary scheme, i.e., 30/9600=3.125 ms). A 30 bits/subframe for 64-ary scheme is chosen because it induces an integral number of bits per subframe at all the signaling rates. The last two rows of table 1 show the quantization bit rates corresponding to different signal-

[2] Downlink refers to the transmission from the base station to a mobile.

[3] Note that each such block contains six coded bits, corresponding to two bits of source information.

ing schemes. Also, table 1 reveals that both 4-ary and 2-ary systems have an identical information bit rate.

Table 1: Relationship between the code rate and the source rate.

M-ary	64	32	16	8	4	2
Num. of coded bits in 0.208 ms	6	10	16	24	32	32
Bit rate (kbps)	9.6	16.4	25.6	38.4	51.2	51.2
Num. of bits per 8x8 subframe	30	50	80	120	160	160
Bits/pixel	0.47	0.78	1.25	1.88	2.5	2.5

3 Basics of Combined Source-Channel Coding

The design of the channel optimized quantizer is based on the principles explained in [4] and [7]. Figure 3 illustrates the block diagram of the corresponding system. The N-level quantizer, described by a function $\gamma(.)$, maps a source output $X(n) \in \mathbb{R}$ into one of N representation values, $Q_0, Q_1, ..., Q_{N-1}$, and generates a label $U(n) \in \{u_0, u_1, ..., u_{N-1}\}$, which is composed of r bits, $r = \lceil \log_2 N \rceil$. Each of these r-bits is submitted to a Binary Symmetric Channel (BSC) with cross-over probability ϵ on a bit-by-bit basis, resulting in the channel output $V(n)$. The decoding operation consists of decoding $V(n)$ into $\hat{X}(n) = g[V(n)]$, which takes on one of the N possible reconstruction levels $\{R_0, R_1, ..., R_{N-1}\}$ (where R_i's are, in general, not equal to the Q_i's).

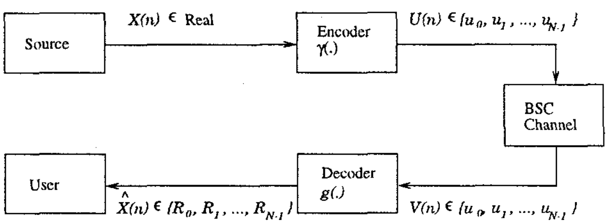

Figure 3: Block diagram of encoding/decoding system.

The channel transition probabilities are given by:

$$\begin{aligned} P_{(k|m)} &= Pr[V(n) = v_k | U(n) = u_m], m, k = 0, \ldots, N-1, \\ &= (\epsilon)^h (1-\epsilon)^{r-h}, \end{aligned} \quad (1)$$

where h is the hamming distance between v_k and u_m.

In this study, our objective is to minimize the mean-square error of the reconstructed image at the receiver. For a fixed decoder $g(.)$, the optimal encoder is described by the following decision region which is the collection of inputs $X(n)$ mapped into $\gamma[X(n)] = u_i$,

$$\begin{aligned} \{x \ : \ & E[(x - \hat{X}(n))^2 | U(n) = u_i] \leq \\ & E[(x - \hat{X}(n))^2 | U(n) = u_j], \forall j \neq i\} \end{aligned} \quad (2)$$

For a fixed encoder $\gamma(.)$, the optimal decoder is described by the conditional expectation of the input given the channel output, i.e.,

$$g(v_i) = E[X(n) | V(n) = v_i], \qquad i = 0, ..., N-1. \quad (3)$$

4 Bit Allocation Using Integer Programming

Block transform coding, like the 2-D DCT used in this work, concentrates the energy of an image in a few components of the transform domain. These components are critical in restoring the transmitted image and must be preserved with finer resolution. Bit allocation is the problem of distributing a given quota of bits among a number of different quantizers such that the total distortion of all the quantizers is minimized. We apply a new method based on the integer programming (IP) to optimally allocate the bits.

Consider the quantization of K random variables, say X^0, X^1, ..., X^{K-1}. Define the normalized quantizer rate-distortion function, $W_i(b_i)$ as the mean square error incurred in quantizing X^i with b_i bits. A multiplicative factor G_i accompanies $W_i(b_i)$ to incorporate the effect of the input variance. The bit allocation vector $\vec{\mathbf{b}} = (b_0, b_1, ..., b_{K-1})$ is computed using:

$$\begin{cases} \text{Minimize: } D(\vec{\mathbf{b}}) = \sum_{i=0}^{K-1} G_i W_i(b_i), \\ \text{subject to: } \sum_{i=0}^{K-1} b_i \leq B, \\ \qquad p_i \leq b_i \leq q_i, \ i = 0, ..., K-1, \end{cases} \quad (4)$$

where b_i's are integer, $D(\vec{\mathbf{b}})$ is the overall distortion, B is the fixed quota of available bits, and p_i, q_i determine the range of the admissible bit assignment for each quantizer. We solve (4) using an IP formulation, which is based on using a set of binary variables $\delta_i(j)$ to specify the integer bit allocated. We set,

$$\delta_i(j) = \begin{cases} 1, & \text{if } j \text{ bits are allocated to quantizer } i, \\ 0, & \text{otherwise.} \end{cases}$$

Using these variables, the problem in (4) is expressed as,

$$\begin{cases} \text{Minimize: } D = \sum_{i=0}^{K-1} \sum_{j=p_i}^{q_i} \delta_i(j) G_i W_i(j), \\ \text{subject to: } \sum_{j=p_i}^{q_i} \delta_i(j) = 1, \ \forall i \in \{0, .., K-1\}, \\ \sum_{i=0}^{K-1} \sum_{j=p_i}^{q_i} j \delta_i(j) \leq B, \ \ \delta_i(j) \in \{0, 1\}. \end{cases} \quad (5)$$

The optimization problem in (5) is solved using an application software called the General Algebraic Modeling System (GAMS) version 2.25.

The conventional methods of bit allocation are based on approximating the integer valued bits by real numbers, and/or making so me assumptions (for example on the convexity) of the quantizer rate-distortion function. The proposed IP method avoids these shortcomings, and computes the optimum integer solution of (4) without making any extra assumption.

It should be mentioned that, in general, the complexity of solving a linear integer optimization problem is substantially higher than the complexity of the underlying linear problem. The important point is that the linear solution of (5) satisfies the corresponding integrality constraints in the majority of the cases (no counter-example observed). It can be shown that in the event of the rare cases that this property does not hold, one can easily compute an integer solution (which is possibly slightly sub-optimum) using a simple round-off of the corresponding linear solution. This property is in the favor of the proposed method for the applications that the problem should be solved dynamically (with a small computational complexity).

5 Numerical Results

Fixing the chip duration, we define the channel *SNR* as the ratio of the average faded signal power to the received noise. This is the true channel *SNR* which provides a consistent way of comparing the performance of different signaling schemes. Figure 4 shows the bit error probability for six values of M as a function of the channel *SNR*.

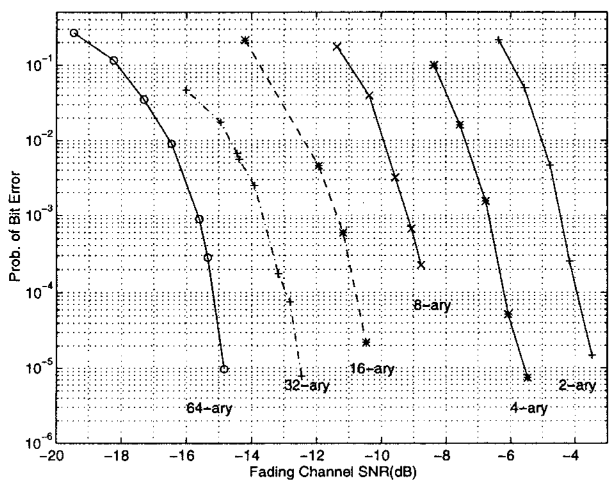

Figure 4: Bit error probability as a function of the channel *SNR* for different values of M.

For a particular value of M and channel *SNR* of interest, we first find out the expected BER from figure 4. We then select a quantizer designed for the closest bit error rate, and make use of the corresponding bit allocation table as computed earlier.

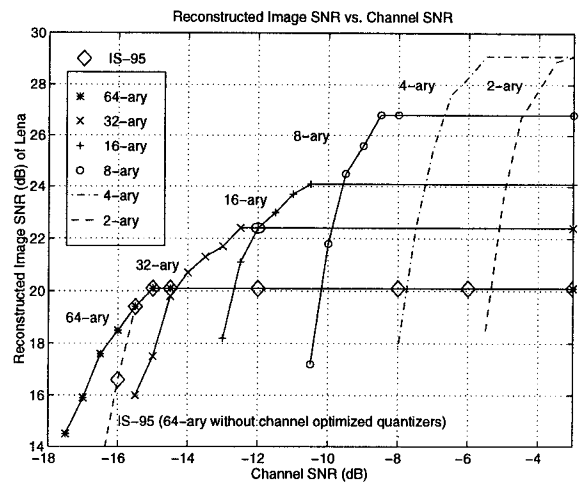

Figure 5: Reconstructed image SNR_o vs. channel *SNR*.

The output signal-to-noise ratio (SNR_o) compares the mean-square error between the original image (gray levels of 8 bits/pixel) and its reproduction at the receiver. Figure 5 shows the output SNR_o versus the channel *SNR* for a Lena image. Several general characteristics are noticeable. Firstly, note the sharp threshold effect which becomes more pronounced as the dimension M decreases. This is because the smaller the M, the bigger is the SNR_o discrepancy between an error free channel and a noisy channel. Secondly, for channel *SNR* in excess of a threshold point, channel errors are rare and the performance is limited solely by the quantization noise. This counts for the flat portion of the curves.

Figure 5 shows that our 64-ary system (with matching channel optimized quantizers) performs better than the ordinary IS-95 system (whose quantizer structure ignores the effect of channel noise). The difference is prominant for low system BER (around 1.0×10^{-3}).

Figure 6 shows two Lena images with $SNR_o = 22.5$dB for $M = 16$ and 32.

As the structure of the quantizer depends on the channel error probability, it would be useful to study its robustness when applied to a channel with a different error probability as the one used in the design phase. Figure 7 show the effect of the channel mismatch on the reconstructed image SNR_o for 64-ary signaling. Similar results for other values of M can be found in [10]. Note that the comparison with the curve corresponding to zero error probability indicates the gain obtained through the use of the combined source-channel coding method.

(a) 32-ary signaling.

(b) 16-ary signaling.

Figure 6: Reconstructed images with same SNR_o.

6 Summary & Conclusions

We have presented an image transmission system over the uplink of an enhanced IS-95 wireless CDMA system using DCT. The proposed combined source-channel coding includes (i) reducing the dimension M in orthogonal signaling for a faster data rate, (ii) optimizing the structure of the quantizers by incorporating the effect of the channel errors, and (iii) generating the corresponding bit assignments using a new approach based on the integer programming.

The numerical results presented show how one can substantially improve the quality of the reconstructed image (especially for good channel condition) at no additional cost.

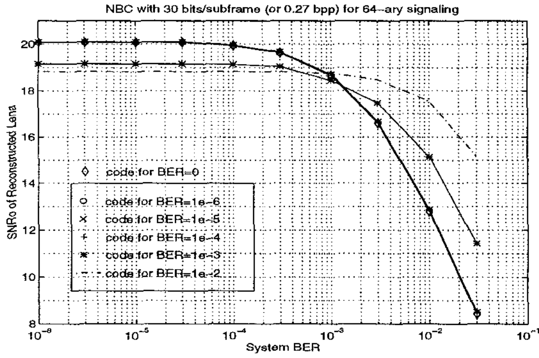

Figure 7: The effect of the channel mis-match on the SNR_o, $M = 64$.

References

[1] L.F.Chang and N.Collenberger, "Comparison of Two Interleaving Techniques for CDMA Radio Communications System", *1992 42nd IEEE Vehicular Technology Conference*, pp. 275–278, 1992.

[2] L.F.Chang and S.Ariyavisitakul, "Performance of a CDMA Radio Communiations System with Feed-Back Power Control and Multipath Dispersion", *Proceedings of GLOBECOMM 91*, pp. 1017–1021, 1991.

[3] A.J.Kurtenbach and P.A.Wintz, "Quantizing for Noisy Channels", *IEEE Transactions on Communication Technology*, vol. COM-17, No. 2, pp. 291–302, April 1969.

[4] N.Rydbeck and C.W.Sundberg, "Analysis of Digital Errors in Nonlinear PCM Systems", *IEEE Transactions on Communications*, vol. COM-24, pp. 59–65, January 1976.

[5] J.W.Modestino and D.G.Daut, "Combined Source-Channel Coding of Images", *IEEE Transactions on Communications*, vol. COM-27, No. 11, pp. 1644–1659, November 1979.

[6] J.W.Modestino, D.G.Daut and A.L.Vickers, "Combined Source-Channel Coding of Images Using the Block Cosine Transform", *IEEE Transactions on Communications*, vol. COM-29, No. 9, pp. 1261–1274, September 1981.

[7] N.Farvardin and V.Vaishampayan, "Optimal Quantizer Design for Noisy Channels: An Approach to Combined Source-Channel Coding", *IEEE Transactions on Information Theory*, vol. IT-33, No. 6, pp. 827–838, November 1987.

[8] V.Vaishampayan and N.Farvardin, "Optimal Block Cosine Transform Image Coding for Noisy Channels", *IEEE Transactions on Communications*, vol. COM-38, No. 3, pp. 327–336, March 1990.

[9] N.Farvardin, "A Study of Vector Quantization for Noisy Channels", *IEEE Transactions on Information Theory*, vol. IT-36, No. 4, pp. 799–809, July 1990.

[10] E.Iun, *Combined Source-Channel Coding for the Transmission of Still Images over a Code Division Multiple Access (CDMA) Channel*, M.A.Sc. Thesis, University of Waterloo, August 1996.

[11] M.Khansari, A.Jalali, E.Dubois and P.Mermelstein, "Low Bit-Rate Video Transmission over Fading Channels for Wireless Microcellular Systems", *submitted to IEEE Transactions on Circuits and Systems for Video Technology*, vol. 6, No. 1, pp. 1–11, February 1995.

[12] W.C. Jakes, Jr., *Microwave Mobile Communications*, New York: John Wiley & Sons 1974.

[13] A.Jalali and P.Mermelstein, "Effects of Diversity, Power Control, and Bandwidth on the Capacity of Microcellular CDMA Systems", *IEEE Journal on Selected Areas in Communications*, vol. 12, pp. 952–961, June 1994.