

# Pricing-based Rate Control and Joint Packet Scheduling for Multi-user Wireless Uplink Video Streaming

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**Abstract:** Video streaming is becoming an important application in wireless communications. In this paper, we consider a cross-layer design approach for uplink video streaming in a single CDMA. We propose a two-stage resource allocation scheme, which includes a price-based rate control algorithm and TDM-based GREEDY scheduling algorithm. In the rate control algorithm, the base station announces a price for the rate, and the mobile users independently choose their average rate by performing optimal content-aware video summarization based on both the price and their utility functions. The base station then performs TDM-based GREEDY scheduling based on the deadlines of the summary frames, and adjusts the price if it is not schedulable. Simulation results show that it significantly improves the network utility compared with the constant rate transmission scheme.

**Key words:** video streaming, pricing, uplink communications, CDMA, cross-layer design, video summarization

## 1. INTRODUCTION

Video streaming over wireless networks is becoming one of the major driving forces for the next generation wireless networks. For the currently deployed cellular networks, the practical data rates are not enough to support full rate, high quality video applications. As a result, many research efforts have been devoted to adapting video content to reconcile the conflict between the high demand of video quality and the limited wireless communication resources among users. A large body of literature utilizes the cross-layer approach, which jointly designs the video coding in the application layer and the resource allocation in lower layers, e.g., [Shan05], [Zhang05], [Schaar03], [Zheng03], [Yoo04], [Zhao02] and [Khayam03], and the references therein.

To ensure the quality of real-time video streaming, smart video coding techniques need to be performed at the application layer to meet the stringent resource constraints at lower layers. Simply coding the video sequences at very low bit rates with content-blind rate control will result in high quantization errors in video frames that are unpleasant to viewers. Instead, a better solution is to perform content-aware video coding, via summarization, which selects a subset of video frames that best represent the sequence, and encodes them at a higher quality.

Various summarization techniques have recently been reported such as in [Liu05], [Li05a], and [Li05b]. The actual adaptation can be achieved through either transcoding or bit stream extraction from scalable video.

In terms of cross-layer design with lower layers, here we follow the approach of “layering as optimization decomposition”, where the network protocols are analyzed and systematically designed as distributed solutions to some global optimization problems in the form of Network Utility Optimization (NUM). This approach provides insight into what the protocols optimize and structures of the network protocol stack. Here each layer corresponds to a decomposed subproblem of the original NUM, and the interfaces among layers are quantified as functions of the optimization variables coordinating the subproblems. This approach has been successfully used to study various cross-layer optimization problems, such as TCP/PHY interaction [Chiang05b] and TCP/IP interaction [Wang03]. This paper attempts to utilize the same framework to jointly design and optimize the application layer (video coding), transport layer (rate control) and data link layer (scheduling) for a multiple user video session.

In the previous work on multi-user uplink video streaming at very low bit rate [Li05c], we try to con-

control the admissible rate profile by iteratively adjusting peak rate and average rate among video users. The drawback is that the convergence is not guaranteed in that approach.

The pricing-based optimization algorithm has been successfully used in resource allocation for elastic data traffic in both wire-line networks [Kelly98], [Lee06] and wireless networks [Sara02], [Zhang01], [Lee02], and [Huang04]. In our previous work [Li05d], we have shown that a pricing-based approach combined with smart video summarization techniques can greatly improve the performance of multi-user wireless downlink video transmissions. In this work, we continue to tackle the problem of video streaming for CDMA-based wireless uplink transmissions, which is more difficult due to the interference-limited nature of the uplink channels. The scheduling part of this paper is motivated by the intuitions derived in [Kumaran03], which implies that large user with high power needs to be served one at a time. Simulation shows that our proposed algorithm achieves very good performance under both deadline and total transmission time constraints, and achieves a good balance between the video distortion and system performance.

The paper is organized as follows. We first introduce the system model in Section 2, and review the main results from [Kumaran03] in Section 3. Then we describe the two-stage resource allocation algorithm in Sections 4 and 5, which includes price-based rate control and Time-division-multiplexing (TDM) based greedy scheduling. Simulation results are shown in Section 6, and we conclude in Section 7.

## 2. SYSTEM MODEL

The uplink capacity for the wideband CDMA system is interference limited [Tse05]. In the case of mixed voice and streaming video uplink transmissions, the objective is to provide the best possible Quality of Service to the video users, without interrupting the transmissions of voice users. This could be translated into a total received power constraint of the video users at the base station as explained next.

Consider a single CDMA cell with a set of  $M$  voice users and  $N$  video users. Each voice user  $i$  needs to achieve a target SINR level at the base station,

$$\frac{W}{R_{voice}} \frac{P_{i,voice}}{n_0W + P_{video} + \sum_{1 \leq j \leq M, j \neq i} P_{j,voice}} \geq \gamma_{i,voice}, \quad (1)$$

where  $W$  is the channel bandwidth,  $R_{voice}$  is the common transmission rate for each voice user,  $P_{i,voice}$  is the received power of voice user  $i$ ,  $n_0$  is the background noise density (including both thermal noise and intra-cell interference), and  $P_{video}$  is the total received power from all video users. Here we assume BPSK modulation for the voice users, i.e., transmitting 1 bit for every channel use. Under the assumption of perfect power control among voice users, we denote  $P_{i,voice} = P_{i,voice}$  and  $\gamma_{i,voice} = \gamma_{i,voice}$  for any voice user  $i$ . Following a similar derivation as in [Sampath95], we can show that voices users' SINRs targets are feasible if

$$\frac{M\gamma_{voice}}{W/R_{voice} + \gamma_{voice}} + \frac{\gamma_{voice}}{W/R_{voice} + \gamma_{voice}} \frac{n_0W + P_{video}}{\min_i \{\bar{P}_{i,voice}\}} \leq 1, \quad (2)$$

where  $\bar{P}_{i,voice}$  is the peak received power from voice user  $i$ , which is determined by the user's individual peak transmission power constraint and path loss to the base station. Given the values of  $\{\gamma_{voice}, \min_i \{\bar{P}_{i,voice}\}\}$ , we can then calculate the maximum value of  $P_{video}$  that satisfies (2), denoted as  $P_{max}$ . This is the maximum total received power constraint from all video users in the cell.

In practice, the value of  $P_{max}$  could change over time to reflect the load change of voice users in the cell. Here we only focus on resource allocation during a single time segment  $[0, T]$ , which corresponds to the time window during which users perform one round of video coding and summarization. The typical value of  $T$  is around 3 secs, which is sufficient short to assume that the voice load and  $P_{max}$  do not change much.

Given the value of  $P_{max}$ , we want to determine the received power function at the base station,  $P_j(t)$ , of each video user  $j$ , during time  $[0, T]$ , such that the total users' utility as function of received video quality is maximized.<sup>1</sup> The Network Utility Maximization (NUM) is

<sup>1</sup> All entities without subscript *voice* are used to denote video users.

$$\begin{aligned} & \max_{P_j(t) \geq 0, 1 \leq j \leq N} \sum_{j=1}^N U_j \left( \int_0^T R_j(t) dt \right), \\ & \text{s.t.} \sum_{j=1}^N P_j(t) \leq P_{\max}, \forall t \in [0, T] \end{aligned} \quad (3)$$

Here  $R_j(t)$  is the rate achieved by user  $j$  at time  $t \in [0, T]$ , and in general is a function of the received power allocation of all users,  $\mathbf{P}(t) = [P_1(t), \dots, P_N(t)]$ .  $U_j$  is the utility of user  $j$  and is an increasing and strictly concave function of the total rate achieved during time  $[0, T]$ . (An example of the utility function will be given in Section 4.) Here we assume that each video user can achieve a peak received power equal to  $P_{\max}$ .

Due to the time-varying nature of the video streaming contents, the optimal solutions of (3) are time-varying functions as well. Together with the fact that the utility functions  $U_j$  usually do not have analytical forms, finding the optimal solutions of (3) is quite difficult. In this paper, we propose a two-stage resource allocation algorithm that tries to approximately solve problem (3). The algorithm is based on the intuition derived from [Kumaran03], where uplink users with large peak received power should be scheduled one-at-a-time to avoid severe interference. Main results of [Kumaran03] will be reviewed in Section 3.

### 3. OPTIMAL SCHEDULING FOR DATA TRAFFIC WITHOUT DEADLINES

The authors in [Kumaran03] consider a scheduling problem in CDMA uplink transmissions with data traffic. The goal is to find the optimal schedule to maximize a total weighted rate  $\sum_j Q_j R_j(t)$  at each time  $t$ , where  $Q_j$  is a priority coefficient of user  $j$ .

In the optimal algorithm derived in [Kumaran03], the base station should schedule “strong” users to transmit one-at-a-time, and “weak” users to transmit simultaneously in larger groups. Here a “strong” user  $i$  has a high peak received, and a “weak” user  $i$  has a low peak received power. The intuition is the following: the transmission of a strong user generates large interference to any other user transmitting simultaneously, so it is better to let such users transmit one-at-a-time. On the other hand, a weak user only generates small interference, thus simultaneous transmissions of multiple weak users will improve the total weighted rate.

The algorithm proposed in [Kumaran03] can not be used directly in our case since it does not consider the deadline constraints encountered in real-time video streaming.<sup>2</sup> However, the intuitions on strong/weak users are still applicable here. Since we assume that each video user can achieve a peak received power of  $P_{\max}$ , this means we are trying to schedule a group of “strong” users for the uplink transmissions.<sup>3</sup> Then it might be beneficial for the base station to schedule the video frames transmissions one at a time, i.e., in a time division multiplexing (TDM) manner to avoid strong mutual interferences. Here interferences from the voice users are treated as part of the background Gaussian noise. As a result, received power from any of the active transmitting video user will be equal to  $P_{\max}$ , and the total length of the transmission (may not be contiguous transmission) has a direct relationship to the achievable rate of each user within the time segment, i.e.,

$$\int_0^T R_j(t) dt = R_{TDM} l_j, \quad (4)$$

where  $R_{TDM}$  is the transmission rate achieved under TDM assumption, and  $l_j$  is the length of active transmission time of user  $j$  during time segment  $[0, T]$ , such that  $\sum_j l_j \leq T$ .

In the next two sections, we will explain the proposed two-stage resource allocation algorithm in detail. In the first stage of pricing-based rate control, the base station announces a price that represents the cost of per unit uplink transmission time. Based on this price, users perform optimal video source summarization and calculate the corresponding total desirable rates. The rates are fed back to the base station, and the price is adjusted such that the resource constraint is tight, i.e.,  $\sum_j l_j = T$ . In the second stage of TDM-based GREEDY scheduling, the base station schedules users’ frames in the increasing order of delivery deadlines. If the deadlines of one or more frames are violated, then base station increases price until the resulting summary video frames become schedulable.

<sup>2</sup> Although it is possible to reflect the deadline constraints by adjusting the priority coefficients, it is difficult to guarantee the feasibility for hard deadline constraints considered here.

<sup>3</sup> If a video user can not reach a high enough received power level, then it is better for him to handoff to a closer base station to achieve better Quality of Service.

#### 4. STAGE I – PRICING BASED RATE CONTROL

In the first stage, we aim at allocating averaged transmission rate among users to maximum total utility. The delivery deadlines of video frames will be considered in the second stage. Based on the discussion above, we can rewrite (3) in the following form

$$\max_{l_j \geq 0, 1 \leq j \leq N} \sum_{j=1}^N \tilde{U}_j(l_j), \text{ s.t. } \sum_{j=1}^N l_j \leq T, \quad (5)$$

where

$$\tilde{U}_j(l_j) = U_j(R_{TDM} l_j) \quad (6)$$

Problem (5) could be solved by the standard dual decomposition technique. First relax the total time constraint by associating it with a dual price,  $\lambda$ , and then solving problem (5) is equivalent to maximizing the following Lagrangian, i.e.,

$$\max_{\{l_j\}} J(\mathbf{l}, \lambda) = \sum_{j=1}^N \tilde{U}_j(l_j) - \lambda \left( \sum_{j=1}^N l_j - T \right), \quad (7)$$

for some optimal nonnegative value  $\lambda$ . Here  $\mathbf{l} = [l_1, \dots, l_N]$ .

Given fixed value of  $\lambda$ , Eq. (7) can be solved by each video user in a distributed fashion. Each user  $j$  will find an optimal value of  $l_j(\lambda)$  such that

$$l_j(\lambda) = \arg \max_{l_j} (\tilde{U}_j(l_j) - \lambda l_j) \quad (8)$$

Since the utility in this case is defined on the adapted video quality in terms of summarization distortion level, user  $j$  chooses an optimal subset of frames coded at a pre-determined PSNR quality level to maximize the payoff function in Eq. (8) as described next.

Let a source video segment of  $n$  frames be denoted by  $V = \{f_0, f_1, \dots, f_{n-1}\}$ , and its video summary of  $m$  frames by  $S = \{f_{i_0}, f_{i_1}, \dots, f_{i_{m-1}}\}$ , where  $m \leq n$ . After receiving  $S$ , the receiver reconstructs the sequence as  $V_S' = \{f_0', f_1', \dots, f_{n-1}'\}$  by substituting the missing frames with the most recent frame that is in the summary  $S$ . The video summary quality, which is defined as the average distortion caused by the missing frames, is given as,

$$D(S) = \frac{1}{n} \sum_{k=0}^{n-1} d(f_k, f_k') \quad (9)$$

where  $d(f_k, f_k')$  is the distance between the  $k$ th original frame and the constructed frame. Therefore, the op-

timization problem in (8) can be transformed into the problem of summarization with a price on total transmission time,

$$S_j^*(\lambda) = \arg \min_{S_j} D(S_j) + \lambda l_j(S_j) \quad (10)$$

where the total transmission time  $l_j$  is a function of the resulting video summary bit rate. Eq. (10) can be solved with a Dynamic Programming (DP) approach at the video sources, more detail can be found in our energy efficient video summarization work in [Li05b].

We can verify through experiments that the distortion  $D(S_j)$  is a decreasing and strictly convex function in terms of the total rate achieved by  $S_j$ . As a result, the utility  $U_j$  is an increasing and strictly function in the rate, so is  $\tilde{U}_j(l_j)$  in transmission time  $l_j$ . An example of the rate-distortion tradeoff curve is plotted in Figure 1, where the video sequence corresponds to frames 150-239 from the ‘‘foreman’’ sequence. The per frame distortion is averaged over all 90 frames.

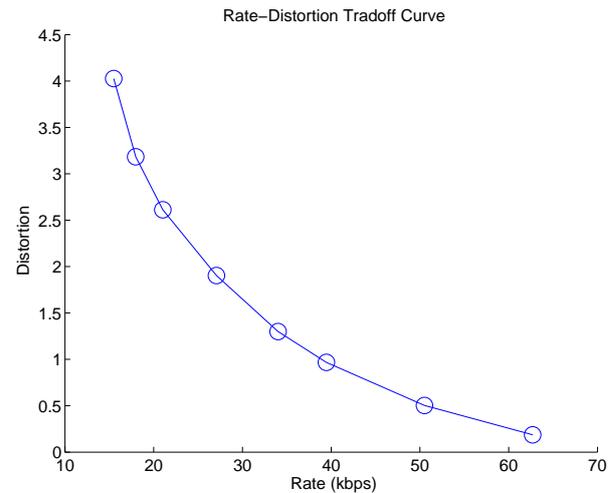


Figure 1: Rate-distortion tradeoff curve of frames 150-239 from the ‘‘foreman’’ sequence in a 3 sec time segment

Once  $S_j^*(\lambda)$  is found, the corresponding transmission time  $l_j(S_j^*(\lambda))$  can be computed assuming a rate of  $R_{TDM}$ . Each user  $j$  sends the value of  $l_j(S_j^*(\lambda))$  to the base station, which wants to solve the following dual problem

$$\max_{\lambda \geq 0} J(\mathbf{l}(\lambda), \lambda), \quad (11)$$

This can be solved by a subgradient method, where the subgradient is determined by the level of violation of the resource constraint. To be specific, the price  $\lambda$  could be updated according to the following,

$$\lambda^{i+1} = \max \left\{ 0, \lambda^i + \alpha^i \left[ \sum_{j=1}^N l_j(S_j(\lambda^i)) - T \right] \right\}. \quad (12)$$

where  $\alpha^i$  is the step-size at price iteration  $i$ . In (12), if the requested total transmission time is larger than  $T$ , the price is revised up in the next iteration and vice versa for the case when requested total time is below  $T$ .

**Proposition 1:** *If the step-sizes satisfy  $\lim_{i \rightarrow \infty} \alpha^i = 0$  and  $\sum_i \alpha^i \rightarrow \infty$ , then updates (8) to (12) converge to the optimal solution of problem (5).*

The proposition can be shown by similar techniques [Srikant04] and is omitted here.

During stage I, we vertically decompose the NUM problem in (3) into video summarization problem (7) that can be solved in the application layer, and rate control problem (11) that can be solved in the transport layer. Furthermore, horizontal decomposition is used such that problem (7) can be solved in a distributed fashion by letting each video user solve a subproblem (8).

Let's denote the price that corresponds to the optimal solution of (5) as  $\lambda^*$ , then the resulting  $\{S_j(\lambda^*)\}$  or  $\{l_j(\lambda^*)\}$  are just indication of the resource consumption levels for delivering certain level of utility for each user. The actual transmission schedule of individual frames is computed by the scheduling algorithm in the stage II.

## 5. STAGE II – TDM GREEDY SCHEDULING

To ensure the satisfying reception of the video streaming application, each video summary frame has to be delivered to the receiver before a certain deadline. The deadline is typically determined as follows. The first frame of each video clip is intra-coded, thus has to be included in the summary and typically has a large size. Since the receiver end can not play the video clip until the first frame is received, an initial delay that is large enough to transmit the first frame needs to be added. Thus the actual deadline requirements of the summary frames are sum of the initial delay and their positions in the original clip. The pricing-based rate control algorithm leads to an “optimal” averaged rate allocation without considering the deadlines of video summary frames. The TDM GREEDY scheduling algorithm targets at meeting all the deadline requirements.

Assume all video frames from different users to be transmitted in time segment  $[0, T]$  are available at time 0, and the video users communicate the individual frame sizes and deadlines to the base station. The GREEDY algorithm works as follows. The base station first sorts the frames in the increasing order of the delivery deadline. Assume the  $k$ -th frame has a frame size and deliver deadline  $\{B^k, T^k\}$ . The base station transmits the frames one-at-a-time, with constant rate  $R_{TDM}$ , such that the video SINRs meet the target value

$$\frac{2W}{R_{TDM}} \frac{P_{\max}}{n_0 W + MP_{\text{voice}}} \geq \gamma_{\text{video}}, \quad (13)$$

Here we assume QPSK modulation for the video transmission, such that each channel use transmits 2 bits of information. The transmission time of the  $k$ th packet will then be determined by  $B^k/R_{TDM}$ . Although the GREEDY algorithm is simple, it is optimal among all TDM-based algorithms:

**Proposition 2:** *If any TDM-based scheduling algorithm can meet the deadlines of all video frames, the GREEDY scheduling algorithm also can.*

Proposition 2 can be proved as follows: pick any TDM-based scheduling algorithm where all deadlines are met and one or more packets are transmitted out of the deadline order. Then by rearranging the corresponding out of order packets by the deadline as in the GREEDY algorithm, all the deadline constraints are still satisfied. Detailed proof is omitted here.

It is also not difficult to show that if no TDM-based scheduling algorithm can meet all deadline constraints, then the GREEDY algorithm incurs the least deadline violation. To formally state the result, let us define

$$\Delta^\Pi = \max_k (T_\Pi^k - T^k) \quad (14)$$

as the maximum delay violation under TDM-based scheduling policy  $\Pi$ , where  $T_\Pi^k$  denotes the actual delivery time of the  $k$ th packet under TDM-based algorithm  $\Pi$ . If  $\Delta^\Pi(\lambda) \leq 0$ , then all deadline constraints are met. Then we have

**Proposition 3:** *Among all the TDM-based scheduling algorithms, the GREEDY algorithm yields the smallest value of  $\Delta^\Pi$ .*

In fact, Proposition 2 is just a special case of Proposition 3, and the same proof technique can be generalized to prove the latter.

In the case of  $\Delta^{\text{GREEDY}} > 0$ , the base station needs

to increase price so that video users request less rate. One way of adjusting price is the following

$$\lambda^{i+1} = \max\{0, \lambda^i + \beta \max\{\Delta^{GREEDY}(\lambda^i), 0\}\}, \quad (15)$$

where  $\beta$  is a small step-size. In other words, the price is increased until the resulting frame sequences are schedulable (i.e., all deadline constraints can be met under GREEDY algorithm). There is a tradeoff between the value of  $\beta$  and convergence speed. If  $\beta$  is large, then the schedulability will be achieved by one or two adjustments; however, a significant portion of the time segment  $[0, T]$  might be wasted. If  $\beta$  is small, then it might take a longer time to achieve schedulability, but the resource utilization will be high.

## 6. SIMULATION RESULTS

We demonstrate the effectiveness of our two-stage resource allocation algorithm through simulations. We choose four different video clips with different content activity levels, similar as in [li05d]. Clips 1 and 2 are segments from the “foreman” sequence, frames 150-239 and frames 240-329, while clips 3 and 4 are frames 50-139 and 140-229 from the “mother-daughter” sequence, respectively. In other words, there are 90 frames within each video clip with frame sampling frequency of 30Hz, which corresponds to a time segment of  $T=3$ secs. Besides the GREEDY scheduling algorithm, we also simulate a constant rate transmission algorithm, where all four video users are allowed transmitting simultaneously with the same rate. The simulation parameters are listed in Table 1.<sup>4</sup>

Item	Symbol	Value
Bandwidth	$W$	1.228MHz
Noise density	$n_0$	$8.3 \cdot 10^{-7}$ mW/Hz
Number of voice users	$M$	28
Voice target SINR	$\gamma_{voice}$	6dB
Voice modulation		BPSK
Voice received power	$P_{voice}$	1mW
Voice spreading gain	$G_{voice}$	128
Voice transmission rate	$R_{voice}$	9.6kbps
Video target SINR	$\gamma_{video}$	6dB
Video modulation		QPSK

<sup>4</sup> While choosing the transmission rate  $R_{TDM}$  and  $R_{CR}$ , we insure that the spreading gains in both cases, which are defined by  $2W/R_{TDM}$  and  $2W/R_{CR}$ , to be powers of 2.

Maximum video received power	$P_{max}$	4mW
Video transmission rate under GREEDY algorithm	$R_{TDM}$	76.8kbps
Video transmission rate under constant rate transmission	$R_{CR}$	19.2kbps

Table 1 Simulation Parameters

First consider the pricing-based rate control algorithm. Based on the assumption of TDM scheduling, pricing on transmission time is equivalent to pricing on the achievable rate. Starting from an initial price  $\lambda=0.01$  with constant step-size  $\alpha=0.01$ , the pricing converges in 4 iterations, with final price  $\lambda^*=1.08 \cdot 10^{-2}$ , and a total transmission time  $\sum_j l_j = 2.98$  secs, i.e., achieving around 99% of the maximum allowable transmission time 3sec. The changes of price, total summary distortion of all four users, and the total transmission time is shown in Figure 2. As we can see, with the decrease of price, the total distortion decreases due to the increase in transmit time (i.e., rate).

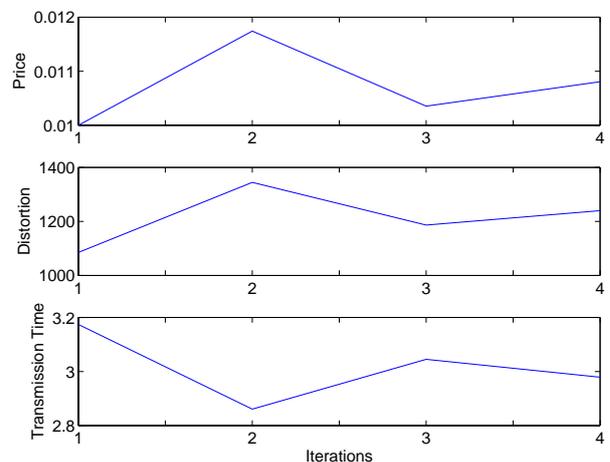


Figure 2: Pricing-based rate allocation

In general, the convergence speed of the pricing algorithm depends on the video contents, the initial price and the choice of step-size. The latter two parameters can be chosen to match the statistical properties of the video contents transmitted in the past. In practice, it is usually good enough to achieve partial convergence (e.g., stops when the total transmission time is above a certain percentage of the maximum allowable time), in order to improve the convergence

speed and avoid unschedulable summary results in stage II.

The resulting video summary distortions based on the optimal price  $\lambda^*$  are plotted in Figure 3. The vertical arrows indicate video summary frame locations in the sequence. Notice that the distortion is zero at summary frame locations. The optimal pricing gives a good tradeoff between total transmitting power and total video summary distortion. Clips 1 and 2 are coded at an average PSNR of 27.8dB, and clips 3 and 4 at 31.0dB. The resulting average bit rates for 4 clips are 15.50, 43.74, 7.67 and 9.34kbps, respectively.

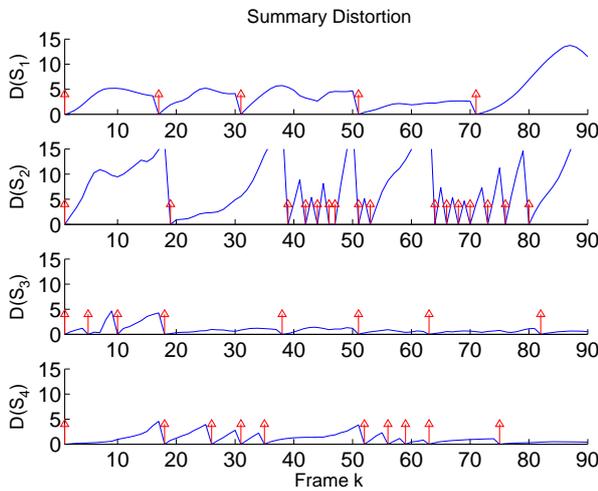


Figure 3: Resulting video summary distortion at the optimal pricing

Based on the summarization results, the GREEDY algorithm performs scheduling based on sorted packet deadlines. The received power from each user over time as the result of the GREEDY algorithm is plotted in Figure 4, and the resulting delivery times of summary frames are plotted in Figure 5. Under an initial delay of 31 frames, the GREEDY algorithm successfully transmits all packets within 3 secs and meets all deadline requirements. As discussed in section 5 the choice of initial delay guarantees that all four initial frames of the users are delivered successfully. In practice, the initial delay can only be chosen at the beginning of the first time segment of the entire video sequence, so it is important to correctly estimate the sizes of the first frames of each time segment and choose a tight initial delay value.

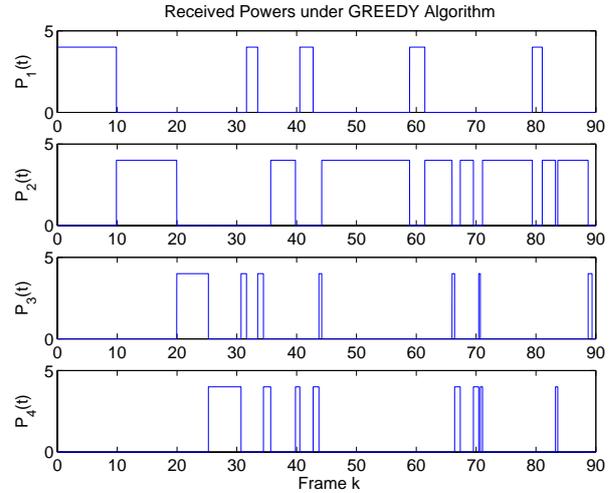


Figure 4: Video users' received powers at the base station under GREEDY scheduling algorithm (power is measured in mW)

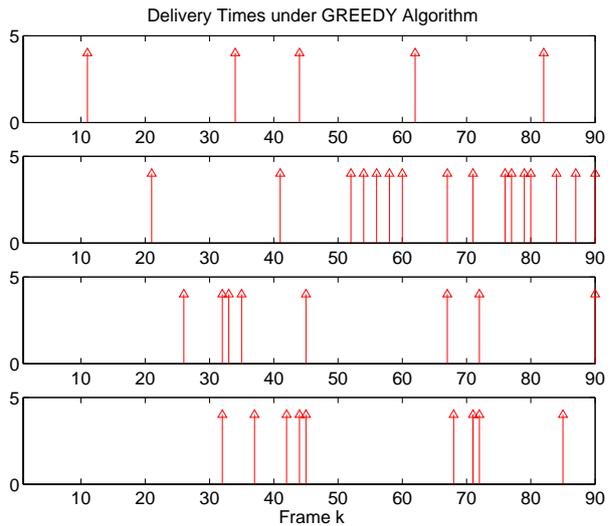


Figure 5: Frame delivery times under GREEDY scheduling algorithm

As we mentioned in Section 5, if the current summary frames can not be scheduled (i.e., deadline violation occurs), then the base station needs to increase the price and let the users re-compute the summarization. However, in all the simulations that we perform, the summarization result from the pricing-based rate control is always schedulable under a feasible and tight initial delay. This is due to the fact that by taking advantage of the multi-user content diversity, the deadline requirements of the summary frames are typically spread out through the time segment, thus is relatively easy to satisfy. This implies that as long as there are enough content differences among the video users, the two stages of the algorithm

can actually be operated separately in practice. This avoids unnecessary iterations among the two stages and ensures fast convergence of the algorithm.

For comparison purpose, we also simulate a constant rate transmission algorithm, where all four video users are allowed to transmit simultaneously. Each video user can only generate a received power of 1mW at the base station. The base station can only guarantee a constant rate of 19.2kbps for each user, so that each user meets the target SINR constraint of  $\gamma_{video}=6dB$ . All other system parameters are the same as in the GREEDY case, as shown in Table 1. Due to the unbalanced loads of the video users, the constant rate transmission scheme leads to a maximum of 95 frames of deadline violation, under the same 31 frames initial delay relaxation. The resulting packets delivery times are shown in Figure 6. Notice that user 2 needs more than 190 frames to finish transmitting all its summary frames.

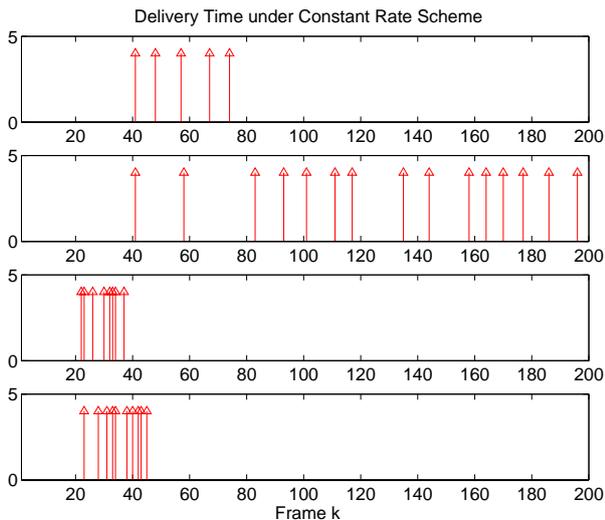


Figure 6: Frame delivery times under constant rate transmission scheme

It can be shown that by ensuring the same transmission rate for each user, the total rate achieved by all users can only stay the same or decrease compared with the TDM case. Moreover, since no multi-user diversity is taken into account in the content-blind constant rate transmission scheme, a video user with very busy contents (e.g., user 2 here) typically suffers most and incurs the largest deadline violation. Since in practice all frames that can not be delivered within the time segment (i.e., 3 secs) will be discarded, then the constant rate transmission scheme will lead to a much worse video quality than the

GREEDY algorithm.

## 7. CONCLUSION AND FUTURE WORK

In this paper, we consider a cross-layer design approach for uplink video streaming in a single CDMA. The application layer (video coding), transport layer (rate control) and data link layer (scheduling) are jointly optimized. We propose a two-stage resource allocation scheme, which includes a price-based rate control algorithm and TDM-based GREEDY scheduling algorithm. In the rate control algorithm, the base station announces a price for the rate, and the mobile users independently choose their average rate by performing optimal content-aware video summarization based on both the price and their utility functions. In other words, the operations in the application layer (video coding and summarization) and transport layer (rate control) are coupled only through a single price signal. In the data link layer, the base station performs TDM-based GREEDY scheduling based on the deadlines of the summary frames, and adjusts the price if it is not schedulable. Simulation results show that it significantly improves the network utility compared with the constant rate transmission scheme. This work is another step towards understanding the “layering as optimization decomposition” framework [Chiang05a] for cross-layer design in communication networks.

One might imagine other content-aware scheduling algorithms that lie between the TDM scheme and the constant rate transmission scheme. For example, we can schedule a subset of video users to transmit simultaneously. Due to the time-variant nature of the video frames, we need to divide the time segment  $[0, T]$  into several sub-segments, and calculate the corresponding active user subset for each sub-segment. Then for each subset, the corresponding transmit power can be determined using techniques discussed in the literature, e.g., [Yates95]. It is clear to see that such algorithm would be much more computationally complex than the GREEDY algorithm, and might not be suitable for online scheduling. However, finding an efficient algorithm along this direction could still be an interesting research topic for future exploration.

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