A New Loading Algorithm for Image Transmitting over Spectrally Shaped Channels: Combined Source Coding and Multicarrier Modulation Approach

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Abstract

A combined source coding and multicarrier modulation scheme for transmitting image over noisy channels is proposed. The source image is divided into several layers which are transmitted in parallel, each occupying a number of subchannels. For spectrally shaped channels, the existing loading algorithms try to remove the property that channel gain and noisy variance are quite different across the subchannels, and use the power and rate allocation to provide an uniform error performance at the usable subchannels. In contrast, we deem the above property as an advantage and develop a new loading algorithm to provide unequal error protection as well as achieve better power efficiency. For subband coded images transmission, simulations show that the proposed algorithm achieves significant performance improvement, especially, 4-10dB improvement over the exsisting algorithms for typical spectrally shaped channels.

1. Introduction

The asymmetric digital subscriber lines (ADSL)[1] is designed to transmit compressed multimedia data via twisted pair telephone loop to telephone subscribers. Typical channels in ADSL are spectrally shaped channels with characteristics shown in Figure 1. Multicarrier modulation (MCM) [2] also referred to as orthogonal frequency division multiplexing (OFDM) or discrete multiton (DMT) is currently considered as a standard channel coding scheme for ADSL. By applying the discrete Fourier transform (DFT) or fast Fourier transform (FFT) and their inverse, the available channel bandwidth is subdivided into a number of subchannels that achieves bandwidth efficiency. Cyclic prefix is used to remove the interblock interference and produce independent subchannels.

MCM transmits data in parallel over the subchannels. Since each subchannel has different channel gain and channel noise variance, the bit rate (modulation rate) and transmitted power should be allocated among the subchannels to optimize the overall performance. The loading algorithms in literature are all designed to achieve that all the usable subchannels perform with the same error rate. Hughes-Hartogs algorithm[2] assigns the bits successively to the subchannels until the target bit rate (bit rate sum of all the subchannels) is reached. For ADSL, it requires extensive computation for large target bit rate. An improved version is now known as Campello Algorithm[4]. In [9], channel capacity of the subchannels is used to compute the modulation rate distribution, for given bit error rate. On the other hand, [5] use the relationship between the transmitted power and bit rate and develop a less complex loading algorithm which minimize the overall error rate under the target bit rate and transmitted power constraint. Recently, a combined source-channel coding scheme using MCM to provide unequal error protection for additive Gaussian white channel(AGWN) is developed in [6, 7]. MCM allows different bits within a codeword to be transmitted at different subchannels while proper power allocation provides different error performance to different bits according to their importance. In this design, the number of subchannel changes as the length of the codeword changes. And no bit rate allocation is applied. Therefore, it is not applicable to spectrally shaped channels.

In this paper, we want to design a new framework to transmit layered coded image over spectrally shaped channels. We consider the fixed number of subchannels and target bit rate, so that the transmitter/receiver remains the same during the whole transmission. The essence of the proposed approach is to allow the source layers of different importance to be transmitted simultaneously, each occupying a set of subchannels, while a new loading algorithm allocates the transmitted power and bit rate among the subchannels to provide unequal error protection. We show that parallel transmission which assigns different error performance to the subchannels achieve better performance than the named serial transmission which assigns the same error performance across the subchannels or even changing the error performance at each transmission.

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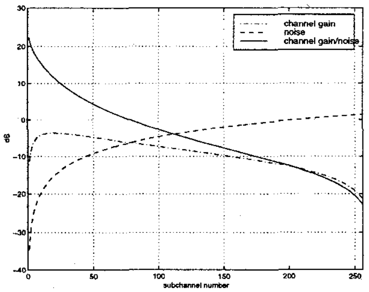

Figure 1. typical spectrally shaped channel

2. Combined Layered Coding and MCM

Layered or scalable source coding scheme in conjunction with joint source/channel coding approach offers the potential for robust performance in the presence of channel error effects. The encoded data is represented in terms of a number of layers, each resulting in a distinct data stream, which represent different perceptually relevant components of source material. The different layers may have distinctly different tolerances to channel errors and the corresponding data streams can then be handled differently by the transmitter or network. Unequal error protection for different layers was adopted by many schemes [3, 10] and yielded unquestionable performance improvement over equal error protection. MCM has the advantage of allowing the transmitted power, modulation rate and even the channel encoder of each subchannel to be changed flexibly without affecting other subchannels. Optimum use of the channel can be obtained by making optimum use of each subchannel.

Traditionally, the multimedia data layers are transmitted in consecutive order as in data transmission through spectrally shaped channels. The loading algorithm assigns the same bit error rate to all subchannels by adapting the power and modulation rate, similar to that of [2, 9, 5]. We name it serial transmission. Unequal error protection can be introduced to serial transmission by varying the power sum of the subchannels during a particular layer transmission. Larger amount of transmitted power is assigned to the layer of higher importance to reduce the error rate. It also leads to frequent change of subchannel power at both transmitter and receiver.

It is obvious that serial transmission tries to remove the property that subchannels have different channel gain to noise ratio(CGNR). In contrast, we believe that the existence of different CGNR across the subchannels offers the potential for robust transmission, by considering transmitting each layer through different set of subchannels, as illustrated in Figure 2. The transmission time of all the layers are forced to be the same so that the number of subchannels a layer occupying can be decided by the number of data bits of this particular layer as well as the number of data bits required per transmission.

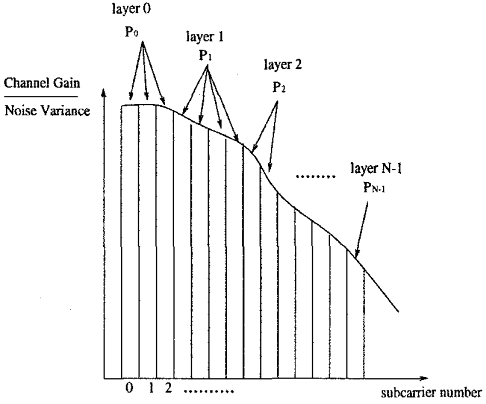

Figure 2. Transmission model

3. System Model

Since CGNR differs quite a lot across the subchannels, appropriate assignment of subchannels to the layers can potentially increase power efficiency. We want to assign the subchannels with higher CGNR to the layers of higher importance. Such assignment will ensure the most important layers are transmitted over reliable channels without much of power usage. It becomes more advantageous under low power constraint.

3.1 Assignment of Subchannels to Layers

Step 1: Sort the subchannel in increasing CGNR order, sort the layers in increasing importance order(in terms of weighting factor).

Step 2: Given the modulation rate $\{R_m\}_{m=1}^{M}$, compute the number of subchannels that each layer needs,

$$c_m = \lfloor \frac{Bit_m B_T}{R_m Bit_{total}} \rfloor, \quad m = 1..M, \tag{1}$$

where Bit_m is the total number of bits of layer m and Bit_{total} is that of whole image, B_T is the number of bits transmitted during each transmission. The Bit_m and Bit_{total} only depend on the source image while B_T depends on the channel. For a given $\{R_m\}_{m=1}^{N}$, adjust $\{c_m\}_{m=1}^{N}$ until

$$\sum_{m=1}^{N} c_m R_m = B_T. \tag{2}$$

The optimal design requires all the subchannels assigned to the same layer have the same error performance. We accomplish it in two ways.

Approach I:

Assign the same modulation rate to the subchannels belong to the same layer. The c_m subchannels corresponding to layer m have the same channel SNR=$\frac{E_m G_m}{c_m}$, modulation rate R_m. E_m is the power sum of the subchannels transmitting layer m, $E_m = \sum_{k=1}^{c_m} E_{k,m}$ and G_m is the CGNR averaged over c_m subchannels, $G_m = \frac{c_m}{\sum_{k=1}^{c_m} \frac{1}{g_{k,m}}}$ where $g_{k,m}$ is the CGNR of the kth subchannel transmitting layer m. The objective is to find the best $\{E_m, R_m, c_m, G_m\}_{m=1}^{M}$ as to minimize the channel noise effect. After obtaining E_m, the power allocated to a particular subchannel is $E_{k,m} = \frac{E_m}{c_m} \frac{G_m}{g_{k,m}}, k = 1..c_m$.

Approach II:

Use algorithm in [5] to assign modulation rate and power among the subchannels transmitting the same layer, so they perform at the same BER. Define $R_{m,T}$ as the number of bits of layer m per transmission, decided by Bit_m and B_T. The modulation rate and power of a particular subchannel are computed as

$$\begin{aligned} R_{k,m} &= \text{QUANT}(\frac{R_{m,T}}{c_m} + ld(\frac{G_{k,m}^{c_m}}{\prod_{i=1}^{c_m} g_{i,m}})), \\ E_{k,m} &= \frac{E_m 2^{R_{k,m}}/g_{k,m}}{\sum_{i=1}^{c_m} 2^{R_{i,m}}/g_{i,m}}, \quad k = 1...c_m. \end{aligned} \tag{3}$$

The error probability function of the subchannels transmitting layer m, assuming using QAM modulation, is then

$$\begin{aligned} Pe &= 4Q(\sqrt{\frac{3E_m/c_m}{(2^{\frac{R_{m,T}}{c_m}} - 1)\frac{1}{c_m}\sum_{i=1}^{c_m} \frac{2^{(R_{i,m} - \frac{R_{m,T}}{c_m})}}{g_{i,m}}}}), \\ &= 4Q(\sqrt{\frac{3E_m G_m/c_m}{(2^{R_m} - 1)}}), \end{aligned} \tag{4}$$

where $R_m = R_{m,T}/c_m$ is the averaged modulation rate, $G_m = \frac{c_m}{\sum_{i=1}^{c_m} 2^{(R_{i,m} - R_m)}/g_{i,m}}$ the averaged CGNR. We limit R_m to be integer value so that the optimization procedure is the same as approach I. The difference between these two approaches is the computation of G_m.

3.2 Mathematical Problem

The objective is to minimize the distortion between the original image and received image. Source rate distribution and channel modulation can be jointly optimized to reduce the overall distortion[10]. We choose the fixed source rate distribution in our design for simplicity. Therefore, the objective becomes to minimize the channel distortion through the optimal power and bit rate distribution. For layered coding image, the channel distortion is defined as [7]

$$D_c = \sum_{m=1}^{M} \sum_{i=0}^{N_m - 1} \sum_{j=0}^{N_m - 1} P(i)P(j|i)(y_i - y_j)^2, \tag{5}$$

where M is the total number of layers, N_m is the cardinality of the layer m, y_i and i is the codeword for VQ and binary codeword for transmission. We assume that only single bit error within one binary codeword with probability P_m, (5) becomes

$$D_c = \sum_{m=1}^{M} P_m \sum_{i=0}^{N_m - 1} D_{i,m} = \sum_{m=1}^{M} P_m W_m, \tag{6}$$

where $D_{i,m}$ represents the sum of the distortion between codeword i and the other codeword which differs 1 bit from i, and $W_m = \sum_{i=0}^{N_m - 1} D_{i,m}$ represents the average distortion caused by a single bit error at layer m, deemed as the weighting factor of layer m. Usually, layers with high energy have larger weighting factor and therefore higher importance.

Under the above assumption, the optimization function for the loading algorithm can be formulated as

$$\begin{aligned} &\text{Find} \quad \{E_m, R_m, c_m(R_m), G_m(R_m)\}_{m=1}^{N}, \text{by} \\ &\text{Min} \quad D_c = \sum_{m=1}^{N} Pe(R_m, \frac{E_m G_m}{c_m}) W_m, \\ &\text{subject to} \quad \sum_{m=1}^{N} E_m \leq E_T, \quad \sum_{m=1}^{N} c_m \leq C_T, \end{aligned} \tag{7}$$

where E_T is the total power constraint, C_T is the total number of subchannels, and Pe is the bit error rate. Since for given $\{R_m\}_{m=1}^{N}$, $\{c_m\}_{m=1}^{N}$ are selected until the bit data rate constraint as in (2) are satisfied, the data rate constraint is turned into $\sum_{m=1}^{N} c_m \leq C_T$.

4. Loading Algorithm

Our goal in this section is to develop a computationally efficient solution to (7). We begin with a simple case for AGWN channel and BPSK modulation, then extend it to a complete loading algorithm for spectrally shaped channels.

4.1 AGWN Example

Assuming that all the subchannels have the same CGNR normalized to 1 and the same modulation type BPSK, the probability of error function for BPSK modulation is given as [8]: $Pe(E) = Q(\sqrt{2E})$. (7) is simplified to

$$\begin{aligned} &\text{Min} \sum_{m=1}^{N} Q(\sqrt{\frac{2E_m}{c_m}}) W_m, \\ &\text{subject to} \quad \sum_{m=1}^{N} E_m \leq E_T. \end{aligned} \tag{8}$$

By applying Lagrange multiplier, the optimal solution satisfies

$$W_m \sqrt{\frac{1}{E_m c_m}} \exp \frac{-E_m}{c_m} = \lambda. \tag{9}$$

Define $\Phi_a(x) = \sqrt{\frac{a}{x}} exp(-ax)$. The optimal λ can be found by solving

$$\sum_{m=1}^{N} \Phi_{a_m}^{-1}(\lambda/W_m)|_{a_m = 1/c_m} = E_T. \tag{10}$$

Since $\Phi_a(x)$ is a monotonic function of x for $a, b > 0$, Φ^{-1} can be solved simply by bisection method.

4.2 The Complete Loading Algorithm

The loading algorithm needs to find the optimal $\{E_m, R_m\}_{m=1}^{N}$ to minimize the overall distortion as given in (7). As we will show, similar to the above example, the optimal power distribution can be derived according to the probability of error function for fixed modulation rate distribution. Therefore, seeking the optimal modulation rate distribution becomes the key procedure.

(a) Given Rate $\{R_m\}_{m=1}^{N}$ determine Power $\{E_m\}_{m=1}^{N}$.
For square QAM constellation, the uncoded probability of error Pe at the receiver can be written as [8]

$$Pe(R_m, \frac{E_m G_m}{c_m}) \approx 4Q(\sqrt{\frac{3E_m G_m}{c_m(2^{R_m}-1)}}). \qquad (11)$$

Given $\{R_m\}$, the optimal power allocation is computed similarly as in the above section by applying Lagrange multiplier and finding Φ^{-1}, i.e. by finding

$$E_m = \Phi_{a_m}^{-1}(\lambda/W_m) \qquad (12)$$

where $a_m = \frac{3G_m}{2c_m(2^{R_m}-1)}$.

(b) Determine Rate R_m.
Usually in practical applications, the allowed modulation rates of all subchannels are limited to the range $R_{min} \leq R_m \leq R_{max}$, where R_{min}, R_{max} are the allowed upper bound and lower bound, respectively. Based on this assumption, we propose the following rate searching algorithm:

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1. $R_m = R_{max}, m = 1..N$, compute $\{c_m\}_{m=1}^{N}$. If $C = \sum_{m=1}^{N} c_m \geq C_T$, increase $R_{max}$ until $C \leq C_T$.
   Compute $\{E_m\}_{m=1}^{N}$ and $D_c$ as in (7).

2. Find layer $k$ yields the smallest $D_c$ by subtracting one bit from $R_k$.
   for i=1 to N,
   $R_i = R_i - 1$, compute $\{c_m\}_{m=1}^{N}$.
   if $C = \sum_{m=1}^{N} c_m \leq C_T$, compute $\{E_m\}_{m=1}^{N}$ and $D_c(i)$.
   $R_i = R_i + 1$.
   end;
   $k$=arg $\min_{i=1..N} D_c(i)$, set $R_k = R_k - 1$.

3. Continue step 2 until for all layers, $R_m$'s reach $R_{min}$ of corresponding layer, or $C \geq C_T$.
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5. Computer Simulation

Subband coding in conjunction with vector quantization(VQ) has been a well known scheme for image and video compression[10, 7]. In our design, the images are first four level subband decomposed using Daubechies 16 wavelet filter, then vector quantized using full search LBG algorithm and fixed length coded. We compare our result to that of [7] and single carrier modulation on AGWN flat channels, using BPSK modulation. Figure 3 plots the PSNR of reconstructed Lena and Pepper images as a function of the channel SNR at different source rates. For Lena, at 4dB channel SNR, 0.1bpp and 1.0bpp source rates, the proposed system performs 1dB and 4.01dB better than that of [7], 1.96dB and 6.98dB better than single carrier system. The improvement increases as source rate increases and channel SNR decreases.

We also compare our loading algorithm to that of [5] by transmitting the subband coded image through a spectrally shaped channel. The optimization is based on minimizing error effect under transmitted power and bit rate constraint. We assume that a total of 256 subchannels, each MCM symbol carries 512 bits or 640 bits e.g. $C_T = 256, B = 512$ or $B = 640$. Set $R_{max} = 6$ and $R_{min} = 2$. From Figure 4, although approach II slightly outperforms approach I for low E_{avg}, we choose approach I considering the complexity. Figure 5 sketches the received image PSNR versus $E_{avg} = \frac{\text{total power}}{C_T}$ for Lena’. The proposed algorithm shows 8-10dB PSNR improvement for E_{avg} below 15dB at 1.0bpp source rate. The improvement drops to 4-6dB as source rate decreases to 0.1bpp. Increasing B decreases the performance since it results in larger bit rate at some subchannels. For $B = 640$, the PSNR of [5] improve much slower than that for $B = 512$ as E_{avg} increases. In contrast, the propose system maintains almost constant improving speed for different B. Similarly to AGWN channels, the improvement increases as source rate increases and channel SNR decreases.

6. Conclusion

We have proposed a robust multimedia data transmission system by combining layered source coding and MCM. Unlike the existing schemes, we propose to transmit all the layers simultaneously through different subchannels. A simple yet powerful loading algorithm is presented which efficiently allocates the power and modulation rate to the subchannels according to the importance of the information they transmit. It achieves significant PSNR improvement for spectrally shaped channels based on the idea that good channel transmitting more important information and bad channel transmit less important information. The proposed loading algorithm can also be adapted for H.263 video transmission[11].

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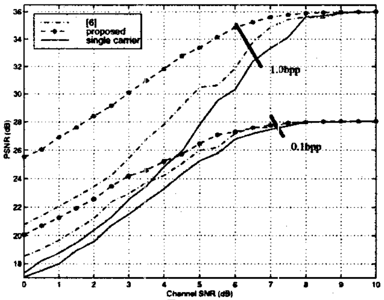
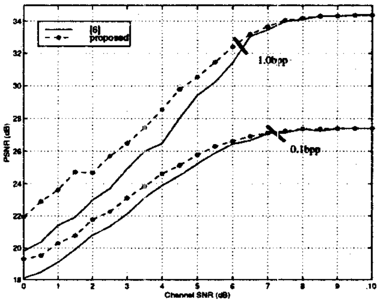


Lena



Pepper

Figure 3. Comparison of proposed algorithm to [6].

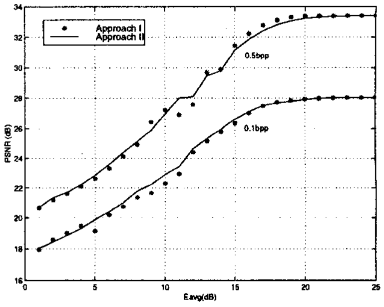
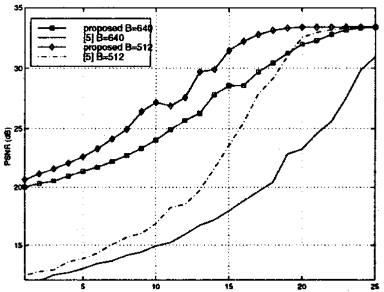


Figure 4. Comparison between Approach I,II.



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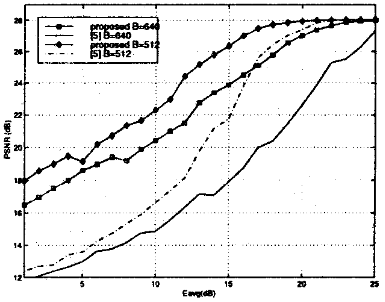

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Figure 5. Comparison of proposed algorithm to [7] using Lena .