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Cross-Layer Optimization for Video Transmission Over Multirate GMC-CDMA Wireless Links

Saurav K. Bandyopadhyay, George Partasides, and Lisimachos P. Kondi

***Abstract*—In this paper, we consider the problem of video transmission over wireless generalized multicarrier code division multiple access (GMC-CDMA) systems. Such systems offer deterministic elimination of multiple access interference. 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. Furthermore, each of these channels can utilize a different number of subcarriers. We propose a cross-layer optimization method to select the source coding rate, channel coding rate, number of subcarriers per GMC-CDMA channel and transmission power per GMC-CDMA channel given a maximum transmission power for each video user and an available chip rate. Universal rate distortion characteristics (URDC) are used to approximate the expected distortion at the receiver. The proposed algorithm is optimal in the operational rate distortion sense, subject to the specific setup used and the approximation caused by the use of the URDC. Experimental results are presented and conclusions are drawn.**

***Index Terms*—Generalized multicarrier code division multiple access (GMC-CDMA), rate-distortion optimization, scalable video, wireless video transmission.**

I. 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 intersymbol 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 is presented. The tradeoffs of source coding, channel coding and spreading for image transmission in DS-CDMA systems are considered in [2]. In [3]–[5], cross-layer optimization techniques are proposed for energy constrained systems. In [6], layered video transmission over DS-CDMA systems is proposed. In [7], performance analysis of minimum total squared spreading codes is considered for scalable video transmission via a single-rate or a multirate DS-CDMA channel. In [8], a joint source channel framework is discussed for optimizing video quality subject to the energy consumption. In [9], transmission of an embedded bitstream over an orthogonal frequency division multiplexing (OFDM) system is considered. A cross layer diversity technique is proposed, which uses multiple description coding and frequency diversity.

Wireless multiarrier (MC) communication systems and spread spectrum (SS) offer complementary strengths to mitigate multiuser interference (MUI) and intersymbol interference (ISI). Generalized multicarrier CDMA (GMC-CDMA) [10] systems offer deterministic removal of MUI, regardless of the fading channel. In [11], for the first time we proposed to transmit video over a multirate GMC-CDMA channel and developed a cross layer optimization to determine source and channel coding rates as well as the number of subcarriers for each video user. In this paper, we present a cross-layer optimization algorithm for video transmission over GMC-CDMA systems. An MPEG-4 [12] 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 [13]. A multirate GMC-CDMA system is assumed, where each video user can be assigned two GMC-CDMA channels, one for the base layer and for the enhancement layer. Furthermore, each one of these channels is allowed to have a different symbol rate by utilizing a variable number of subcarriers. The proposed algorithm provides a method for optimally allocating the power among the two GMC-CDMA channels, given a total power constraint for the video user. Universal rate distortion characteristics (URDC) are used to approximate the expected distortion at the receiver. The algorithm is optimal in the operational rate distortion sense. That is, given our transmission setup, the algorithm selects (from discrete sets of values) the source coding rates, channel coding rates, number of subcarriers per channel, and transmission power that minimize the expected distortion at the receiver. This is subject to the approximation caused by the use of URDC curves. In the rest of the paper, the term “optimality” refers to operational rate-distortion optimality. Some preliminary results were presented in [14].

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

II. GMC-CDMA Basics

We next describe the basics of GMC-CDMA systems. More information can be found in [10]. The discrete time equivalent baseband system model for m users is shown in Fig. 1. In the following, a GMC-CDMA system is assumed with M users. A multipath fading channel is assumed that is modeled as a finite impulse response (FIR) filter of order L. Transmission is block-based and, in the nonmultirate case, each user is transmitting K information symbols per block. As will be explained later, these K information symbols are spread into $J = K + L$ symbols that correspond to the J subcarriers allocated to the user. The inverse fast Fourier transform (IFFT) of size N is then taken followed by the addition of a cyclic prefix (CP) of size L to avoid interblock interference (IBI). Thus, the length of the transmitted block is $P = N + L$ and the user's K information symbols are spread into

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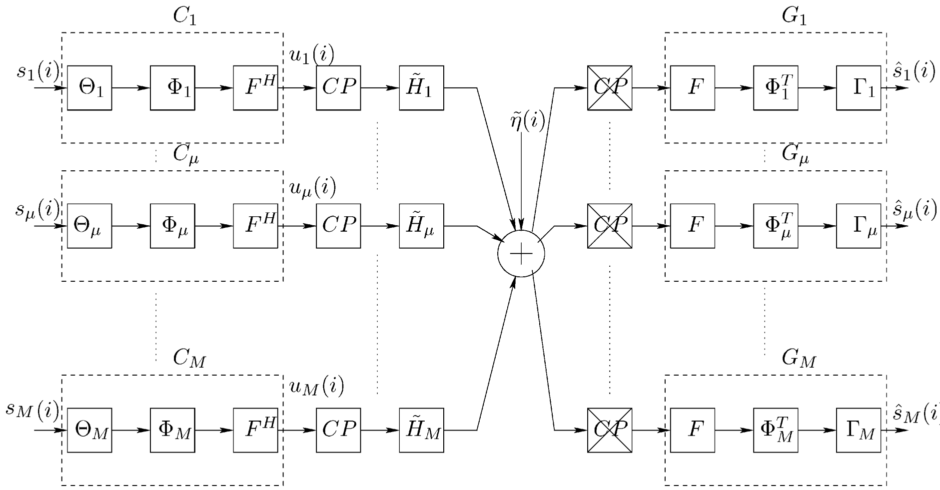

Fig. 1. Discrete time baseband equivalent signal model for the M users occupying GMC-CDMA wireless channels.

P transmitted symbols. At the receiver, after CP removal, the received signal for block i is

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

where $\mathbf{s}_\mu$ is the $K \times 1$ vector that denotes the K information symbols of user μ and $\mathbf{u}_\mu(i) = C_\mu \mathbf{s}_\mu(i)$ denotes the $N \times 1$ transmitted symbols of user μ before the addition of the CP. C_μ is a $N \times K$ spreading matrix and $\tilde{H}_\mu$ is an $N \times N$ circulant matrix representing the multipath channel for user μ. $\tilde{\eta}(i)$ corresponds to additive noise.

The received block for user μ is

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

where G_μ is user μ's $K \times N$ receive matrix.

In [10], C_μ and G_μ were defined as

$$C_\mu = F^H \Phi_\mu \Theta_\mu \tag{3}$$

and

$$G_\mu = \Gamma_\mu \Phi_\mu^T F. \tag{4}$$

F is the discrete Fourier transform (DFT) matrix. Thus, multiplication by F corresponds to taking the FFT of a signal while multiplication by F^H corresponds to taking the inverse FFT (^{H} denotes the Hermitian). Θ_μ is a $J \times K$ matrix, where $J = K + L$. This matrix spreads the user's K information symbols into J symbols. 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 frequency response coincide with the user's subcarriers. Φ_μ is a $N \times J$ matrix that maps these J symbols into the J subcarriers assigned to the user and consists of only ones and zeros. An appropriate choice for Θ_μ is [10]

$$[\Theta_\mu]_{l+1,k+1} = A_\mu \rho_{\mu,l}^{-k}, \tag{5}$$

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

$$\rho_{\mu,l} = e^{j\frac{2\pi}{N}(lM+\mu)}. \tag{6}$$

For zero forcing (ZF) detection, matrix Γ_μ can be defined as

$$\Gamma_\mu = (D_\mu \Theta_\mu)^\dagger \tag{7}$$

where † denotes the pseudoinverse and

$$D_\mu = diag\left[H_\mu(\rho_{\mu,0}), \ldots, H_\mu(\rho_{\mu,J-1})\right] \tag{8}$$

where $H_\mu(z)$ is the transfer function of user μ's channel (FIR filter).

The above matrix selections guarantee that the received symbol block $\mathbf{s}_\mu(i)$ in (2) is free from multiple access interference (MAI) and is degraded only by the additive noise [10].

III. Extension to the Multirate Case

So far, we have assumed the case of M users (to which we also refer as "channels") each occupying J subcarriers $(MJ = N)$. In the multirate GMC-CDMA case, we allow different users to occupy a different number of subcarriers and thus have different transmitted symbol rates. In the following, we assume two user classes, one that transmits K_L information symbols per block using $J_L = K_L + L$ subcarriers and one that transmits K_H information symbols per block using $J_H = K_H + L$ subcarriers, where $K_L < K_H$. Assuming an even number of users, half the users $(M/2)$ are low-rate (utilize J_L subcarriers), while the other half are high-rate users (utilize J_H subcarriers). As long as the sets of subcarriers of each user are disjoint, deterministic MUI elimination can still be guaranteed [15]. In this work, we chose to allocate the first $M/2 \times J_L$ subcarriers to the low-rate users and the remaining $N - M/2 \times J_L$ subcarriers to the high-rate users.

Thus, for the low-rate users

$$\rho_{\mu,l} = e^{\frac{j2\pi}{N}(lM/2+\mu)} \tag{9}$$

for $l = 0, \ldots, J_L - 1$ and $\mu = 0, \ldots, M/2 - 1$. For the high-rate users

$$\rho_{\mu,l} = e^{\frac{j2\pi}{N}[lM/2+(\mu-M/2)+J_L \times M/2]} \tag{10}$$

for $l = 0, \ldots, J_H - 1$ and $\mu = M/2, \ldots, M-1$.

Then, for the low-rate users

$$[\Theta_\mu]_{l+1,k+1} = A_{\mu 1} e^{-\frac{j2\pi}{N}(lM/2+\mu)k} \tag{11}$$

for $l = 0, \ldots, J_L - 1$ and $\mu = 0, \ldots, M/2 - 1$.

For the high-rate users

$$[\Theta_\mu]_{l+1,k+1} = A_{\mu 2} e^{-\frac{j2\pi}{N}[lM/2+(\mu-M/2)+J_L \times M/2]k} \tag{12}$$

TABLE I
BER TABLE COMPARISON FOR 16- AND 12.98-dB CHANNELS

Channel Coding Rate	K	BER (16 dB)	BER (12.98 dB)
1/2	30	1.05×10^{-4}	1.28×10^{-4}
1/2	15	3×10^{-6}	4.9×10^{-6}
2/3	30	1.77×10^{-4}	6.35×10^{-4}
2/3	15	1.07×10^{-4}	3.07×10^{-4}
4/5	30	7.78×10^{-4}	2.6×10^{-3}
4/5	15	3.85×10^{-4}	8.05×10^{-4}

for $l = 0, \dots, J_H - 1$ and $\mu = M/2, \dots, M-1$. A_{μ_1} and A_{μ_2} control the transmission power for the low-rate and high-rate channels, respectively.

If we assume, for example, $K_L = 15$ and $K_H = 30$, a low-rate user is transmitting 15 information symbols using P transmitted symbols (chips), whereas a high-rate user is transmitting 30 information symbols using P transmitted symbols. Assuming the same transmitted power per block for each user, low-rate users transmit at half the information symbol rate than the high-rate users; however, the low-rate users transmit at twice the energy per information symbol. Thus, the low-rate users are expected to have a lower symbol error rate than the high-rate users. This tradeoff is explored here for GMC-CDMA in the context of video transmission.

We next present some experimentally obtained bit error rates; 4-state quadrature amplitude modulation (4-QAM) i.e., two bits per symbol was used for modulation. The total number of subcarriers was $N = 220$. The length of the multipath was $L = 5$ and the six fading coefficients were independent complex Gaussian random variables with zero mean and equal variance. The SNR of each user is defined as

$$\mathrm{SNR} = \frac{E_s}{N_0} \sum_{i=0}^{L} \left(E\left\{ |\alpha_i|^2 \right\} \right) \tag{13}$$

where E_s is the energy per symbol (chip), $N_0/2$ is the power spectral density of the additive white Gaussian noise, and $\alpha_i, i = 0, \dots, L$ are the fading coefficients. The channel is a block fading channel, thus, the fading coefficients remain constant for each block of $P = N + L = 225$ symbols. The total number of transmitting users was $M = 8$. Four of them were transmitting $K_L = 15$ symbols per block (low rate users) while the other four were transmitting $K_H = 30$ symbols per block (high rate users). RCPC codes with rates 1/2, 2/3, and 4/5 were used for channel coding [13]. Two different SNRs were used for the user of interest: 16 and 12.98 dB (a user with SNR of 12.98 dB transmits at half the power than a user with SNR of 16 dB). All SNRs reported refer to the SNR per chip. It should be emphasized that the SNR 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. The BERs can be seen in Table I. As expected, for the same transmitted power, $K_L = 15$ gives a better BER than $K_H = 30$ at the expense of a lower transmission rate.

IV. OPTIMAL RESOURCE ALLOCATION

We next describe the optimal resource allocation for the cases where each video user is allowed to transmit over one or two GMC-CDMA channels. The optimization constraint in both cases is the available chip rate $R_{\mathrm{budget}}^{\mathrm{chip}}$. The optimization target is the minimization of the expected distortion of the received video of the video user of interest. We refer as chips to the symbols that are actually transmitted by each user, after taking the IFFT and adding the CP.

A. Single GMC-CDMA Channel Case

If a single GMC-CDMA channel is used for the transmission of all scalable layers of a video user, the layers are time-multiplexed. If J subcarriers are allocated to user μ, the user can transmit $K = J - L$ information symbols for every $P = N + L$ transmitted chips. Let B be the number of bits per transmitted symbol. For example, for 4-QAM modulation, $B = 2$. Thus, the available transmission bit rate is

$$R_{\mathrm{budget}} = B \frac{J - L}{P} R_{\mathrm{budget}}^{\mathrm{chip}}. \tag{14}$$

The available bit rate R_{budget} has to be allocated between scalable layers and, within each layer, between source and channel coding. The formal statement of the problem that we are solving is as follows: Given an overall bit rate R_{budget} and a transmission power that is controlled by A_μ, we want to optimally allocate bits between source and channel coding such that the overall mean-square distortion D_{s+c} is minimized. Let $R_{s,l}$ be the source coding rate for scalable layer l and $R_{c,l}$ be the channel coding rate for scalable layer l, $l = 1, \dots, T$, where T is the number of scalable layers. Then, the total rate for layer l is $R_{s+c,l}$ can be written as $R_{s+c,l} = R_{s,l}/R_{c,l}$. It should be emphasized that $R_{s,l}$ is in bits/s and $R_{c,l}$ is a dimensionless number. The total transmission rate is $R_{s+c} = \sum_{l=1}^{T} R_{s+c,l}$. Thus, the goal of the optimization is to determine $R_{s,l}$, $R_{c,l}$, $l = 1, \dots, T$ in order to minimize

$$\min D_{s+c} \text{ subject to } R_{s+c} \leq R_{\mathrm{budget}} \tag{15}$$

where D_{s+c} is the resulting expected squared error distortion which is due to both source coding (quantization) errors and channel errors. Utilizing Lagrangian optimization, the constrained problem in (15) is transformed into the unconstrained problem of minimizing $L(\lambda) = D_{s+c} + \lambda R_{s+c}$ where, λ is the Lagrangian multiplier. Before applying Lagrangian optimization, pruning is performed in order to eliminate rate-distortion points that do not lie on the convex hull of the operational rate-distortion curve.

The task described in (15) is a discrete optimization problem: $R_{s,l}$ and $R_{c,l}$ can only take values from discrete sets that are predefined as part of the problem. To reduce the computational complexity of the procedure, it is useful to write the overall distortion D_{s+c} as the sum of the distortions per scalable layer given by $D_{s+c} = \sum_{l=1}^{T} D_{s+c,l}$.

We define the distortion per layer as the differential improvement of including the layer in the reconstruction. Therefore, in the absence of channel errors, only the distortion of Layer 1 (base layer) would be positive and the distortions of all other layers would be negative since inclusion of these layers reduces the overall mean squared error (MSE) [16].

Another observation that should be made is that the differential improvement in MSE due to a given layer depends on the rates of the previous layers. The differential improvement depends on the picture quality before the inclusion of the scalable layer in question. Therefore, the overall distortion is better written as $D_{s+c} = \sum_{l=1}^{T} D_{s+c,l}(R_{s+c,1}, \dots, R_{s+c,l})$ [16].

B. Multiple GMC-CDMA Channel Case

We next discuss the case where each scalable video layer is transmitted over a separate GMC-CDMA channel. In that case, we have

$$R_{s+c,i} = B \frac{J_i - L}{P} R_{\mathrm{budget}}^{\mathrm{chip}} \tag{16}$$

where J_i is the number of subcarriers allocated to layer i. Thus, if two layers are assumed the ratio $R_{s+c,1}/R_{s+c,2}$ is fixed and equal to $(J_1 - L)/(J_2 - L)$. This is in contrast to the single GMC-CDMA channel case where the allocation of the available bit rate to each individual scalable layer is part of the optimization. Our optimization problem now is as follows, for the case of T layers. For a given chip budget $R_{\rm chip}^{\rm budget}$ and total transmitted power for all layers (which is determined by A_μ), determine $R_{s,i}, R_{c,i}, J_i, A_{\mu_i}, i = 1, \ldots, T$, in order to minimize the overall mean-square distortion D_{s+c}:

$$\min D_{s+c} \text{ subject to } R_{s+c,i} \leq B\frac{J_i - L}{P} R_{\rm chip}^{\rm budget} \quad \text{for } i = 1, \ldots, T. \quad (17)$$

D_{s+c} can be written as $D_{s+c} = \sum_{l=1}^{T} D_{s+c,l}(R_{s+c,1}, K_1, A_{\mu_1}, \ldots, R_{s+c,l}, K_l, A_{\mu_l})$, where $\sum_{l=1}^{T} A_{\mu_l} = A_\mu$. The constrained problem of (17) can be converted to an unconstrained problem using Lagrangian optimization [16].

C. Estimation of Rate-Distortion Functions

To solve the problems of (15) and (17), we need to estimate the expected distortion D_{s+c} that results from specific choices of the source coding rate $R_{s,i}$, channel coding rate $R_{c,i}$, number of subcarriers J_i and power levels A_{μ_i} for each layer i. In this paper, an approach based on the universal rate distortion characteristics (URDCs) is utilized for the estimation of D_{s+c}. The URDCs plot the expected video distortion as a function of the bit error rate for the source coding rates of interest. More details are given in [16] and [17]. The use of the URDCs was selected here due to their simplicity at the expense of less accuracy compared with the recursive optimal per-pixel estimate (ROPE) and similar methods [18], [19].

D. Operational Optimality of the Solution

The solutions to the problems presented here are optimal in the operational rate-distortion sense. Thus, the optimization algorithms select the system parameters that give the minimum expected distortion. This is subject to the specific setup we are assuming. Thus, operational optimality is subject to the specific coding schemes and sets of coding rates assumed for source and channel coding, the values specified for N, M, K_H, and K_L, the assumed number of low-rate and high-rate users, the channel model used and the fact that parameters are selected once for the entire transmission period. Also, the solutions are optimal subject to the approximation caused by the use of the URDC, as discussed previously.

V. Experimental Results

We next present experimental results for video transmission over GMC-CDMA channels. The video sequences used are the "Foreman" sequence and "Akiyo" sequence (176 × 144 size, 300 frames, 30 frames per second). An MPEG-4 compatible video source codec is used to create two SNR scalable layers. 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 RCPC codes from [13]. A multirate GMC-CDMA system is assumed with $N = 220$. The length of the multipath is $L = 5$ and the six fading coefficients are independent complex Gaussian random variables with zero mean and equal variance. The channel is a block fading channel, thus, the fading coefficients remain constant for each block of $P = N + L = 225$ symbols. All SNR values refer to the SNR per chip. There are eight user channels $(M = 8)$. Four of these channels have $K = 15$ and the other four have $K = 30$. Each video user is allowed to occupy one or two of these user channels.

In Experiment 1, the video user of interest occupies a single channel (single GMC-CDMA channel case). The video user of interest has an SNR of 16 dB. The seven interfering channels also have an SNR of 16 dB; however, this does not affect the BER of the video user of interest, since the interference is completely removed deterministically.

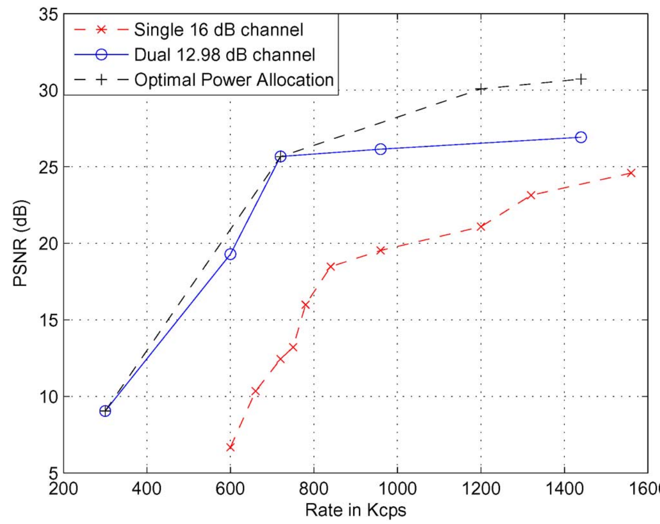

Fig. 2. PSNR comparison of scalable video transmission over wireless GMC-CDMA channels using one channel per video user, two channels per video user and equal power allocation between the channels, and two channels per video user and optimal power allocation between the channels ("Foreman" sequence.)

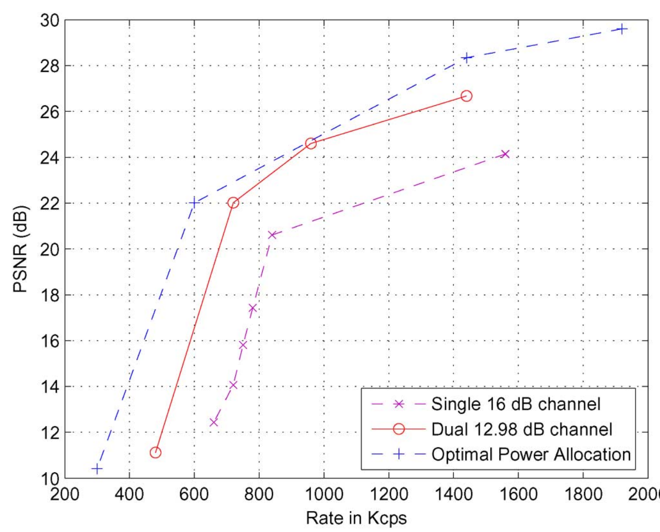

Fig. 3. PSNR comparison of scalable video transmission over wireless GMC-CDMA channels using one channel per video user, two channels per video user and equal power allocation between the channels, and two channels per video user and optimal power allocation between the channels ("Akiyo" sequence.)

In Experiment 2, the video user of interest occupies two GMC-CDMA channels (dual GMC-CDMA channel case). The base layer is transmitted over the first channel while the enhancement layer is transmitted over the second channel. Transmission power is distributed equally between the two channels. Thus, the SNR of each of the video user's of interest channels is 12.98 dB so that the total transmitted power of the video user of interest is exactly the same as in the single GMC-CDMA channel case.

In Experiment 3, the video user of interest occupies two GMC-CDMA channels and the power is optimally distributed between them by selecting the appropriate A_{μ_1} and A_{μ_2}. The values A_{μ_1} and A_{μ_2} are varied in equal steps, so that their sum is always equal to the A_μ used in Experiment 1. 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.

Figs. 2 and 3 show a plot of the expected PSNR versus the target chip rate for Experiments 1, 2, and 3 for "Foreman" and "Akiyo" sequences, respectively. It can be seen that, for the chip rates considered, the dual channel case with optimal power allocation (Experiment 3) outperforms the dual channel case with equal power allocated to each channel (Experiment 2) and the single channel case (Experiment 1).

VI. Conclusions

In this paper, we have proposed the use of GMC-CDMA systems for wireless video transmission. Such systems offer deterministic MAI elimination. A frequency selective block fading model is assumed. Our proposed algorithm selects the source coding rates, channel coding, rates, number of subcarriers per channel and transmission power, in order to minimize the expected video distortion at the receiver. These parameters are selected from discrete sets. The constraint is the available chip rate. Thus, the proposed algorithm is optimal in the Operational rate-distortion sense, subject to the specific setup we are using and the approximations that are present due to the use of URDC curves. We have shown that, for the same transmitted power, allocating a larger number of subcarriers to a user increases the user's information symbol rate at the expense of an increase in symbol error rate. We have considered the case where the video user of interest occupies a single GMC-CDMA channel as well as the case where the video user of interest occupies two GMC-CDMA channels. For the chip rates considered, the dual channel case with optimal power allocation outperforms the dual channel case with equal power allocation and the single channel case.

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