OPTIMAL POWER ALLOCATION FOR SCALABLE VIDEO TRANSMISSION OVER MULTIRATE GMC-CDMA WIRELESS LINKS

Saurav K. Bandyopadhyay, Lisimachos P. Kondi

Multimedia Communications Laboratory, Dept. of Electrical Engineering
University at Buffalo, The State University of New York
Buffalo, NY 14260, USA
email: {skb3, lkondi}@eng.buffalo.edu

ABSTRACT

Generalized Multi Carrier Code Division Multiple Access (GMC-CDMA) is a promising technique for achieving high data rate transmission capacity in interference-limited cellular systems. A key challenge in a multirate GMC-CDMA system for video transmission is the optimal power allocation between the sub-channels that maximizes the received video quality subject to a data rate budget. In this paper, we propose a method for joint source and channel coding with optimal power allocation for scalable video transmission over multirate GMC-CDMA wireless links. A GMC-CDMA system offers deterministic elimination of Multiple User Interference (MUI). A scalable video source codec is used and a multirate setup is assumed i.e., each video user is allowed to occupy more than one GMC-CDMA channels. Each of the GMC-CDMA channels can utilize a different number of subcarriers. The optimal solution selects the set of source and channel coding rates for the user of interest along with the number of sub-carriers and power allocated to each GMC-CDMA channel that minimizes the end to end distortion subject to the rate budget. Universal Rate Distortion Characteristics (URDC) are used along with the Channel Characteristic Plots to obtain the optimal solution. Experimental results are presented and conclusions are drawn.

Index Terms— Video coding, Generalized Multi Carrier Code Division Multiple Access (GMC-CDMA), scalable video, MPEG-4, rate-distortion optimization.

1. INTRODUCTION

Recently, there has been significant interest in the topic of video transmission over wireless channels. For transmission over wireless dispersive media, frequency selective multipath propagation is a major limiting factor. A frequency selective fading channel manifests itself as a convolutive fading channel and leads to Inter Symbol Interference (ISI). By spreading information across the available bandwidth, a Direct Sequence Code Division Multiple Access (DS-CDMA) system offers tolerance to multipaths. In [1], a joint source-coding-power control approach for video transmission over DS-CDMA systems was presented. However, a theoretical study was performed in which no specific spreading sequences and despreading methods were assumed. The tradeoffs of source coding, channel coding and spreading for image transmission in DS-CDMA systems were considered in [2]. In [3, 4, 5, 6], video transmission over a DS-CDMA system was considered. The channel model that was used was frequency-selective (multipath) Rayleigh fading. At the receiver, an adaptive antenna array Auxiliary-Vector (AV) linear filter that provides space-time RAKE-type processing (thus, taking advantage of the multipath characteristics of the channel) and multiple-access interference suppression was employed.

Wireless Multi Carrier (MC) communication systems and spread spectrum (SS) offer complementary strengths to mitigate Multi User Interference (MUI) and Inter Symbol Interference (ISI). Generalized Multi Carrier CDMA system offers deterministic elimination of MUI. In [7], for the first time, we proposed to transmit video over a multirate GMC-CDMA channel and developed a cross-layer optimization algorithm to determine the source and channel coding rates as well as the number of subcarriers for each video user. However, no optimal power allocation between the sub-channels was considered. In this paper, we consider a multirate GMC-CDMA [8] approach with optimal power control to make the video data MUI and ISI resilient regardless of the frequency selective channel fading and without sacrificing bandwidth. An MPEG-4 [9] compliant video source codec is used. SNR scalability is utilized and a layered bitstream is produced, consisting of one base layer and one enhancement layer. Each layer is channel-coded using Rate Compatible Punctured Convolutional (RCPC) codes [10]. A multirate GMC-CDMA system is assumed where each video user can be assigned two GMC-CDMA channels, one for the base layer and the other for the enhancement layer. Each of the channels is allowed to occupy a variable number of subcarriers. The proposed algorithm provides a method for optimally allocating the power among the two GMC-CDMA channels. The power is distributed between the GMC-CDMA channels such that the total power remains the same. The experimental results show substantial improvement in PSNR and reduced transmission error.

The rest of the paper is organized as follows. In section II, the basics of multirate GMC-CDMA are presented. In section III, the optimal resource allocation problem is formulated. In section IV, experimental results are presented. Finally, in section V, conclusions are drawn.

2. SYSTEM MODEL

In this section, we discuss the basics of GMC-CDMA. MUI and ISI are the major limiting factors for performance degradation in a wireless channel. GMC-CDMA [8] relies on FDMA like techniques for eliminating MUI. Let us consider M users. In the following, we use the term "GMC-CDMA channel" to refer to transmission using a certain spreading code. In the non-multirate case, each video user occupies a single GMC-CDMA channel. A multipath fading channel is modeled as a Finite Impulse Response (FIR) filter of order L. In the multirate GMC-CDMA case, a video user is allowed to occupy more than one GMC-CDMA channels, each one of which can utilize a variable number of subcarriers. Transmission is block based and each user transmits K information symbols per block using $J = K + L$ subcarriers. That way even if L of the J subcarriers are hit by channel zeros, the K symbols will survive. The Inverse Fourier Transform (IFFT) of size N is then taken.

The transmitted sequences are grouped in blocks of size $P = N + L$ that include a Cyclic Prefix (CP) of length L for Inter Block Interference (IBI) cancellation. The μth user's channel will be represented by a $N \times N$ circulant matrix $\tilde{H}_\mu$. Defining C_μ to be user μ's spreading matrix, the transmitted matrix of the μth user can be written as $\mathbf{u}_\mu(i) = C_\mu \mathbf{s}_\mu(i)$ where $\mathbf{s}_\mu$ is the transmitted information symbol vector for the μth user. C_μ is a $N \times K$ spreading matrix for a specific user. After CP removal, the received $N \times 1$ signal block of the μth user can be written as:

$$\tilde{\mathbf{x}}(i) = \sum_{\mu=0}^{M-1} \tilde{H}_\mu C_\mu \mathbf{s}_\mu(i) + \tilde{\eta}(i) \tag{1}$$

where $\tilde{\eta}(i)$ correponds to additive noise. After detection, the received block for user μ, after CP removal, can be written as:

$$\hat{\mathbf{s}}_\mu(i) = G_\mu \tilde{\mathbf{x}}(i) \tag{2}$$

where G_μ is the μth user's receiver matrix. The spreading and despreading matrices $\{C_\mu, G_\mu\}_{\mu=0}^{M-1}$ [8] can be written as

$$C_\mu = F^H \Phi_\mu \Theta_\mu, \qquad G_\mu = \Gamma_\mu \Phi_\mu^T F. \tag{3}$$

where Θ_μ is a $J \times K$ matrix that maps the K information symbols of the ith block to J symbols $\Theta_\mu \mathbf{s}_\mu(i)$. As mentioned previously, this is done in order to be able to recover the symbols even in the extreme case where all L zeros of the multipath channel coincide with the user's subcarriers. Φ_μ is a $N \times J$ matrix that maps those J symbols into J subcarriers allocated to user μ and consists of only ones and zeroes. F is the Discrete Fourier Transform (DFT) matrix. An appropriate choice for Θ_μ is [8]

$$[\Theta_\mu]_{l+1,k+1} = A_\mu \rho_{\mu,l}^{-k}, \tag{4}$$

where A_μ controls user μ's power. $\rho_{\mu,l}$, $l = 0, \ldots, J-1$ are the subcarriers of user μ. We chose to allocate the N subcarriers to the M users in a cyclic fashion:

$$\rho_{\mu,l} = e^{j\frac{2\pi}{N}(lM+\mu)}. \tag{5}$$

The user independent IFFT matrix F^H implements an OFDM modulator at the transmitter stage. At the receiving stage, F represents FFT of the received vector. The Zero Forcing (ZF) detection, based on Γ_μ can be defined as $\Gamma_\mu = (D_\mu \Theta_\mu)^\dagger$, where † denotes the pseudoinverse and $D_\mu = diag[H_\mu(\rho_{\mu,0}), \ldots, H_\mu(\rho_{\mu,J-1})]$ where $H_\mu(z)$ is the transfer function of user μ's channel (FIR filter). Γ_μ is used to equalize the ISI channel and recover the symbols $\hat{\mathbf{s}}_\mu$.

3. EXTENSION TO POWER ALLOCATION IN MULTIRATE GMC-CDMA

In this section, we extend the concept of video transmission over GMC-CDMA wireless links to multirate GMC-CDMA channels with optimal power control. In this extension, we presume that there are M channels transmitting together. $M/2$ channels are high rate and the remaining $M/2$ channels are low rate. The high rate channels use twice the number of subcarriers as the low rate channels. Mathematically, if the high rate channels are transmitting K_H symbols and the low rate channels are transmitting K_L symbols, the number of subcarriers required are $J_L = K_L + L$ and $J_H = K_H + L$ respectively [8, 11]. In this work, the video user of interest uses two GMC-CDMA channels, one for transmitting the base layer and the other for the enhancement layer. The power is distributed among the two channels such that the total power remains the same. Let A_{μ_1} and A_{μ_2} be the factors controlling the power assigned to the low-rate and high-rate channels respectively. Therefore, the total factor affecting the power level of the user of interest can be written as: $A_\mu = A_{\mu_1} + A_{\mu_2}$. We define the power level as $PL_\mu = 10\log_{10} A_\mu$. We chose to allocate the first $M/2 \times J_L$ subcarriers to the low-rate channels and the remaining $N - M/2 \times J_L$ subcarriers to the high-rate channels. Thus, for the low-rate channels,

$$[\Theta_\mu]_{l+1,k+1} = A_{\mu_1} e^{\frac{j2\pi}{N}(lM/2+\mu)}, \tag{6}$$

for $l = 0, \ldots, J_L - 1$, $A_{\mu_1} \leq A_\mu$ and $\mu = 0, \ldots, M/2 - 1$. For the high-rate channels,

$$[\Theta_\mu]_{l+1,k+1} = A_{\mu_2} e^{\frac{j2\pi}{N}[lM/2+(\mu-M/2)+J_L \times M/2]} \tag{7}$$

for $l = 0, \ldots, J_H - 1$, $A_{\mu_1} + A_{\mu_2} = A_\mu$ and $\mu = M/2, \ldots, M-1$. The proposed formulation finds the optimal allocation of power between the two GMC-CDMA channels for the video user of interest.

4. OPTIMAL RESOURCE ALLOCATION

In our discrete optimization problem, the total available bit budget is shared between source and channel coding. In the multirate case, each scalable layer is transmitted over a separate GMC-CDMA channel. Let J_i be the number of subcarriers allocated to the ith layer of user μ, to transmit $K_i = J_i - L$ information symbols for every $P = N + L$ transmitted chips. The transmitted symbols P are referred to as chips. The contraints in the optimization are the total transmitted chip rate R_{budget}^{chip} and the transmitted power. If Quadrature Amplitude Modulation (4-QAM) is used, one information symbol corresponds to two bits. Therefore, the available bit rate for each scalable layer i can be written as:

$$R_{s+c,i} = 2\frac{J_i - L}{P} R_{budget}^{chip} \tag{8}$$

Thus, if two layers are assumed, the ratio $R_{s+c,1}/R_{s+c,2}$ is fixed and equal to $(J_1 - L)/(J_2 - L)$. The overall distortion D_{s+c} is the sum of the distortions for each scalable layers and can be written as $D_{s+c} = \sum_{i=1}^{2} D_{s+c,i}$. The distortion per layer is defined as the differential improvement of including the layers in the reconstruction. Therefore, in the absence of channel errors, only the distortion for layer 1 (base layer) would be positive and the distortions for all other layers would be negative since the inclusion of these layers reduces the Mean Squared Error (MSE) [12]. The differential improvement depends on how good the picture quality was to start with before the inclusion of the next scalable layer. For example in a layered video coding with two layers, a specific enhancement layer rate will cause a differential improvement in MSE [12] depending on the rate used for the base layer. On the other hand, transmitted signal quality depends on the power level of the base and enhancement layers. Therefore, we can write, $D_{s+c} = D_{s+c,1}(R_{s,1}, R_{c,1}, A_{\mu_1}) + D_{s+c,2}(R_{s,1}, R_{c,1}, R_{s,2}, R_{c,2}, A_{\mu_2})$ where, $D_{s+c,1}(R_{s,1}, R_{c,1}, A_{\mu_1})$ is the distortion for the base layer and depends on the base layer source and channel coding rates and factor affecting the power level.

$D_{s+c,2}(R_{s,1}, R_{c,1}, R_{s,2}, R_{c,2}, A_{\mu_2})$ is the enhancement layer distortion and depends on the source and channel coding rates and the factor affecting the power level of the enhancement layer. Hence, our optimization problem can be written as

$$\min D_{s+c} \quad \text{subject to} \quad R_{s+c,i} \leq 2\frac{J_i - L}{P} R_{budget}^{chip}$$
$$\text{and} \qquad A_\mu = A_{\mu_1} + A_{\mu_2}, \forall i = 1, 2. \qquad (9)$$

For each layer we determine the source coding rate $R_{s,i}$, the channel coding rate $R_{c,i}$, the number of subcarriers J_i and the factor A_{μ_i} determining the power level. The total bit rate depends on the number of subcarriers chosen for each layer. Since the minimization of the distortion for each layer will result in the minimization of the overall distortion, our problem can be broken into separate problems for each layer, thus simplifying the optimization. The contrained problem of Eq. (9) can be converted to an unconstrained problem using Lagrangian optimization [12].

Our problem now reduces to finding the Operational Rate Distortion Functions (ORDF) $D_{s+c,i}$ for each scalable layer. Though it is possible to simulate transmission of the actual data over the channel, this leads to extremely high computational complexity even for small number of source and channel coding rates and channel conditions and makes the process impractical in many ways. Thus we have chosen to relax the optimality of the solution and use the Universal Rate Distortion Characteristics (URDCs) [12, 13]. For a given choice of power allocated to each GMC-CDMA channel of the user of interest, channel codes and number of subcarriers, the probability of error P_b is calculated for the set of channel coding rates. P_b establishes a reference to the performance of the channel coding over the particular channel with the given parameters. This channel performance needs to be done only once. The URDCs plot the expected distortion $D_{s+c,i}$ based on the bit error rates P_b after channel decoding.

The URDCs are obtained experimentally using simulations. To obtain the URDC for $D_{s+c,i}$, the ith layer of the bitstream is corrupted with independent errors with bit error rate P_b. Layers $1, \ldots, i-1$ are not corrupted. The bitstream is then decoded and the mean squared error is calculated. The experiment is repeated many times (in our studies, 30 times). If $i > 1$, i.e. we are calculating the URDC for an enhancement layer, we need to subtract the distortion of the first $i-1$ uncorrupted layers, since $D_{s+c,i}$ in this case is the differential improvement of including layer i as mentioned earlier.

In order to avoid calculating the expected distortion for a wide range of P_b values, we can use a few probability values and then utilize a model for finding the URDC. The URDC model used in this paper is given by

$$D_{s+c,i} = a\left[\log_{10}\left(\frac{1}{P_b}\right)\right]^b \qquad (10)$$

where a and b are chosen such that the approximation error is minimized. Assuming two scalable layers, three channel coding rates per layer and three possible source coding rates, three URDCs will be required for the base layer, one for each source coding rate. Again, nine URDCs would be required for the enhancement layer, since for each admissible source coding rate for the enhancement layer, we would need three URDCs, once for each base layer source coding rate.

Using the channel characteristic plots and the universal rate-distortion characteristics, operational rate-distortion functions for each scalable layer are constructed as follows. First, for the given channel parameters, we use the channel characteristic plot to determine the resulting bit error rates for each of the available channel coding rates. Then, for each of these probability values we use the universal rate-distortion characteristic to obtain the resulting distortion for each available source coding rate. By also obtaining the total rate R_{s+c} for each combination of source and channel codes, we have the rate-distortion operating points for the given channel conditions. More information can be found in [12].

5. SIMULATION RESULTS

In this section, we present experimental results for the optimization problem shown in Eq. (9). A number of experiments were conducted using different video sequences. Some of results using the "Foreman" sequence are reported below. An MPEG-4 compatible video source codec was used to create two SNR scalable layers. In our discrete optimization problem the total number of subcarriers were $N = 220$. The total number of GMC-CDMA channels was $M = 8$. Four of the channels were transmitting $K_L = 15$ (low rate channel) symbols per block and the other four were transmitting $K_H = 30$ (high rate channel). The video user of interest is transmitting the base layer and enhancement layer using either a high-rate or a low rate channel. The total number of multipaths was $L = 5$ and the path coefficients were independent complex Gaussian random variables with zero mean and equal variances, adding to 1. The admissible source coding rates for each of the two scalable layers are 64, 96, 128 and 256 kbps. The admissible channel coding rates are $1/2$, $2/3$ and $4/5$, using Rate Compatible Punctured Convolutional (RCPC) codes from [10]. 4-QAM (i.e., two bits per symbol) was used for modulation. The power level of the user of interest and the interferers are 16 dB. The noise variance of $\tilde{\eta}$ is chosen as 1. Therefore, the factor affecting the power level of the user of interest is $A_\mu = 39.8107$. The values A_{μ_1} and A_{μ_2} are varied in steps of 5, so that their sum is always equal to A_μ.

Table 1 shows the results of optimal resource allocation with power control. The source and channel coding rates, the number of subcarriers and the power level were optimally determined for each scalable layer. It should be emphasized that the power level of the interferers does not affect the Bit Error Rate (BER) of the user of interest, since, in GMC-CDMA, all interference is completely removed deterministically.

In Fig. 1, we compare the performance of the proposed algorithm with results obtained using optimal bit and number of subcarrier allocation for equal power allocation between the two GMC-CDMA channels. It can be seen that optimal power allocation results in a substantial improvement in video quality.

6. CONCLUSIONS

In this paper, we have proposed an optimal power allocation formulation for multirate Generalized Multi Carrier Code Division Multiple Access (GMC-CDMA) systems for wireless video transmission. Such systems offer deterministic elimination of Multiple User Interference (MUI) and Inter Symbol Interference (ISI) irrespective of the frequency selective fading channel and without sacrificing bandwidth. We have presented a cross-layer optimization algorithm to determine the source and channel coding rates for each scalable layer as well as the number of subcarriers and power level used to transmit each layer. By utilizing the parametric model for the Universal Rate Distortion Characteristics we estimated the distortion for all the bit error rates and power levels by only finding the disortion values for a few bit error rate values and power levels. This led to considerable saving in computational complexity. The choice of optimal

$R_{s,1}$	$R_{c,1}$	K_1	PL_1	$R_{s,2}$	$R_{c,2}$	K_2	PL_2	R^{chip}_{budget}	P^*_{s+c}
128	2/3	15	14.89	96	1/2	15	9.49	1440	30.72
128	1/2	15	15.55	256	1/2	15	5.92	1200	30.08
64	2/3	15	12.98	96	1/2	30	12.98	720	25.66
64	4/5	30	12.98	64	4/5	30	12.98	300	9.05

Table 1: Optimal resource allocation for two-layer SNR scalable video over two GMC-CDMA channels with optimal power level per channel for the video user of interest.
* Total rate is in kcps and ,PL_1, PL_2, P^*_{s+c} are the power levels measured in dBs

$R_{s,1}$, $R_{c,1}$, K_1, $R_{s,2}$, $R_{c,2}$, K_2, A_{μ_1} and A_{μ_2} leads to a reduced end-to-end distortion.

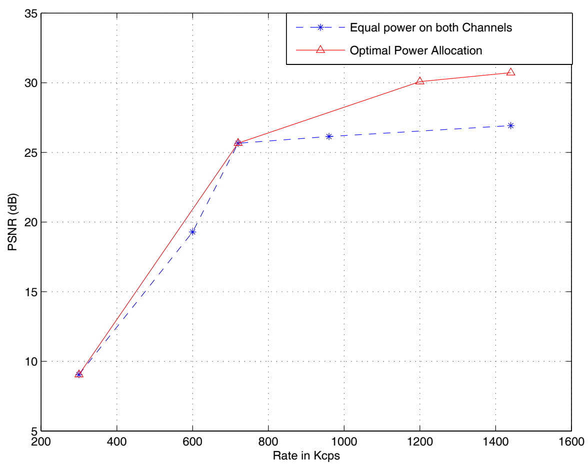

Fig. 1: Comparison of Rate Distortion Optimization curves for scalable video transmission over two multirate GMC-CDMA Wireless Channels for equal power level and optimal power allocation.

7. REFERENCES

[1] Y. S. Chan and J. W. Modestino, "A joint source coding-power control approach for video transmission over CDMA networks," *IEEE Journal on Selected Areas in Communications*, vol. 21, pp. 1516–1524, Dec. 2003.

[2] Q. Zhao, P. Cosman, and L. B. Milstein, "Tradeoffs of source coding, channel coding and spreading in CDMA systems," in *Proc. MILCOM*, vol. 2, (Los Angeles, USA), pp. 846–850, Oct. 2000.

[3] L. P. Kondi, S. N. Batalama, D. A. Pados, and A. K. Katsaggelos, "Joint source-channel coding for scalable video over DS-CDMA multipath fading channels," in *Proceedings of the IEEE International Conference on Image Processing*, vol. 1, (Thessaloniki, Greece), pp. 994–997, Oct. 2001.

[4] L. P. Kondi, D. Srinivasan, D. A. Pados, and S. N. Batalama, "Layered video transmission over multirate DS-CDMA wireless systems," *IEEE Transactions for Circuits and Systems for Video Technology*, vol. 15, pp. 1629–1637, Dec. 2005.

[5] D. Srinivasan, L. P. Kondi, and D. A. Pados, "Scalable video transmission over wireless DS-CDMA channels using minimum TSC spreading codes," *IEEE Signal Processing Letters*, vol. 11, pp. 836–840, Oct. 2004.

[6] D. Srinivasan and L. Kondi, "Optimal resource allocation for video transmission over DS-CDMA channels with multirate detection," in *Proceedings of the International Conference on Acoustics, Speech and Signal Processing*, (Montreal, Canada), May 2004.

[7] G. Partasides and L. P. Kondi, "Scalable video transmission over multirate GMC-CDMA wireless channels," in *Proc. of the IEEE International Conference on Acoustics, Speech and Signal Processing*, vol. 2, (Philadelphia, PA), pp. 297–300, Mar. 2005.

[8] Z. Wang and G. B. Giannakis, "Wireless multicarrier communications: Where Fourier meets Shannon," *IEEE Signal Processing Magazine*, vol. 17, pp. 29–48, May 2000.

[9] ISO/IEC 14496-2 MPEG-4, "Information technology-coding of audio-visual objects: Visual," October. 1997.

[10] J. Hagenauer, "Rate-compatible punctured convolutional codes (RCPC codes) and their applications," *IEEE Transactions on Communications*, vol. 36, pp. 389–400, April 1988.

[11] Z. Wang and G. B. Giannakis, "Block precoding for MUI/ISI-resilient generalized multicarrier CDMA with multirate capabilities," *IEEE Transactions on Communications*, vol. 49, pp. 2016–2027, Nov. 2001.

[12] L. P. Kondi, F. Ishtiaq, and A. K. Katsaggelos, "Joint source-channel coding for motion-compensated DCT-based SNR scalable video," *IEEE Transactions on Image Processing*, vol. 11, pp. 1043–1052, Sept. 2002.

[13] M. Bystrom and J. Modestino, "Combined source- channel coding schemes for video transmission over an additive white gaussian noise channel," *IEEE Journal on Selected Areas in Communications*, vol. 18, pp. 880–890, June 2000.