OPTIMIZED EMBEDDED MULTICARRIER MODULATION FOR EFFICIENT DELIVERY OF LAYERED VIDEO DATA.

S. Sandeep Pradhan and Kannan Ramchandran

Beckman Institute and Department of ECE
University of Illinois, Urbana, IL 61801
E-mail: pradhan@ifp.uiuc.edu and kannan@ifp.uiuc.edu

ABSTRACT

We tackle the problem of efficient image transmission over Multi-Carrier Modulation (MCM) systems, proposing the use of a layered or multiresolution (MR) framework. In this work, we treat the source as being characterized by multiple layers of importance, and therefore deserving of multiple levels of noise immunity, i.e., having different BER requirements. We present the idea of Embedded Multi-Carrier Modulation (EMCM) as a very effective way of achieving this, and introduce a fast table-lookup based power allocation algorithm that optimizes the multicarrier constellation design in terms of maximizing the deliverable throughput bitrates for the different resolution layers, subject to a total power constraint. Simulation results of our EMCM system reveal substantial gains (up to about 35%) in deliverable bit rates over optimized TDM-based MCM designs. Further, in typical image transmission simulations using an embedded wavelet image coder, the EMCM approach yields almost 3 dB gains in delivered quality over conventional single-resolution MCM systems.

1. INTRODUCTION

Multi-Carrier Modulation (MCM) has been of interest lately for efficient data transmission [1], [2], [3], [4] to provide greater immunity against impulsive noise and multipath fading. Typical applications include voice-band modems, high-speed digital subscriber lines (HDSL), multi-carrier CDMA, digital audio and video broadcast. MCM is a parallel data transmission scheme where we have N sub-channels, in which there are parallel data streams modulating N subcarriers. A schematic of MCM is shown in Fig. 1. Here, each modulator 'i' uses power $P_i$ and transmits bits at rate $R_i$.

When the spectrum of the channel transfer function and the channel noise are non-flat, the system in which all modulators use equal power and transmit at equal rates is suboptimal. In such cases one has to perform optimal power allocation among the individual sub-carriers to maximize the total deliverable bit-rate. The problem of power/bit allocation among the MCM sub-channels has been studied in [5], (so-called loading or water-pouring algorithms) where an iterative algorithm is suggested for optimizing the power distribution among the carriers in MCM.

Figure 1: MCM System

The contributions of this paper are two-fold. First, we present a fast table-lookup based optimal solution to the loading problem. Secondly, we extend the idea of MCM to multiple layers, based on a novel embedded MCM approach, in order to more efficiently address multi-layered sources like images and video, which are typically characterized by different layers of importance. For example, in video, there are "critical" motion vectors which have to be transmitted reliably to the decoder and high-frequency coefficients which form the detail component. We consider, without loss of generality, a 2-layered multiresolution (MR) transmission scheme involving "coarse" and "fine" descriptions of the source, which are characterized by different levels of noise immunity, measured as BER’s $B_1$ and $B_2$ respectively.

Consider a source transmitting information over 2 channels of unequal capacities. Suppose it wants to send information $\{R, S\}$ to the receiver 1 (with its corresponding channel having higher capacity) and $\{R\}$ to the receiver 2 (with a lower capacity channel). Note that $R$ represents the common information to be conveyed to both receivers. The optimal strategy involves superimposing the "detail" information meant for the stronger receiver on the "coarse" information meant for the weaker receiver. This has been shown by Cover [6] in an information-theoretic setting. A practical way of realizing this embedding gain was described in [7] using the idea of embedded modulation.

The idea of MR constellations was first proposed in [7] for digital broadcast. An MR constellation consists of "clouds" of "satellites." Coarse information bits are assigned to the clouds and the fine information bits to the satellites. Fig. 2 illustrates several 2-level MR constellations, characterized by (unequal) distances $d_1$ and $d_2$. Note that $d_1$ and $d_2$ can be designed to meet the desired BER’s for the "coarse" and "fine" information bit-streams.

In this paper, we first present a fast power allocation...
algorithm for the conventional single resolution MCM system. We next extend it to the MR case using a multiplexed framework (dubbed MUX-MCM). We then present a superior method based on embedded modulation using the proposed Embedded MCM (dubbed EMCM) scheme that increases the deliverable bit rates for the “coarse” and “fine” information bit streams over the MUX-MCM system.

2. SINGLE RESOLUTION TRANSMISSION

2.1. Optimization Approach

Let us consider an MCM system operating at a particular BER (typically $10^{-7}$). For simplicity we consider only $2^{2m}$-ary QAM constellations for each sub-carrier, where $m$ is an integer. With a fixed power constraint, bits have to be optimally allocated among the sub-channels of the MCM system in order to maximize the deliverable throughput bit-rate. For an AWGN channel with unit noise variance, we can obtain the power-rate curve for the $2^{2m}$-ary QAM system for a given BER. It can be shown that this curve is convex in $R$.

This P-R curve defines a function $P = f(R)$, where $R \in \{0, 2, 4, 6, 8, 10\}$. Let $P_i$ and $R_i$ denote power and rate in $i^{th}$ sub-channel respectively. Since noise variance is generally unequal in different channels, we have different curves for each channel. Thus we have, $P_i = f_i(R_i)$. As is well known, individual MCM sub-channels are accurately modeled as AWGN channels. Thus for any sub-channel with noise variance of $n_i$, we have

$$P_i = f_i(R_i) = n_i f_i(R_i)$$  \hspace{1cm} (1)

Note that the P-R curve corresponding to a particular BER for sub-channel $i$ having noise variance $n_i$, is simply a scaled version (by $n_i$) of the unit-noise-variance P-R curve corresponding to the same BER. To maximize the throughput rates across the channel we have to optimally assign QAM constellations for each sub-carrier of the MCM system under a total power constraint, i.e. we have to maximize: $\sum_{i=1}^{N} R_i$ subject to the constraint that $\sum_{i=1}^{N} n_i f_i(R_i) \leq P_{\text{budget}}$.

Thus the problem of optimum power allocation among the sub-channels can be formulated using the Lagrange multiplier method, as follows:

$$\max_{R_i \in \{0, 2, 4, 6, 8, 10\}} \left\{ \sum_{i=1}^{N} R_i + \lambda \left[ P_{\text{budget}} - \sum_{i=1}^{N} n_i f_i(R_i) \right] \right\}$$  \hspace{1cm} (2)

where $P_{\text{budget}}$ is the power budget, and $\lambda$ is the Lagrange multiplier (trading off power for rate) which can be optimally matched to $P_{\text{budget}}$.

Thus for a given $\lambda$, we can find for each $i$, the optimal $R_i^*$ which maximizes the sum in eqn. 2. In [8], a fast algorithm has been suggested for this. It has been shown that this optimization can be done off-line with a fast table look-up on-line operation. For this optimal $R_i^*$, in the sub-channel $i$, $n_i f_i(R_i^*)$ is the power associated with it. The optimum value of the cost function can be shown to be convex in $\lambda$. Thus we have to choose the “correct” value of $\lambda$ to satisfy the power constraint. This optimum value of $\lambda$ can be found using fast convex search algorithms like Newton’s method or bisection method.

3. MULTIRESOLUTION TRANSMISSION

We now consider the MR case, where the source has 2 bitstreams needing unequal levels of channel noise immunity, given by BER’s $B_1$ and $B_2$ respectively. Without loss of generality, we will assume throughout the rest of this paper that $B_1 = 10^{-7}$ and $B_2 = 10^{-3}$ for the low resolution (LR) and high resolution (HR) detail information respectively.

3.1. Time Division Multiplexed MCM

We first consider the conventional extension of the single resolution algorithm of Section 2 to the MR case, where the source layers are multiplexed. Here, we consider time-division multiplexing (TDM), where the LR and HR bitstreams are time-switched. Let $R_0$ and $R_1$ be the respective throughput rates corresponding to a particular power constraint. The algorithm of Section 2 can be used for optimal bit allocation among the MCM sub-carriers. In this case, we have 2 P-R curves for 2 different BER’s. Thus the optimal power allocation can be done separately for LR and HR bits in a straightforward manner. Thus all the channels are operating at one resolution at any given instant of time. With an appropriate TDM of the LR and HR modes, in which all the carriers are operating in either the LR or the HR mode simultaneously, we can get arbitrary desired ratios of LR and HR throughput rates. Again the table look-up algorithm suggested in [8] can be easily extended to the MR case.

3.2. Frequency Division Multiplexed MCM

Here we remove the constraint that all the subchannels should operate at the same resolution (either LR or HR) at any given instant of time. We achieve arbitrary ratios of LR and HR rates instead by optimally assigning frequency sub-channels to either LR or HR mode (for the entire time-period between periodic reloading resets to track slow changes in the channel transfer function).

This optimal assignment problem can be formulated as follows. Let $P_0 = f_0(R_0)$ and $P_1 = f_1(R_1)$ be the power-
rate functions for LR and HR respectively, when the noise variance is unity. As discussed before, for each subchannel $i$, the power-rate functions are just scaled version of the above two functions. Thus we have $P_{li} = n_i f_i (R_{li}, R_{li})$, where $n_i$, $P_{li}$, $P_{si}$, $R_{li}$ and $R_{si}$ are the noise power, power for LR bits, power for HR bits, LR rate and HR rate respectively for the subchannel $i$.

But for a given subchannel $i$, both $R_{li}$ and $R_{si}$ cannot be strictly positive as each subchannel can be only in either LR or HR mode but not both. So we form a single valued, 2-variable composite power-rate function as $P_i = n_i f_i (R_{li}, R_{li})$. When $R_{li}$=0, (HR mode) we have $f_i (R_{li}, R_{li}) = f_i (R_{li})$, and when $R_{li}$=0, (LR mode) we have $f_i (R_{li}, R_{li}) = f_i (R_{li})$. Thus, the domain (say, the set $S$) of the above function has the following form: $R_{li}, R_{li} \in \{0, 2, 4, 6, 8, 10\}$ and either $R_{li}$ = 0 or $R_{li}$ = 0.

Now we have to maximize the LR and HR throughput rates; arbitrary ratios of LR and HR throughput rates are achieved only by careful assignment of channels to different resolutions. It can be noted that for the transmission, at a given rate, for LR bits which have a stricter BER requirement of $B_1 = 10^{-7}$, we need more power than that for the HR bits which can tolerate a higher BER of $B_2 = 10^{-3}$; i.e. the LR and HR bits have unequal costs (in terms of power). Thus we maximize the weighted sum of LR and HR rates chosen from the set $S$. So we maximize $(1 - a) \sum_{i=1}^{N} R_{li} + a \sum_{i=1}^{N} R_{li} + \lambda \left[ P_{\text{budget}} - \sum_{i=1}^{N} n_i f_i (R_{li}, R_{li}) \right]$. (3)

where $a$ is the weighting factor and 0 $\leq$ $a$ $\leq$ 1. By varying $a$ we get a tradeoff between LR and HR throughput rates. When $a=0$, the system operates in LR mode. and when $a=1$, the system operates in HR mode. Thus by varying $a$ we get arbitrary ratios of LR and HR throughput rates.

Now for a given $\lambda$, we can get the optimal bit-rate pair $(R_{li}, R_{li})$ for the subchannel $i$, and the function $n_i f_i (R_{li}, R_{li})$ fixes the power. Thus for the optimal $\lambda^{*}$, the power constraint will be met and as in the TDM case, we can use the convex search algorithm to arrive at this optimal value.

3.3. Embedded System

As a generalization of this FDM system, we propose an embedded constellation system (EMCM) in which we use the optimal MR-QAM constellation for each carrier. Let $R_{li}$ and $R_{li}$ denote the transmission rates for LR and HR bits in the $i$th sub-channel. Here we further relax the constraint that for any given subchannel $i$, either $R_{li}$ = 0 or $R_{li}$ = 0; i.e. we allow for both modes to be present at the same time in the same subchannel. For example, when $N=3$, an optimum MR-QAM assignment may be as shown in Fig. 3. It can be noted that $R_{li} = (2, 2), (R_{li} = (2, 2)$ and $R_{li} = (2, 4)$ respectively. Note that for each carrier, the constellation distance parameters $d_1$ and $d_2$ are chosen for the given BERs.

Figure 3: MR-QAM Constellations for a Typical System

Using MR-QAM constellations we can simultaneously transmit information bits at the rate given by the pair $(R_{li}, R_{li})$. To have a fair comparison between the multiplexed schemes and embedded scheme, we restrict ourselves to a maximum of $2^{16}$ points in the MR constellation. Again, in this case we can obtain the power-rate function for the embedded MR-QAM constellation. When the noise variance is unity, let this function be given by $P_i = f_i (R_{li}, R_{li})$.

For the channel with non-uniform noise variance, it is given by $P_i = n_i f_i (R_{li}, R_{li})$ where $n_i$ is the noise variance in the sub-channel $i$. The domain (say, the set $T$) of this function has the following form: $R_{li}, R_{li} \in \{0, 2, 4, 6, 8, 10\}$ and $R_{li} + R_{li} = 10$.

Thus the optimization using Lagrange multiplier method is formulated as follows.

$$\max_{(R_{li}, R_{li}) \in T} \left\{ (1 - a) \sum_{i=1}^{N} R_{li} + a \sum_{i=1}^{N} R_{li} + \lambda \left[ P_{\text{budget}} - \sum_{i=1}^{N} n_i f_i (R_{li}, R_{li}) \right] \right\}. \quad (4)$$

where $a$ is the weighting factor similar to the FDM case. By varying $a$, we can shift the priority from one resolution to another. When $a \approx 0$, all the carriers are in LR mode, and as we increase $a$, more bits are allotted to HR mode. Finally when $a \approx 1$ is large, all the subchannels will be in HR mode. As in the multiplexed case, we can solve the above optimization problem using fast convex search. It should be again noted that the optimization procedure can be a fast table look-up on-line operation.

4. SIMULATION RESULTS

4.1. Single Resolution Framework

We first applied the proposed bit allocation algorithm for a MCM system, with 256 sub-carriers, in a single resolution framework for BER of $10^{-7}$. Consider the noise power spectral density as shown in Fig. 4. So the algorithm allocates the optimal QAM system for each carrier. Fig. 5 shows the optimal bit allocation when $P_{\text{budget}} = 2500$ power units.

4.2. Multiresolution Framework

For the noise spectral density given in Fig. 4, with $B_1=10^{-7}$ and $B_2=10^{-3}$, we have done the bit allocation using a time-multiplexed scheme where power budget is taken to be 2500
power units. The optimized but "naive" TDM-MCM system can obtain arbitrary ratios of LR and HR throughput rates by suitably time-division multiplexing between these two modes of operation. This corresponds to the dotted line of Fig. 6. For the same total power of 2500 units, we have done the optimal bit allocation using the FDM scheme. This is shown as the dashed line in Fig. 6. As we sweep the values of \( a \) we get different ratios of LR and HR bitrates.

Further, the power allocation algorithm for the embedded modulations is shown in Fig. 6. It is shown as the solid line comparing with the TDM system (shown in dotted line). It can be noted that ECMC outperforms all the other multiplexed schemes. ECMC system gives an improvement of about 24\% and 22\% in HR and LR throughput rates respectively over that of TDM scheme. The improvements over that of FDM is around 5\% in both resolutions.

By sweeping \( a \), we can trace out the entire FDM-MCM and ECMC curves, corresponding to different LR-HR attainable rates. Thus it can be seen that the set of achievable throughput rates for a MR embedded scheme is higher than the time-multiplexed system. This corresponds to the improvement suggested by Cover [6] by superposition of information.

4.3. Image Transmission

We have simulated the transmission of images (video is currently being addressed) over the proposed EMMC system. We have used the state-of-the-art embedded zerotree wavelet coder of [9] as the image coding platform. Due to the embedded nature of the bitstream, decoding is aborted when an error is detected, with the decoding quality depending on how far along the bitstream the error is detected. In this setting, the problem becomes how to optimally partition the bitstream into "high priority" (the early part of the stream) and "low priority" (the latter part) components, so that they can be optimally matched to the available ratios of the LR/HR ratios of the EMMC system. For a typical simulation involving the Lena image, if a single resolution quality of service is used (typically, BER = 10\(^{-7}\)), the optimal power allocation gives a PSNR of 29.25 dB. Using the EMMC system (and a two-resolution BER set of 10\(^{-7}\) and 10\(^{-3}\)) yields a PSNR of 32.06 dB, almost a 3 dB gain. Note that these particular choice of BER's only serve to illustrate the potential of our proposed framework: by additionally optimizing the choice of BER's to the characteristics of the layered source, even greater gains can be expected. This will be tackled as part of future work.

5. REFERENCES