Rate-Distortion Optimized Video Transmission Over DS-CDMA Channels with Auxiliary Vector Filter Single-User Multirate Detection

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Abstract— **In this paper, we consider the rate-distortion optimized resource allocation for video transmission over multirate wireless direct-sequence code-division-multiple-access (DS-CDMA) channels. We consider the performance of transmitting scalable video over a multipath Rayleigh fading channel via a combination of *multi-code multirate CDMA* and *variable sequence length multirate CDMA* channel system. At the receiver, despreading is done using adaptive space-time auxiliary-vector (AV) filters. We propose a new interference cancelling design that uses just a single AV filter for single-user mutirate despreading. Our experimental results show that the proposed interference cancelling design has excellent performance in scalable video transmission over DS-CDMA systems that use a combination of multicode multirate and variable processing gain multirate CDMA. The proposed design takes advantage of the fact that single user's video data is transmitted using two spreading codes, one for the base layer and one for the enhancement layers, and of the fact that these spreading codes can have different processing gains. The proposed interference cancelling design is compared with two conventional single-user multirate CDMA receiver configurations, however now we use an AV filter rather than a simple matched filter. We also propose a resource allocation algorithm for the optimal determination of source coding rate, channel coding rate and processing gain for each scalable layer, in order to minimize the expected distortion at the receiver.**

Index Terms— **Wireless video transmission, multirate DS-CDMA, multirate detection, rate-distortion optimization.**

I. Introduction

In the recent past, a considerable amount of research has been devoted to joint source-channel scalable video coding and wireless DS-CDMA systems. There has also been a rapid proliferation in the type of video decoders compatible with the variable bandwidth services offered by various wireless transmission techniques. Scalable video offers the ability of coping gracefully with the variability of bandwidth typically encountered in wireless channels.

An important demand on the evolving third-generation (3G) wireless systems would be their ability to support users with a variety of data services at different data rates. Such systems are said to be multirate systems and enable the transmission of voice, video and other traffic simultaneously.

As the wideband wireless systems become more prevalent, the processing complexity of the receivers also increases. However, these receivers must continue to coexist with the existing lower complexity receivers and also be compatible with the multimedia decoders of varying complexity that are connected with them. Scalability aids in the transmission of video streams compatible with such heterogeneous receivers and decoders. Since CDMA is considered to be efficient for wireless communications, it would be advantageous to design multirate CDMA systems that would allow efficient transmission of scalable video streams over wireless CDMA systems to heterogeneous receivers.

In [1], video transmission over a direct-sequence code-division-multiple-access (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. The choice of the AV receiver was dictated by realistic channel fading rates that limit the data record available for receiver adaptation and redesign.

Recent research has also focused on multirate CDMA systems with multiuser detection. A resource allocation scheme using adaptive power control and multirate multiuser receiver was developed in [2]. The performance of an energy-add multistage detection scheme using the Cholesky iterative detector was studied for multipath synchronous CDMA systems in [3]. The various ways of multirate video transmission over the internet have been reviewed in [4]. Multiuser multirate CDMA receiver designs have been studied extensively in [5], [6], [7], [8], [9], [10] and [11]. Channel estimation for multirate CDMA systems has been considered in [12] and [13].

The performance of multi-code and variable spreading gain multi-rate CDMA schemes has been compared in [14] using the optimal maximum-likelihood (ML) detector, interference canceller and matched filter (MF) detector theoretically and by numerical simulations. In [15], multi-modulation, variable spreading gain and multi-channel systems have been studied with MF detector and interference cancellation schemes assuming a Gaussian approximation for the multiple access interference. The bit error rates of multi-code and variable spreading gain systems employing the decorrelating, parallel interference canceller (PIC) and groupwise interference canceller (GSIC) have been compared in [16] and [17].

We next review some relevant work on video transmission over CDMA channels. In [18], video transmission over

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correlated fading channels for narrowband Direct Sequence Code Division Multiple Access (DS-CDMA) systems (IS-95) was considered. In [19], a dual-priority video partitioning method for unequally protected video transmission over wireless DS-CDMA systems was presented. In [20], a joint source-coding-power control approach for video transmission over DS-CDMA systems was presented. The tradeoffs of source coding, channel coding and spreading for image transmission in DS-CDMA systems were considered in [21]. A technique for error-resilient non-scalable video transmission over DS-CDMA systems with a bandwidth constraint was presented in [22].

In [23], we have considered DS-CDMA video transmission via a single-rate CDMA channel and compared it against transmission via a combination of *multi-code multirate CDMA* and *variable sequence length multirate CDMA* channel. Some preliminary results can also be found in [24]. The channel behavior was modeled as frequency-selective Rayleigh fading. In both cases, an operational rate-distortion problem was defined and solved in order to optimally select the source coding rates, channel coding rates, and spreading code lengths (processing gains) used for the transmission. In [25], we considered CDMA video transmission using minimum total square correlation (TSC) spreading codes.

In our earlier work [23], the AV filter design used was not specifically designed for multirate detection. Multi-user receivers that do not use AV filtering have been studied for multirate dectection in [11], [16]. While multiuser detection helps in reducing interference, a lot of processing power is required for decorrelating all the channels. So, there is a motivation to develop single-user receivers that would be useful in scalable video reception in mobile handsets where there are rigid constraints in the number of processing blocks used and where the aim is to minimize hardware complexity. In this work, we have constructed three single-user short-data record adaptive AV filter configurations to detect multirate signals.

In this paper, we propose a new interference cancelling design that uses just a single AV filter for single-user mutirate despreading. The advantage of the multirate configurations constructed and studied here is that the same processing block can also be used in the single-rate scenario and this helps in achieving scalablity in cellular phones. Our experimental results show that the proposed interference cancelling design has excellent performance in scalable video transmission over DS-CDMA systems that use a combination of multicode multirate and variable processing gain multirate CDMA. The proposed design takes advantage of the fact that single user's video data is transmitted using two spreading codes, one for the base layer and one for the enhancement layers, and of the fact that these spreading codes can have different processing gains. The proposed interference cancelling design is compared with two conventional single-user multirate CDMA receiver configurations, however now we use an AV filter rather than a simple matched filter. We also propose a resource allocation algorithm for the optimal determination of source coding rate, channel coding rate and processing gain for each scalable layer, in order to minimize the expected distortion at the receiver.

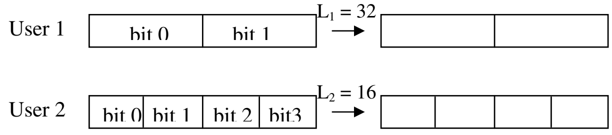

Fig. 1. Variable sequence length CDMA.

The rest of this paper is organized as follows. In Section II, we describe the multirate CDMA methods used in the proposed video transmission system and the received signal in Section III. The multirate auxiliary vector filter configurations are designed in Section IV. In Section V, the resource optimization algorithm for the multirate receiver configurations is described. Experimental results are presented in Section VI and conclusions inferred are in Section VII.

II. Multirate CDMA

CDMA transmission systems that are capable of supporting users with different data rates are said to be multirate CDMA systems and enable the transmission of voice, video and other traffic simultaneously. As mentioned earlier, multirate CDMA would allow efficient transmission of scalable video streams to heterogeneous receivers.

Details about the various multirate access schemes available have been discussed in [26]. Multirate systems can be designed in several ways. They can be classified as multi-modulation systems, variable sequence length systems, multi-code systems and variable chip-rate systems. Further details of the multi-code multirate CDMA and variable sequence length multirate CDMA systems used here are given now.

A. Variable Sequence Length Systems

A variable sequence length or multi-processing spread-spectrum system allocates different processing gains for different rate users as in Fig. 1. The chip rate is maintained constant. If the lowest user bit rate is R_n bits/s, and the chip rate is B chips/s, then the processing gain of the user is B/R_n and for users with rate R_i chips/s, the processing gain is B/R_i. To have a constant chip-period, the symbol rates of all users must be integer multiples of the lowest rate R_n. Existing receivers for single processing gain can be adapted for variable sequence length systems. In this system, the performance of the users with high data rate may be degraded by inter symbol interference (ISI). The spreading code for the high rate users can be represented during a low-rate bit period as being non-zero during the high-rate bit period but zero in the rest of the low-rate bit period.

B. Multi-code Systems

In a multi-code system, the higher data rate users are allowed to transmit their information on more than one channel depending on their data rate as in Fig. 2. Here again the chip-rate in maintained constant. The user with the lowest rate R_n transmits using a single CDMA channel, while users with higher rate R_i are allowed to transmit using R_i/R_n spreading sequences. Each user can be considered to be acting as R_i/R_n equivalent users. The channels of the same user are

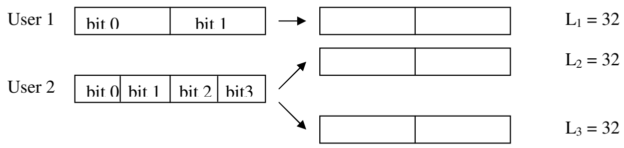

Fig. 2. Multi-code CDMA.

thus synchronous and this fact can be used beneficially in receiver design. The multi-code access method can be used in a single-rate system because the processing gain for each channel remains the same. If we consider the high-rate user as being equivalent to R_i/R_n users, the cross-correlations between pairs of spreading codes of the same user may be non-zero in the multi-code system. In the variable sequence length system, the cross-correlations of spreading codes over a low-rate bit period will be zero due to orthogonality [5].

The widely known receivers for CDMA are not specific to multirate data users and therefore do not exploit the nature of multirate signals. In order for CDMA systems to support multirate data services, multi-user detectors designed for multirate support must be designed.

III. Received Multirate Signal

A system with two data rates (two allowable spreading sequence lengths) is considered. In this section the data rate of the channel refers to the rate before spreading and for the video user it is equal to the product of the source coding rate (R_s) and inverse of the channel coding rate (R_c) used for the channel. The results can be easily extended for more than two rates. In this dual-rate system with K CDMA channels (spreading codes), it is assumed that $K/2$ channels have a low bit-rate and $K/2$ channels have a high bit-rate. Frequency selective multipath fading with $P+1$ resolvable multipaths is assumed. If the bit time-periods of the high-rate and low-rate channels are T_h and T_l respectively, the number of bits of each high-rate channel during each low-rate bit period T_l is denoted by Q, which is equal to the ratio of spreading lengths L_l/L_h = T_l/T_h. After conventional chip-matched filtering and sampling at the chip rate over a multipath extended symbol interval of L_l+P chips, the L_l+P data samples from the mth antenna element, $m=1,\ldots,M$, are organized in the form of a vector $\mathbf{r}_m$ given by (1) with the first term for low-rate channels and the second for high-rate channels.

$$\begin{aligned}\mathbf{r}_m = &\sum_{k=0}^{K/2-1}\sum_{p=0}^{P} c_{k,p}\sqrt{E_k}(b_k\mathbf{s}_{k_l,p} + b_k^-\mathbf{s}_{k_l,p}^- + b_k^+\mathbf{s}_{k_l,p}^+)\mathbf{a}_{k,p}[\mathrm{m}]\\ &+\sum_{q=0}^{Q-1}\sum_{k=K/2}^{K-1}\sum_{p=0}^{P} c_{k,p}\sqrt{E_k}(b_{k,q}\mathbf{s}_{k_h,p} + b_{k,q}^-\mathbf{s}_{k_h,p}^-\\ &\qquad\qquad + b_{k,q}^+\mathbf{s}_{k_h,p}^+)\mathbf{a}_{k,p}[\mathrm{m}]\\ &+\mathbf{n}\,, \qquad m=1,\ldots,M, \quad Q=L_l/L_h \end{aligned} \tag{1}$$

where, with respect to the kth CDMA signal, E_k is the transmitted energy per chip, b_k, b_k^-, and b_k^+ are the present, the previous, and the following transmitted bits of the low-rate user, respectively. $b_{k,q}$, $b_{k,q}^-$, and $b_{k,q}^+$ are the present, the previous, and the following transmitted bit of the high-rate channels, respectively. $\{c_{k,p}\}$ are the coefficients of the frequency-selective slowly fading (quasi-static) channel modeled as independent zero-mean complex Gaussian random variables that are assumed to remain constant over a few symbol intervals. L= $\{L_l,\ L_h\}$ are the sequence lengths of $\mathbf{s}_{k_l}$ and $\mathbf{s}_{k_h}$ used for spreading the bits in the low-rate and high-rate channels respectively. For the qth high-rate bit, the spreading sequence of the high-rate users are $\mathbf{s}_{k_h}$ in the qth high-rate bit interval but zero otherwise. $\mathbf{s}_{k_l,p}$ represents the 0-padded by P, p-cyclic-shifted version of the signature of the kth SS signal $\mathbf{s}_{kl}$, $\mathbf{s}_{k_l,p}^-$ is the 0-filled (L_l-p)-left-shifted version of $\mathbf{s}_{k_l,0}$, and $\mathbf{s}_{k_l,p}^+$ is the 0-filled (L_l-p)-right-shifted version of $\mathbf{s}_{k_l,0}$. Similar notations apply for the high-rate channels. Finally, $\mathbf{n}$ represents additive complex Gaussian noise with mean $\mathbf{0}$ and autocorrelation matrix $\sigma^2\mathbf{I}_M$, and $\mathbf{a}_{k,p}[\mathrm{m}]$ is the mth coordinate of the kth CDMA signal, pth path, array response vector:

$$\mathbf{a}_{k,p}[\mathrm{m}] = e^{j2\pi(m-1)\frac{\sin\theta_{k,p}d}{\lambda}}\ ,\ m=1,\ldots,M, \tag{2}$$

where $\theta_{k,p}$ identifies the angle of arrival of the pth path of the kth CDMA signal, λ is the carrier wavelength, and d is the element spacing (usually $d=\lambda/2$).

The auxiliary-vector (AV) adaptive filter is used for despreading. Theoretical analysis of the AV algorithm was pursued in [27]. The AV filter has been shown to be effective under limited data record support in rapidly changing wireless communications environment and so it is chosen to be used here. An unsupervised (blind) J-divergence AV filter estimator procedure is presented in [28]. While the AV filtering process was discussed in our earlier work [23], the AV filter configuration has to be suitably modified for despreading multirate signals. Such AV filter configurations are designed and their performance evaluated in the following sections.

IV. AV Filtering

In this section, we first present the basics of AV filtering and then propose AV filter designs for multirate reception.

A. AV Filtering Basics

The AV algorithm generates a sequence of AV filters making use of two basic principles: (i) The maximum magnitude cross-correlation criterion for the evaluation of the auxiliary vectors and (ii) the conditional mean-square optimization criterion for the evaluation of the scalar AV weights. In summary, constrained to be distortionless in a vector direction of interest, a new element of the AV filter sequence is obtained as the sum of the previous filter in the sequence and a weighted auxiliary vector that is orthogonal to the constraint vector. The auxiliary-vector direction is chosen to maximize the magnitude of the statistical cross-correlation between the previous filter output and the projection of the data onto the auxiliary vector itself, while the corresponding scalar weight is chosen to minimize the new filter output variance. The sequence of filters obtained by the above conditional optimization procedure was shown to converge to the minimum-variance-distortionless-response (MVDR) solution under ideal setups (perfectly known input autocovariance matrix) [27]. When filter estimation based on a finite data record is performed by utilizing the sample-average estimate of the ideal input autocovariance matrix, the sequence of AV filter estimates was shown to converge to the sample-matrix-inversion (SMI) MVDR filter estimate [27]. Viewed as a sequence of estimators of the ideal MVDR filter, the sequence of AV-filter estimators exhibits the following characteristic that makes it a favorable choice for multiple-access-interference suppression in rapidly changing communication environments: The early non-asymptotic elements in the sequence offer favorable bias/variance balance and outperform significantly in mean-square filter estimation error the LMS, RLS or SMI adaptive filter implementations [27]. We conclude this section with a brief presentation of the AV algorithm. The AV filter sequence $\{\mathbf{w}_{AV}^{(d)}\}$, $d = 0, 1, 2, \ldots$ is initialized at the S-T vector direction of interest, i.e. the normalized S-T RAKE matched filter for the SS signal of interest, $\mathbf{w}_{AV}^{0} = \mathbf{w}_{\text{R-MF}}$. Then, for $d = 1, 2, \ldots$, $\mathbf{w}_{AV}^{(d)} = \mathbf{w}_{AV}^{(d-1)} - \mu_d \mathbf{g}_d$ where

$$\mathbf{g}_d = (I - \mathbf{w}_{\text{R-MF}} \mathbf{w}_{\text{R-MF}}^H) \mathbf{A} \mathbf{w}_{AV}^{(d-1)},$$

and

$$\mu_d = \frac{\mathbf{g}_d^H \mathbf{A} \mathbf{w}_{AV}^{(d-1)}}{\mathbf{g}_d^H \mathbf{A} \mathbf{g}_d}$$

(I denotes the identity matrix and $\mathbf{A}$ is the input space-time autocovariance matrix, $\mathbf{A} = E\{\mathbf{r}\mathbf{r}^H\}$). For the selection of the best AV filter in the sequence (best number of auxiliary vectors d), please see [28].

B. AV Filter Designs for Multirate Reception

The auxiliary vector filter used in [23] is a single-user detector that is optimized in the direction of the user of interest. In scalable video reception in a multirate scenario, each video user has more than one CDMA channel to decode. Each of these channels experience the same multipath fading and the same antenna elements are used for diversity reception. However, the signature sequences may not be orthogonal due to their different lengths. Now, each video user needs a multiuser detector to detect the bits in the channels of interest. The multirate channels can be converted to several single-rate channels and separate AV filters can be used to simultaneously detect bits in the channels.

In a simple configuration, as many AV filters as the number of scalable layers being sent can be used. Each of them can detect bits in the respective channels over the bit period in that channel. This configuration does not take into effect the different correlation properties of parts of the signature sequences of low-rate channel with the signature sequence of the high-rate channel during each bit period of the high-rate channel. In this paper, we propose three alternative configurations that are suitable for multirate detection. The relative performances of the receivers for scalable video transmission is analyzed using the experimental results.

C. High-rate AV (AVHR) configuration

In the AVHR configuration, the individual AV filters perform filtering operations with the samples of each bit extending over the multipath symbol interval of $L_h + P$ chips. The individual AV filters are denoted as HR-AV filter blocks in Fig. 3. Each low-rate user is converted into Q separate high-rate co-channels. The spreading chips are for the qth co-channel are then given by

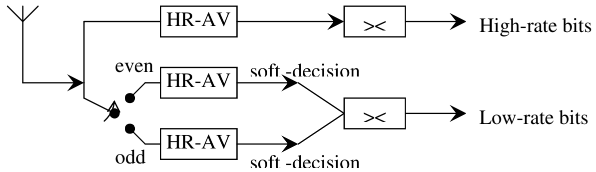

Fig. 3. High-rate AV based detector.

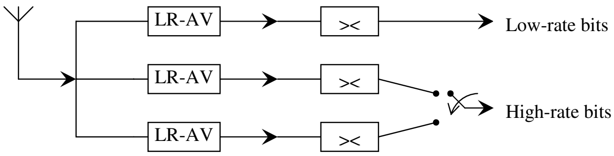

Fig. 4. Low-rate AV based detector.

$$[s_{k_l}[q * L_h], \ldots, s_{k_l}[(q+1) * L_h]] \qquad q = 0, \ldots, Q-1. \quad (3)$$

For reconstructing each low-rate bit, Q soft estimates are maintained over each high-rate bit interval. For a dual-rate system with Q being equal to 2, three AV filters processing in parallel are required as in Fig. 3.

D. Low-rate AV (AVLR) configuration

In the AVLR configuration, the individual AV filters perform filtering operations with the samples of each bit extending over the multipath symbol interval of $L_l + P$ chips. The individual AV filters are denoted as LR-AV filter blocks in Fig. 4. The bits are detected at the end of the low-rate bit interval. Each high-rate user is converted into Q separate low-rate co-channels with spreading sequences of length L_l. For the qth co-channel, the spreading code of the high-rate user can be represented over a low-rate bit period as

$$\mathbf{S}_{k_{h,q}} = \begin{cases} \mathbf{s}_{k_h}, & qT_c \le t < (q+1)T_c \\ 0, & otherwise \end{cases} \quad (4)$$

where T_c is the chip interval and $q = 0, \ldots, Q-1$. For a dual-rate system with Q having a value of 2, three AV filters processing in parallel are required as in Fig. 4.

E. Interference-Cancelling AV (AV-IC) configuration

The above two configurations require more than one AV filter block. We propose a new multirate despreading design that can use just a single AV filter block. For detecting the high-rate user's bits, an AV filter is used to perform filtering operations with the samples of each bit extending over the multipath symbol interval of $L_h + P$ chips. Then, the signal corresponding to the high-rate bits is reconstructed and subtracted from the received signal removing the interference of the high-rate bits on the low-rate bits to be detected. The low-rate bits are then detected by using another AV filter to perform filtering operations with the samples of each bit extending over $L_l + P$ chips. This behaves like an interference

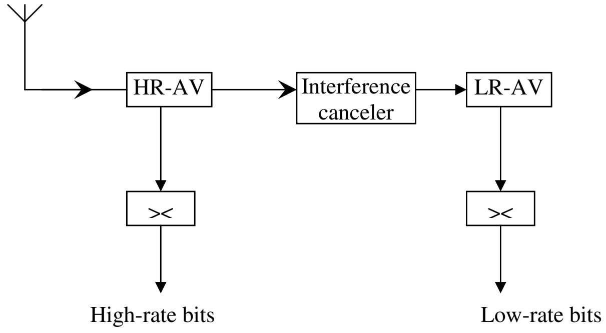

Fig. 5. Interference-cancelling AV based detector.

canceller that cancels the multiple access interference (MAI) of the high-rate channel leading to an improved bit error rate (BER) performance. Moreover, decoding the high-rate channel serves as a kind of channel estimation technique and gives good initial values that the AV filter can use for training and decoding the low-rate bits. This requires just two AV filters as shown in Fig. 5 to detect the high-rate bits and then the low-rate bits at the expense of some delay. The number of blocks can be reduced by reusing the same AV for the high-rate bits and then the low-rate bits that may be apt for being used in mobile handset architectures.

Since it has been shown that the multi-rate channels can be converted into many single-rate channels, the AV filter operations can be used as in a single-rate scenario, the details of which can be found in [23].

V. Optimal Resource Allocation

In this section, the optimal resource allocation procedure for the cases of video transmission over two CDMA channels is described. Since the chip rate is usually fixed in a DS-CDMA system, the optimization constraint is the available chip rate, R^{chip}_{budget}. Fixed energy per chip is assumed. Each scalable video layer is transmitted over a separate DS-CDMA channel. The available bit rate for scalable layer i is

$$R_{s+c,i} = \frac{R^{chip}_{budget}}{L_i} \quad (5)$$

where L_i is the spreading length for layer i. Thus, if two layers are assumed, the ratio $R_{s+c,1}/R_{s+c,2}$ is fixed and equal to L_2/L_1. This is in contrast to the single CDMA channel case [23] where the allocation of the available bit rate to each individual scalable layer is part of the optimization.

The optimization problem now is as follows (for the case of T layers):

$$\min D_{s+c} \text{ subject to } L_i R_{s+c,i} \leq R^{chip}_{budget}, \text{ for } i = 1, \ldots, T, \quad (6)$$

where D_{s+c} is the expected video distortion at the receiver. For each layer, the source coding rate $R_{s,i}$, the channel coding rate $R_{c,i}$, and the spreading length L_i are to be determined.

For T scalable layers, the total transmitted bit rate R_{s+c} is equal to

$$R_{s+c} = \sum_{l=1}^{T} R_{s+c,l} \quad (7)$$

where $R_{s+c,l}$ is the bit rate used for source and channel coding for the scalable layer l. $R_{s+c,l}$ is equal to

$$R_{s+c,l} = \frac{R_{s,l}}{R_{c,l}} \quad (8)$$

where $R_{s,l}$ and $R_{c,l}$ are the source and channel rates, respectively, for the scalable layer l. It should be emphasized that $R_{s,l}$ is in bits/s and $R_{c,l}$ is a dimensionless number.

It is useful to write the overall distortion D_{s+c} as the sum of distortions per scalable layers:

$$D_{s+c} = \sum_{l=1}^{T} D_{s+c,l}. \quad (9)$$

In a subband-based scalable codec, it is straightforward to express the distortion as the sum of distortions per layer since each layer corresponds to different transform coefficients. However, in the scalable codec considered here, the distortion per layer needs to be redefined as the *differential improvement* of including the layer in the reconstruction [29]. 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 inclusion of these layers reduces the overall mean squared error (MSE).

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. For example, for a two layer case an enhancement layer of 28 kbps will cause a different improvement in MSE depending on the rate used for the base layer. The differential improvement depends on the picture quality before the inclusion of the scalable layer in question. Therefore, the distortion per layer is better written as

$$D_{s+c} = \sum_{l=1}^{T} D_{s+c,l}(R_{s+c,1}, \ldots, R_{s+c,l}). \quad (10)$$

As mentioned previously, the total bit rate allocated to a scalable layer depends only on L_i and not on any decisions made for another layer. It is clear from Eq. (10) that the problem can be broken into separate problems for each layer, thus simplifying the optimization when compared to the single CDMA channel case. For the case of two layers, the two problems to be solved can be written as follows.

$$\{R^*_{s,1}, R^*_{c,1}, L^*_1\} = \arg\min D_{s+c,1}(R_{s+c,1}) \quad \text{subject to } L_1 R_{s+c,1} \leq R^{chip}_{budget} \quad (11)$$

and

$$\{R^*_{s,2}, R^*_{c,2}, L^*_2\} = \arg\min D_{s+c,2}(R^*_{s+c,1}, R_{s+c,2}) \quad \text{subject to } L_2 R_{s+c,2} \leq R^{chip}_{budget}. \quad (12)$$

Thus, optimization for the two-channel video transmission case is algebraically simpler than optimization in the single-channel case [23]. Since there is no dependency between layers, the above two problems can be solved independently using Lagrangian optimization.

In order to solve the optimization problem of Eqs. (11) and (12), we need to estimate the *operational rate-distortion functions* (ORDF) $D_{s+c,l}(\cdot, \ldots, \cdot)$ for each scalable layer. One way to proceed is to experimentally obtain the expected distortion for each layer for all possible combinations of source and channel rates and all possible channel conditions. However, this becomes prohibitively complex for even a small number of admissible source and channel rates and channel conditions. Thus, instead the *universal rate-distortion characteristics* are utilized. (URDC) at the expense of a small performance penalty. URDC characteristics show the expected distortion per layer as a function of the bit error rate (after channel coding). Their use is discussed in Section V-A.

A. Channel Characteristic Plots and Universal Rate-Distortion Characteristics

So far, the problem was formulated and the solution was outlined for video layer rate design assuming that the optimal rate-distortion characteristics of the individual layers, $D_{s+c,i}(.)$, are given. Now, the technique used to obtain $D_{s+c,i}(.), i = 1, \ldots, T$ is described.

While it is possible to simulate transmission of the actual source coded data over a channel, gather statistics and develop an optimal strategy based on these results, in practice this leads to extremely high computational complexity and makes the process impractical in many ways. For every bitstream, we would have to simulate transmission of the data over the channel using all combinations of source and channel coding rates per scalable layer and channel conditions of interest. Clearly, the computational complexity of this approach is prohibitive. To circumvent this problem, *universal* rate-distortion characteristics of the source coding scheme are utilized [30], [29]. This approach is described next.

1) Channel Characteristic Plots with Multirate Receivers: For given channel SNRs, spreading lengths and choice of channel codes, the probability of bit error of a channel, P_b, is dependent on the channel coding rate and spreading length of the channel and also on the spreading length of the user's second channel. Hence P_b is calculated for the set of channel coding rates of interest and each combination of spreading lengths of the two CDMA channels used by the user of interest. P_b of the low-rate channel of the video user is also calculated for each of the spreading lengths of the high-rate channel and vice-versa. P_b establishes a reference as to the performance of channel coding over the particular channel with the given parameters and this performance analysis is done once for each AV filter configuration. These channel characteristic plots differ from the plots in [23] where the AV filter was used for single-rate decoding. Now, we require a channel characteristic plot for each combination of spreading lengths of the user's two channels $\{ L_l, L_h \}$. It should also be noted that a separate Channel characteristic plot is required for each multirate AV filter configuration. An illustration plot showing the performance of channel coding as a function of a given channel parameter is shown in Fig. 6 for a set of channel coding rates $R_{cn}, n = 1, \ldots N$ and a combination of spreading lengths of the user's two channels $\{ L_l, L_h \}$.

2) Universal Rate-Distortion Characteristics: Towards calculating the impact of the errors due to both lossy source coding and channel disturbance on a set of data, it is realized that for a given set of preceding layer source rates the distortion for a particular layer, $D_{s+c,i}$, given a particular source coding rate, $R_{s,i}$, is a function of the bit error rate. Thus, the rate-distortion function of the layer for a fixed source rate, $R_{s,i}$ (given the preceding layer source rates), is a function of the bit error rate (after channel decoding), P_b. It is then possible to plot a family of $D_{s+c,i}$ versus $1/P_b$ curves given a set of source coding rates of interest as shown in Fig. 7. These are defined as the universal rate-distortion characteristics (URDCs) of the source. Due to the use of variable length codes in the video coding standards, it would be a formidable task to analytically obtain the URDCs. Thus, 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

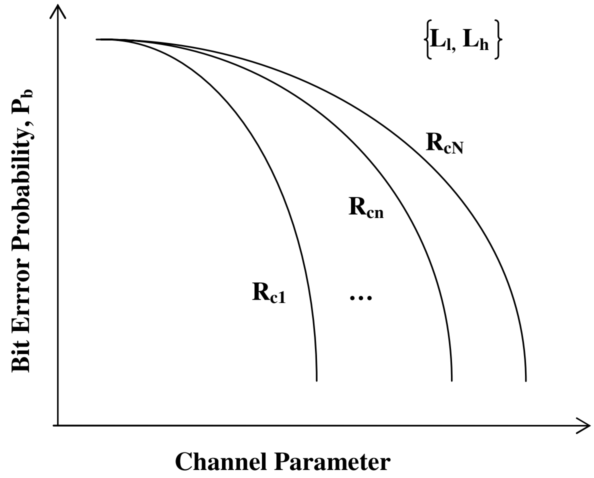

Fig. 6. An example of a channel characteristic plot.

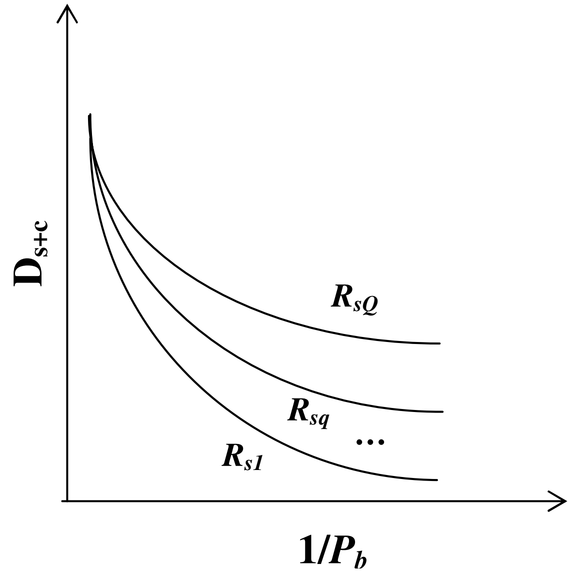

Fig. 7. An example of universal rate-distortion characteristics.

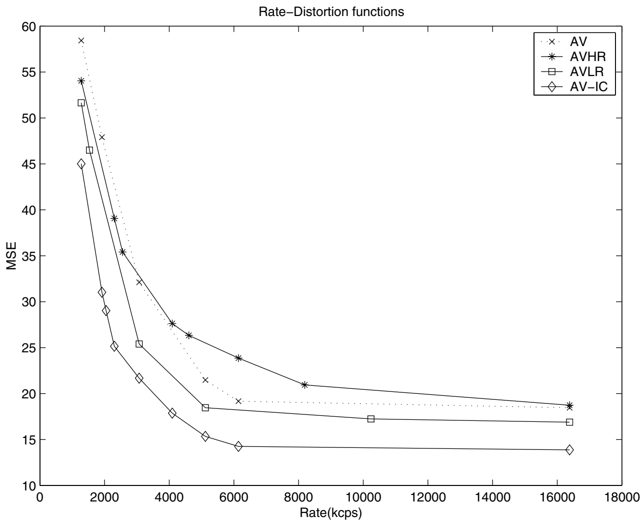

Fig. 8. Rate-distortion performance of scalable video transmission of the “Foreman” sequence over a DS-CDMA wireless system using different AV filter configurations.

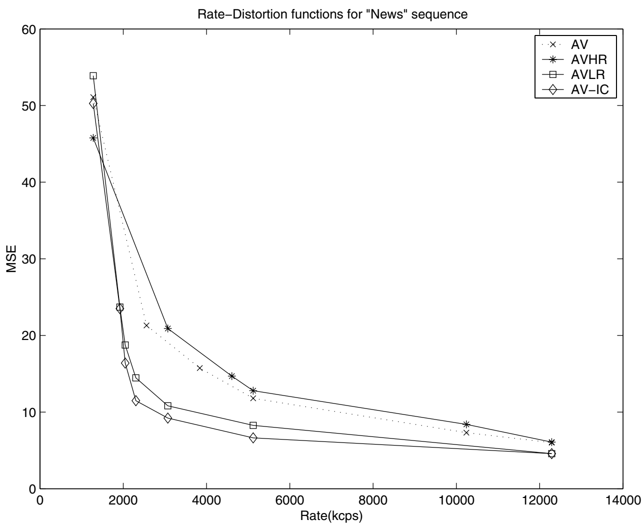

Fig. 9. Rate-distortion performance of scalable video transmission of the “News” sequence over a DS-CDMA wireless system using different AV filter configurations.

the differential improvement of including layer i as mentioned earlier.

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, the channel characteristic plot is used to determine the resulting bit error rates for each of the available channel coding rates. Then, for each of these probability values, the universal rate-distortion characteristic is used 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, the rate-distortion operating points are generated for the given channel conditions.

VI. Experimental Results

We next present simulation results for the signal model in (1) that compare scalable video transmission over two DS-CDMA channels detected using different multirate AV filter configurations. The physical-layer receiver is equipped with a uniform linear antenna array of $M = 4$ elements. All received CDMA signals $k = 0, 1, \ldots, K-1$ experience $P + 1 = 3$ resolvable multipaths with independent fading per path and equal mean power $E\{|c_{k,p}|^2\}$, $p = 0, 1, \ldots, P$. All paths of all signals have independent angle of arrival $\theta_{k,p}$ drawn uniformly in $(-90^o, 90^o)$. The fading realization $c_{k,p}$ of each path of each signal remains constant across the antenna elements (antenna diversity effects are not considered/exploited here). The SNR values identified in the experimental study at this section also refer to the total SNR per chip, defined as $\frac{\sum_{p=0}^{P} E\{|c_{k,p}|^2\} E_k}{\sigma^2}$, $k = 0, 1, \ldots, K-1$.

TABLE I

Optimal rate allocation for two-layer SNR scalable “Foreman” video sequence using a simple AV detector.

Total Rate	Total Distortion	Base Layer			Enhancement Layer			Base Distortion
R_{budget}^{chip*}	D_{s+c}^*	$R_{s,1}^*$	$R_{c,1}^*$	L_1^*	$R_{s,2}^*$	$R_{c,2}^*$	L_2^*	$D_{s+c,1}^*$
1280	58.44	64	4/5	16	64	4/5	16	67.29
1920	47.91	96	4/5	16	96	4/5	16	56.59
3072	32.12	64	2/3	16	96	1/2	16	35.14
5120	21.48	128	4/5	16	256	4/5	16	21.88
6144	19.17	96	1/2	16	256	2/5	16	19.59
16384	18.46	256	1/2	16	256	1/2	32	18.75

TABLE II

Optimal rate allocation for two layer SNR scalable “Foreman” video sequence using the AVHR filter detector

Total Rate	Total Distortion	Base Layer			Enhancement Layer			Base Distortion
R_{budget}^{chip*}	D_{s+c}^*	$R_{s,1}^*$	$R_{c,1}^*$	L_1^*	$R_{s,2}^*$	$R_{c,2}^*$	L_2^*	$D_{s+c,1}^*$
1280	54.05	64	4/5	16	64	4/5	16	61.93
2304	39.07	96	1/2	16	96	4/5	16	50.62
2560	35.42	64	4/5	32	64	1/2	32	48.28
4096	27.62	128	1/2	16	64	4/5	32	28.34
4608	26.33	96	2/3	32	96	2/5	32	26.95
6144	23.86	256	2/3	16	96	1/2	32	24.36
8192	20.95	128	1/2	32	256	1/2	16	21.16
16384	18.73	256	1/2	32	256	1/2	32	19.05

An MPEG-4 compatible video source codec is used along with rate compatible punctured convolutional (RCPC) channel codes. Auxiliary-vector filtering followed by soft decision Viterbi decoding is used at the receiver. A dual-rate system is modeled with eight active CDMA interferers occupying eight distinct channels (spreading codes), all at an SNR of 8 dB. Two channels (codes) are used by the video user of interest and have an SNR of 4.98 dB.

The admissible source coding rates are 64000, 96000, 128000, and 256000 bits per second for both the base and enhancement layer. The admissible channel coding rates for both layers are $1/2$, $2/3$, and $4/5$, while the admissible spreading codes are Walsh-Hadamard of length 16 and 32. Four of the interferers have a high-bit rate with a spreading length of 16 while the other interferers have a low-bit rate

TABLE III
OPTIMAL RATE ALLOCATION FOR TWO LAYER SNR SCALABLE "FOREMAN" VIDEO SEQUENCE USING THE AVLR FILTER DETECTOR

Total Rate	Total Distortion	Base Layer			Enhancement Layer			Base Distortion
R_{budget}^{chip*}	D_{s+c}^*	$R_{s,1}^*$	$R_{c,1}^*$	L_1^*	$R_{s,2}^*$	$R_{c,2}^*$	L_2^*	$D_{s+c,1}^*$
1280	51.65	64	4/5	16	64	4/5	16	60.14
1536	46.51	64	2/3	16	64	2/3	16	61.16
3072	25.41	128	2/3	16	64	2/3	32	28.60
5120	18.45	128	4/5	32	256	4/5	16	18.86
10240	17.24	256	4/5	32	256	4/5	32	15.62
16384	16.88	256	1/2	32	256	1/2	32	15.19

TABLE IV
OPTIMAL RATE ALLOCATION FOR TWO LAYER SNR SCALABLE "FOREMAN" VIDEO SEQUENCE USING THE AV-IC FILTER DETECTOR

Total Rate	Total Distortion	Base Layer			Enhancement Layer			Base Distortion
R_{budget}^{chip*}	D_{s+c}^*	$R_{s,1}^*$	$R_{c,1}^*$	L_1^*	$R_{s,2}^*$	$R_{c,2}^*$	L_2^*	$D_{s+c,1}^*$
1280	45.01	64	4/5	16	64	4/5	16	54.60
1920	31.03	96	4/5	16	96	4/5	16	41.74
2048	29.03	64	1/2	16	64	1/2	16	41.11
2304	25.15	96	2/3	16	96	2/3	16	38.21
3072	21.67	128	2/3	16	128	2/3	16	24.14
4096	17.86	64	1/2	32	128	1/2	16	18.48
5120	15.33	128	4/5	32	256	4/5	16	15.78
6144	14.25	256	2/3	16	128	2/3	32	14.69
16384	13.88	256	1/2	32	256	1/2	32	14.26

with a spreading length of 32. Fig. 8 and Fig. 9 show a comparison of the performance of scalable video transmission over a dual-rate DS-CDMA system when the video user of interest occupies two channels, for the "Foreman" and "News" sequences, respectively. The mean squared error is plotted against the total chip rate. It can be seen that, for the SNRs under consideration, the AV-IC gives better performance than the simple AV, AVHR and AVLR configurations. The AVHR has poor performance for low-rate users because the spreading code of the low-rate users are considered partially over the high-rate bit period. The AVHR hence performs poorly at many rates. The AVLR gives a lower distortion as it gives a lower BER for both low and high-rate channels. The AV-IC offers a lower BER due to interference cancellation and consequently a better rate-distortion performance than the other multirate AV configurations.

The optimal allocation of source coding rate, channel coding rate and spreading length for the Simple AV, AVHR, AVLR and the AV-IC configurations are given in Table I, Table II, Table III and Table IV, respectively, for the "Foreman" sequence, and in Table V, Table VI, Table VII and Table VIII, for the "News" sequence.

VII. CONCLUSION

AV filter configurations such as the AVHR, AVLR and AV-IC configurations, suitable for multirate DS-CDMA detection were designed. The rate-distortion optimization performance of scalable video transmission over multirate DS-CDMA systems using the multirate AV filter configurations was compared. It was experimentally found for the given setup that employing the multirate AV filter configurations leads to better performance than the single-rate AV filter due to their ability to reduce the multi-user interference. The performance is dependent on the number of multirate users in the system and also on the ratio of the spreading sequence lengths used for the channels of different data rate users. Any of the multirate AV filter configurations can also be used in the single-rate scenario and is thus suitable for receiving scalable video. The AV-IC design gives the best rate-distortion performance suitable for scalable video transmission over a wide range of chip rates.

TABLE V
OPTIMAL RATE ALLOCATION FOR TWO-LAYER SNR SCALABLE "NEWS" VIDEO SEQUENCE USING A SIMPLE AV DETECTOR.

Total Rate	Total Distortion	Base Layer			Enhancement Layer			Base Distortion
R_{budget}^{chip*}	D_{s+c}^*	$R_{s,1}^*$	$R_{c,1}^*$	L_1^*	$R_{s,2}^*$	$R_{c,2}^*$	L_2^*	$D_{s+c,1}^*$
1280	51.10	64	4/5	16	64	4/5	16	51.42
2560	21.30	64	4/5	32	64	4/5	32	21.71
3840	15.74	96	4/5	32	96	4/5	32	16.67
5120	11.80	128	4/5	32	128	4/5	32	12.78
10240	7.32	256	4/5	32	256	4/5	32	9.42
12288	6.01	256	2/3	32	256	2/3	32	7.11

TABLE VI
OPTIMAL RATE ALLOCATION FOR TWO LAYER SNR SCALABLE "NEWS" VIDEO SEQUENCE USING THE AVHR FILTER DETECTOR

Total Rate	Total Distortion	Base Layer			Enhancement Layer			Base Distortion
R_{budget}^{chip*}	D_{s+c}^*	$R_{s,1}^*$	$R_{c,1}^*$	L_1^*	$R_{s,2}^*$	$R_{c,2}^*$	L_2^*	$D_{s+c,1}^*$
1280	45.77	64	4/5	16	64	4/5	16	46.22
3072	20.91	64	2/3	32	64	2/3	32	21.71
4608	14.69	96	2/3	32	96	2/3	32	16.67
5120	12.78	128	4/5	32	128	4/5	32	13.79
10240	8.39	256	4/5	32	256	4/5	32	8.41
12288	6.08	256	2/3	32	256	2/3	32	7.11

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TABLE VII

OPTIMAL RATE ALLOCATION FOR TWO LAYER SNR SCALABLE "NEWS" VIDEO SEQUENCE USING THE AVLR FILTER DETECTOR

Total Rate	Total Distortion	Base Layer			Enhancement Layer			Base Distortion
R_{budget}^{chip*}	D_{s+c}^{*}	$R_{s,1}^{*}$	$R_{c,1}^{*}$	L_1^{*}	$R_{s,2}^{*}$	$R_{c,2}^{*}$	L_2^{*}	$D_{s+c,1}^{*}$
1280	53.89	64	4/5	16	64	4/5	16	54.38
1920	23.71	96	4/5	16	96	4/5	16	24.39
2048	18.75	64	1/2	16	64	1/2	16	19.59
2304	14.49	96	2/3	16	96	2/3	16	15.67
3072	10.82	128	2/3	16	128	2/3	16	12.29
5120	8.26	128	4/5	32	128	4/5	32	9.78
12288	4.58	256	2/3	32	256	2/3	32	6.11

TABLE VIII

OPTIMAL RATE ALLOCATION FOR TWO LAYER SNR SCALABLE "NEWS" VIDEO SEQUENCE USING THE AV-IC FILTER DETECTOR

Total Rate	Total Distortion	Base Layer			Enhancement Layer			Base Distortion
R_{budget}^{chip*}	D_{s+c}^{*}	$R_{s,1}^{*}$	$R_{c,1}^{*}$	L_1^{*}	$R_{s,2}^{*}$	$R_{c,2}^{*}$	L_2^{*}	$D_{s+c,1}^{*}$
1280	50.28	64	4/5	16	64	4/5	16	50.42
1920	23.50	96	4/5	16	96	4/5	16	23.71
2048	16.39	64	1/2	16	64	1/2	16	16.67
2304	11.49	96	2/3	16	96	2/3	16	11.98
3072	9.21	128	2/3	16	128	2/3	16	10.42
5120	6.63	128	4/5	32	128	4/5	32	8.11
12288	4.58	256	2/3	32	256	2/3	32	6.11

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