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Cross Layer Resource Allocation Design for Uplink Video OFDMA Wireless Systems

Dawei Wang, Pamela C. Cosman and Laurence B. Milstein
Department of Electrical and Computer Engineering,
University of California, San Diego
La Jolla, California, USA 92093-0407
daw017@ucsd.edu, pcosman@ece.ucsd.edu, milstein@ece.ucsd.edu

***Abstract*—We study an uplink video communication system with multiple users in a centralized wireless cell. The multiple access scheme is Orthogonal Frequency Division Multiple Access (OFDMA). Both physical layer channel state information (CSI) and application layer rate distortion (RD) information of video streams are collected by the base station. With the goal of minimizing the average video distortion across all the users in the system, we design an iterative resource allocation algorithm for subcarrier assignment and power allocation. Based on the physical layer resource allocation decision, the user will adapt the application layer video source coding rate. To show the advantage of this cross layer algorithm, numerical results are compared with two baseline resource allocation algorithms using only physical layer information or only application layer information. Bit-level simulation results are presented which take into account the imperfection of the video coding rate control, as well as channel errors.**

***Index Terms*—Cross layer design, multiuser video communications system, OFDMA, video multiplexing.**

I. Introduction and Background

With the increasing demand for video and multimedia wireless communications, system designs which account for source characteristics have been studied intensively, and techniques like multiple description coding [3] [7], unequal error protection (UEP) [2] [4] and joint source channel coding [9] [11] have been developed. By allocating different subcarriers according to each user's channel state information (CSI) in a multiuser setting, Orthogonal Frequency Division Multiple Access (OFDMA) is a flexible and low-complexity way of managing communication resources. The problem of assigning resources in an OFDMA system was studied in [21] [22] with the goal of either maximizing the physical layer sum rates, or minimizing the total power consumed to achieve a certain quality of service (QoS). Utility-driven resource allocation in OFDMA was investigated in [15] [16], and most recently in [12], in a statistical setting.

On the other hand, video multiplexing aims to improve the overall video quality when multiple video streams are sharing the same resource pool [17] [18] [23] . In [23], the authors considered a multiple camera surveillance system. By exploiting the difference between high and low motion videos, the long term video average performance of the system can be improved. References [17] and [18] use the economics concept of competitive equilibrium to allocate bit rate. For all of these papers, and most of the other literature on video multiplexing, the resource pool is bit rate, and the authors assume an error-free scenario. When multiplexing videos over a wireless channel, bit rate will depend on bandwidth, transmission power, modulation format and CSI. Thus, multiplexing video streams in a wireless environment with a resource pool of power and bandwidth will be more challenging than conventional video multiplexing.

In a cellular wireless OFDMA video transmission system, knowledge of the CSI as well as the complexity of the video streams can be collected by the base station. Both the multiuser channel diversity and video complexity diversity can be used simultaneously to optimize the power and subcarrier assignment. In this paper, we are interested in a cooperative setting, which means that users will honestly report their RD information to the base station, and the goal of our cross layer resource management is to optimize the average performance of the video transmission across all the users in the system. Similar to the camera surveillance system, video streams with high complexity should be given more subcarriers with strong channel gains, while streams with low complexity can be sacrificed and get a relatively small number of subcarriers. Power allocation should be done according to the CSI and satisfy certain physical layer transmission requirements.

The rest of the paper is organized as follows: Section II presents both the physical layer and application layer models, as well as the cross layer optimization framework. Section III describes our proposed cross layer resource allocation algorithm, and Section IV presents two baseline algorithms for comparison. Simulation results are introduced in Section V, and Section VI draws the conclusions.

II. System Model and Problem Formulation

A. Physical Layer System Model

We consider a centrally controlled celluar OFDMA video communication system with the set of users k={1, 2, 3 ... K} who want to communicate videos to the base station. The system occupies a total frequency band of W (Hz) and is equally divided into M orthogonal subcarriers m={1, 2, 3 ... M}. The bandwidth of the mainlobe for each subcarrier is $\Delta W = W/M$ (Hz). We assume that the channel gain within

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each subcarrier is flat, but different subcarriers will experience independent fading. We further assume that each subcarrier can only be used by one user, but it is possible for one user to get more than one subcarrier. All users adopt adaptive QAM modulation, and the alphabet size of the modulation format is determined by the resource allocation decision.

The system operates in a slotted manner, and the length of one time slot is T_s (sec). One Group of Pictures (GOP) will be transmitted in one time slot. Let $\underline{H_k(s)} = \overline{[H_{k,1}(s), H_{k,2}(s), ...H_{k,M}(s)]}$ denote the complex channel gain of user k for the set of subcarriers in time slot s. In addition, we assume that the channel remains unchanged for the duration of one time slot. The subcarrier assignment, as well as the power allocation decision, will be made on a slot-by-slot basis. In this paper, we ignore the effect of Inter Symbol Interference (ISI) as well as Inter Carrier Interference (ICI), as research in [14] shows that accurate time and frequency synchronization can be achieved using a reasonable amount of overhead.

Let T be the data duration and T_{cp} be the length of the cyclic prefix. We define $T_0 = T + T_{cp}$ to be the duration of an OFDM symbol. The lowpass equivalent transmitted signal for user k can be written as:

$$x_k(t) = \sum_l \sum_{m=1}^{M} \sqrt{P_{k,m}} X_{k,m}[l] \exp(j2\pi mt/T)\Gamma(t - lT_0) \tag{1}$$

where $P_{k,m}$ and $X_{k,m}[l]$ are the transmission power and coded symbol, respectively, of user k on subcarrier m. Also,

$$\Gamma(t) = \begin{cases} 1 & t \in [0, T_0) \\ 0 & otherwise \end{cases} \tag{2}$$

Since we assume flat fading for each subcarrier, the equivalent received signal of user k on subcarrier m is given by:

$$y_{k,m}(t) = \sqrt{P_{k,m}} H_{k,m} X_{k,m}[l] \exp(j2\pi mt/T) + n_{k,m}(t) \tag{3}$$

$n_{k,m}$ is Additive White Gaussian Noise (AWGN) with two-sided power spectral density N_0.

To detect the signal on subcarrier m, a correlation operation is performed:

$$Y_{k,m} = \frac{1}{T}\int_0^T y_{k,m}(t) \exp(-j2\pi mt/T)dt \tag{4}$$

The noise power can be calculated as $P_N = N_0/T$ and the power for the desired signal is $P_{k,m}|H_{k,m}|^2$.

If bits are modulated by MQAM, from [13], the symbol error rate (SER) can be approximated as:

$$SER \approx 4Q(\sqrt{\frac{3}{M-1}\frac{P_{k,m}|H_{k,m}|^2}{P_N}}) \tag{5}$$

and, for a target SER_t, the transmission rate (number of bits each symbol can carry) $R_{k,m}(P_{k,m}, H_{k,m})$ (in bits/symbol) can be written as a function of transmission power and channel response gain:

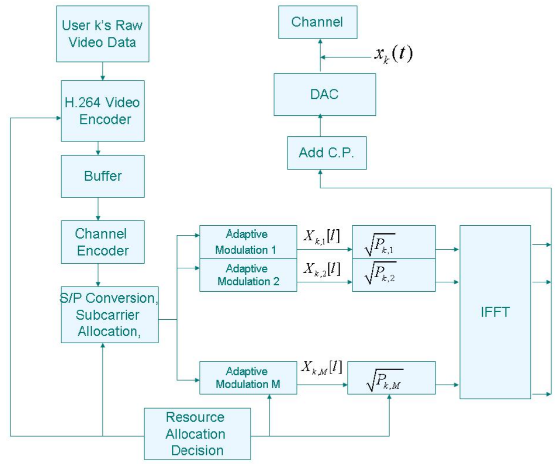

Fig. 1. Uplink OFDMA Video Communication Transmitter Diagram

$$R_{k,m}(P_{k,m}, H_{k,m}) = min\{\lfloor \log_2 \left[1 + \eta P_{k,m}|H_{k,m}|^2\right] \rfloor, R_{max}\} \tag{6}$$

$\eta = \frac{3}{P_N}\left[Q^{-1}\left(\frac{SER_t}{4}\right)\right]^{-2}$ and R_{max} is the largest alphabet size the system allows. The bit rate (in bits/sec) then can be written as: $R_{k,m}(P_{k,m}, H_{k,m})/T_0$.

B. Application Layer Model

Let $D_k^s(R)$ be the rate distortion function of user k in time slot s, where R is the number of bits the encoder generated. For each GOP, the mean square error (MSE) distortion can be approximated as $D_k^s(R) = a_k + \frac{b_k}{R+c_k}$ [19], where a_k, b_k and c_k are constants according to the content of different videos. For video with high complexity (e.g, high motion), the value of b_k would be very large, while for low motion videos, one would expect to see small b_k's. Since the channel slot time is equal to the duration of one GOP, the transmission rate that user k can expect is:

$$\tilde{R}_k = \sum_{m=1}^{M} R_{k,m}(P_{k,m}, H_{k,m})/T_0 \tag{7}$$

The block diagram of the transmitter of the system can be found in Fig. 1. To protect the information data, a channel code of fixed rate u is added. The information data rate which the physical layer channel can support is:

$$R_k = u\sum_{m=1}^{M} R_{k,m}(P_{k,m}, H_{k,m})/T_0 \tag{8}$$

In Section III, we will first ignore the channel errors and use (8) as the channel throughput for our mathematical analysis and algorithm design. The effect of channel errors will be evaluated by simulation in Section V.

C. Cross Layer Optimization Problem Formulation

We assume that each mobile station submits the RD information (a_k, b_k, and c_k) values of the current GOP in its buffer. In addition, we assume that the base station receives perfect CSI for each subcarrier from each user. The cross-layer optimization tries to minimize the sum of distortions of all users. Mathematically, the optimization problem can be written as:

$$\min_{\underline{P}} \sum_{k=1}^{K} \frac{b_k}{c_k + \frac{u}{T_0} \sum\limits_{m=1}^{M} R_{k,m}(P_{k,m}, H_{k,m})} + a_k \tag{9}$$

We also assume that each user has a total power constraint of P_k over all subcarriers, and each subcarrier can only be used by one user, so the feasible solution for this problem should satisfy the following two constraints:

(C1) For $m \in \{1, 2, 3...M\}$, if $\exists k'$, $P_{k',m} \neq 0$, then $P_{k,m} = 0$, $\forall k \neq k'$

(C2) $\sum\limits_{m=1}^{M} P_{k,m} \leq P_k$ For $k \in \{1, 2, 3...K\}$

Unfortunately, this optimization problem is NP-hard. Instead of finding the global optimum, we propose an algorithm for a sub-optimal solution.

III. Iterative Cross Layer Resource Allocation Algorithm Design

To solve the optimization problem defined in (9), we design an iterative algorithm which allows physical layer CSI and application layer RD information to interact with each other. This algorithm first assigns the subcarriers purely based on the channel conditions. However, it is possible that the overall performance (from an average distortion perspective) might be better if we assign some subcarriers to a user with worse channel conditions, but who might need a greater bit rate. We try to reassign one subcarrier to the user with the steepest distortion curve slope. To solve a conventional video multiplexing bit rate allocation problem, a necessary condition for a global optimum is that users are operating at a coding rate with the same slope of their corresponding RD curves [8] [18] . Note that at each iteration we only change the assignment of one subcarrier through a search process. For every subcarrier which is not assigned to the user with the steepest slope, we calculate the distortion loss for the user losing that subcarrier, and the performance improvement for the user with the steepest slope gaining that subcarrier. This calculation is of low complexity because only one subcarrier is involved. We then change the assignment of the subcarrier that can most effectively reduce the overall distortion. We repeat this procedure iteratively until we run out of the possibility of reassigning subcarriers.

We now introduce the following definitions that will be used in the algorithm.

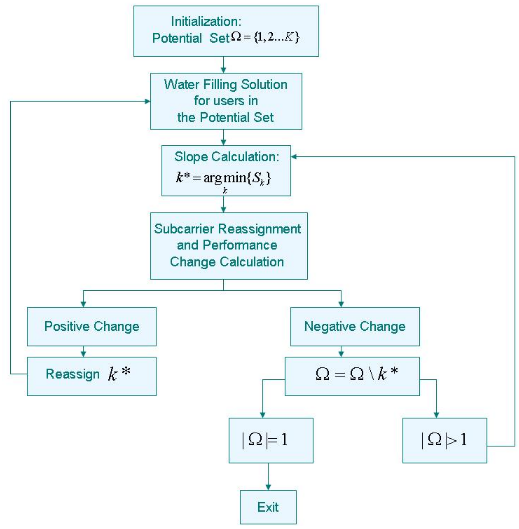

Fig. 2. Algorithm Block Diagram

Definitions:

a) Let $\theta_m^{(i)}$ denote the user who is assigned to use subcarrier m at the i-th iteration. For example, $\theta_2^{(1)} = 3$ means user 3 is assigned to use subcarrier 2 in the first iteration of the algorithm.

b) Define $\mathrm{A}_k^{(i)}$ to be the set of subcarriers assigned to user k at the i-th iteration.

c) Define the Potential Set Ω as the set of users that have the potential to improve distortion by being assigned extra subcarrier(s), and define $|\Omega|$ as the cardinality of the potential set.

d) Define $\Delta_{k,m}$ as the video distortion change of user k by gaining or losing subcarrier m.

Iterative Cross Layer Resource Allocation Algorithm:

Step (1) Initialization:

Initialize $\theta_m^{(0)} = \arg\max_k \{|H_{k,m}|^2\}$ for $m \in \{1, 2, 3...M\}$. Initialize the potential set $\Omega = \{1, 2, 3...K\}$.

We first assign each subcarrier to the user who has the best channel response for that subcarrier, and let the potential set be the total set.

Step (2) Water Filling and Slope Calculation:

After subcarrier assignment, each individual user k solves an MSE distortion minimization problem with a set of subcarriers $\mathrm{A}_k^{(i)}$ as follows:

$$\min_{P_{k,m} m \in \mathrm{A}_k^{(i)}} \frac{b_k}{u \sum\limits_{m \in \mathrm{A}_k^{(i)}} \log_2[1 + \eta P_{k,m} |H_{k,m}|^2]/T_0 + c_k} \tag{10}$$

$$s.t. \sum_{m \in \mathrm{A}_k^{(i)}} P_{k,m} \leq P_k \tag{11}$$

Here, we drop the a_k terms as they are constant with respect to the power.

The optimization problem can be further simplified as:

$$\max_{P_{k,m}, m\in \mathrm{A}_k^{(i)}} \sum_{m\in \mathrm{A}_k^{(i)}} \log_2[1+\eta P_{k,m}|H_{k,m}|^2] \quad (12)$$

The solution to this problem is the conventional power water filling allocation [5]:

$$P_{k,m}^* = [\frac{1}{\lambda_k} - \frac{1}{\eta |H_{k,m}|^2}]^+, \forall m \in \mathrm{A}_k^{(i)} \quad (13)$$

where λ_k can be found numerically to make the sum of the powers equal to P_k. Also, $[x]^+ = x$ if $x > 0$; and $[x]^+ = 0$ if $x \leq 0$. Let

$$r_k^* = \frac{u}{T_0} \sum_{m\in \mathrm{A}_k^{(i)}} \log_2[1+\eta P_{k,m}^*|H_{k,m}|^2] \quad (14)$$

be the optimal rate (in bits/sec) user k can get by using water filling. We then calculate:

$$S_k = \left.\frac{d\frac{b_k}{r_k+c_k}}{dr_k}\right|_{r_k=r_k^*} = -\frac{b_k}{(r_k^*+c_k)^2} \quad (15)$$

which is the slope of each distortion curve evaluated at the rate that the user is assigned. Let

$$k^* = \arg\min_{k\in\Omega}\{S_k\} \quad (16)$$

be the user with the steepest slope in the potential set. This is the user who stands to benefit the most, because he has the largest drop in distortion.

Step (3) Subcarrier Reassignment:

For each subcarrier $m \in \{1,2,3...M\}\backslash \mathrm{A}_{k^*}^{(i)}$ which is not currently assigned to user k^*, calculate the MSE performance gain of the user k^*, $\Delta_{k^*,m} \geq 0$ by acquiring subcarrier m, and the MSE performance loss $-\Delta_{\theta_m^{(i)},m} \leq 0$ of the user $\theta_m^{(i)}$ from losing one subcarrier. In principle, we need to redo the water filling algorithm for any subcarrier reassignment, and the detailed calculation is omitted here for simplicity.

Let $m^* = \arg\max_{m\in\{1,2,3...M\}\backslash \mathrm{A}_{k^*}^{(i)}} (\Delta_{k^*,m} - \Delta_{\theta_m^{(i)},m})$ which maximizes the performance change.

If $(\Delta_{k^*,m^*} - \Delta_{\theta_m^{(i)},m^*}) > 0$, we reassign subcarrier m^* to user k^* at iteration i+1, $\theta_m^{(i+1)} = k^*$, and return to Step (2) to update k^*.

If $(\Delta_{k^*,m^*} - \Delta_{\theta_m^{(i)},m^*}) < 0$, which means that the overall performance will not be increased by reassigning any subcarrier to user k^* , we update the potential set $\Omega = \Omega\backslash\{k^*\}$. User k^* will be dropped from the potential set. This means that user k^* will keep the subcarriers that he has already been assigned, but will not be assigned any additional subcarriers. Next, we check the cardinality of Ω. If $|\Omega| = 1$, we stop, otherwise, we increment the iteration index i and return to step (2) to update user k^*. A block diagram of the algorithm can be found in Fig. 2.

IV. BASELINE ALGORITHM DESIGN

When both physical layer CSI and application layer RD information is available at the base station, the cross layer optimization algorithm iteratively adjusts the resource allocation decision and video encoding rate. To get a perspective as to how much we can gain by the cross layer optimization, in this section we assume that only application layer or physical layer information is collected by the base station, and two baseline resource allocation algorithms are designed for comparison.

A. Application Layer Optimization Algorithm

Suppose that only the RD information of the users is used by the base station for resource allocation. Since the CSI is not used, we assume that all subcarriers choose the same alphabet size of 4-QAM, and the resource allocator decides the number of subcarriers assigned to each user according to the video complexity of different users.

To determine the relative resource needs of each video stream, we first set a target distortion value (e.g. $MSE_t = 100$ which corresponds to a PSNR value of 28 dB). For user k, we then can find the target encoding rate to achieve this target distortion based on the RD curve. The number of subcarriers assigned to user k, n_k, is proportional to this target encoding rate, defined as:

$$n_k \sim M \cdot \frac{r_k}{\sum_i r_i} \quad (17)$$

where M is the total number of subcarriers in the system. The values of n_k's are then obtained as integers by rounding these target values to integers and the sum of n_k's is M. After deciding the number of subcarriers each user will have, the base station then randomly assigns subcarriers to users. For each individual user, the power is equally allocated to each subcarrier. The entire process of application layer optimization algorithm is done without any knowledge of the CSI.

B. Physical Layer Optimization Algorithm

We now assume that only the CSI is used for resource allocation. Let $H_{i,m}$ be the channel response of user i at subcarrier m. Subcarrier m is assigned to the user with the largest $H_{i,m}$, or $\arg\max_i \{H_{i,m}\}$. After subcarrier assignment, every user applies the water filling algorithm to allocate power to the assigned subcarriers, and the video encoding rate is determined by the sum of the rates across the subcarriers.

V. SIMULATION SETTING AND RESULTS

In this section, we present simulation results for the performance of an OFDMA system with a total of 16 subcarriers, each of which has a bandwidth of 50 kHz. The total power constraint for each user is set to be $P_t = 100$ mW, and the noise power density is $-120dB/Hz$. The users are assumed to be all at a constant distance of $80m$ from the base station. The path-loss exponent is assumed to be $\gamma = 2.4$. The channel response consists of both path loss and multipath fading, and the magnitude of the channel can be written as $|H_{k,m}| = \alpha \cdot K_0 \cdot (\frac{d_0}{d_k})^\gamma$ [6]. Here, d_k is the distance between

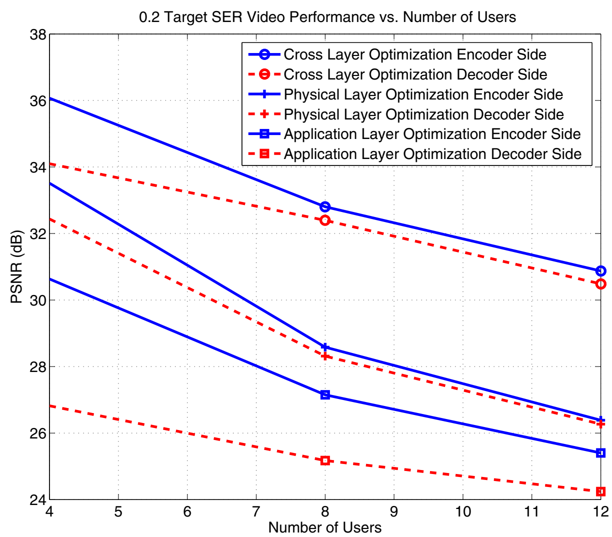

Fig. 3. Average video quality across users vs. number of users when target SER=0.2 and rate 1/2 code is used

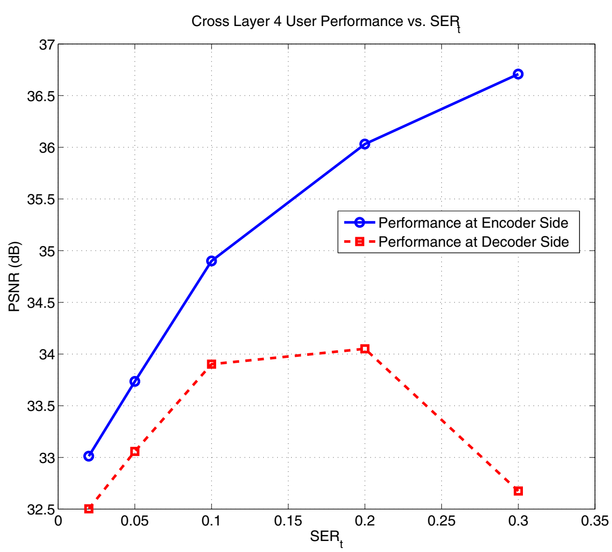

Fig. 4. 4 User Performance Comparison: Encoder Side vs. Decoder Side

user k and the base station. d_0 is a reference distance set to 10m, and K_0 is a constant that is set to be $10^{-2.4}$. In addition, α is a Rayleigh random variable, which is assumed to be independent from one subcarrier to another.

Fig. 3 illustrates typical performance results. The curves correspond to the target symbol error rate $SER_t = 0.2$. For both physical layer and cross layer optimizations, the resource allocations end up with a real number of bits/symbol for rate assignment. This number will then be rounded down to a valid integer value corresponding to a specific modulation alphabet size of MQAM, with M=4, 8, 16, 32, 64, 128 or 256. For example, if the cross layer resource allocation decision assigns a rate of any real value of $R_{1,4} \in [3,4)$ for user 1 at subcarrier 4, the actual alphabet size would be 8-QAM. Due to this roundoff process, the actual raw SER is around 40% of the target SER. In other words, to achieve the target SER for 8-QAM, the power needed is smaller than the result from the resource allocation decision. Note that all three optimization schemes utilize a rate 1/2 convolutional code with constraint length 5 and code generator polynomial of [23, 35] in octal. This code has a free distance of 7, and the coded bits are interleaved across different subcarriers. For example, if one user gets three subcarriers, the first coded bit goes to the first subcarrier, the second coded bit goes to the second subcarrier, etc. For application layer optimization, since we assume that the subcarriers are independently fading, the diversity order should be the minimum of the free distance of the code and the number of subcarriers. On the demodulation side, we use log likelihood ratio demodulation to detect each bit of the MQAM symbol. We then decode the bitstream using soft-decision decoding with eight reliability ranges.

On the application layer side, we use a sequence of CIF videos at a resolution of 352×240 pixels. The video is 50 seconds long and the YUV file consists of 30 frames per second. The video consists of both high motion and slow motion content, and the users are assumed to transmit the same video YUV file cyclicly with different starting points in the cycle. The video streams are compressed by using the baseline profile of H.264/AVC [20] reference software JM 11.0 [1]. The GOP size is 15 frames in an I-P-P-P fashion, and the frames inside one GOP are encoded using H.264 rate control [10]. We encode each GOP at rates of 60, 80, 100, 120, 140, 160, 180, 200, 220, 240, 280, 300, 340, 380, 420, 460, 500, 550, 600, 700, 900 and 1200 kbps, and use these operational points to find the rate distortion function $D(R) = a_k + b_k/(R + c_k)$ by curve fitting offline.

In addition, each video YUV file is source encoded at 10 slices per frame, and any channel error will make the system lose the entire slice. At the decoder side, an error concealment of frame copying will be utilized if a slice loss occurs. To evaluate the quality of the video, we use peak-signal-to-noise ratio (PSNR) in dB, defined as:

$$PSNR = 10\log_{10}\frac{255 \times 255}{\mathbb{E}[MSE]} \tag{18}$$

where $\mathbb{E}[MSE]$ is the average MSE distortion across all the users over all RD and CSI realizations.

We vary the number of users from 4 to 12 in a system of 16 subcarriers, and compare the PSNR performance of three different algorithms. The solid lines are numerical results obtained at the *encoder* using the information of the video encoding rate determined by the resource allocator. Because the quality is being calculated at the encoder side, these curves represent an idealized performance; in particular, there are no channel errors. The dashed lines are bit level simulation results where the bits are passed through the channel and decoded to reconstruct the video. The imperfection of the video coding rate control, as well as the effect of channel errors, are included in the results of the bit level simulation.

When the number of users in the system is small, we see that the performance gap between the cross layer optimization and the physical layer optimization is small, which means that when the system has abundant resources, these two optimization schemes will allow users to operate at a high data rate, or equivalently, in the flat regions of the RD curves. Hence, utilizing cross layer optimization does not improve the overall performance by much. At the other end, if the average resource for each user is small, it becomes crucial to combine the CSI and RD information in the system design. When the system has 12 users, the cross layer optimization outperforms the physical layer optimization by 4 dB, and the gap for the application layer optimization is even larger. If we fix the average PSNR performance at 30 dB, we see that the system utilizing cross layer optimization can support 12 users. With the same resource, the number of users which the physical layer optimization algorithm can support is around 6.

Note that one of the parameters that have to be inputted to the resource allocation algorithm is the target SER, and the performance of the algorithm is sensitive to this value in the following sense: If the target SER is too low, the algorithm becomes overly cautious when choosing an alphabet size, resulting in too few information bits being transmitted. When the target SER is too high, too many errors will be made. This sensitivity to the target SER can be seen in Fig. 4, where the PSNR is plotted for the cross layer optimization case of four users competing for resources when there are 16 subcarriers available. We vary the SER_t and compare the performance of the error-free case on the encoder side and the actual reconstructed performance at the decoder side. We see that the ideal, error-free system performance will improve monotonically with increasing SER_t since the system would choose a larger alphabet size as the target SER is allowed to increase. The best performance for the non-ideal case occurs with $SER_t = 0.2$. Because of rounding, actual SERs are noticeably smaller than target SERs.

VI. Conclusion

In this paper, we proposed a cross layer iterative resource allocation algorithm for transmitting video in an uplink multiuser OFDMA setting. The power allocation and subcarrier assignment strategy is jointly determined by each user's channel state information and rate distortion characteristic. Compared with the resource allocation algorithms using only either application layer information or physical layer information, with the same video performance, the cross layer optimization can yield a significant increase in the capacity of the system. When the number of users in the system is small, or when the bandwidth for each user is abundant, the cross layer optimization will only slightly outperform either physical layer optimization or application layer optimization. However, the advantage of using cross layer optimization is significant when the number of users is large relative to the resources.

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