PRICING BASED COLLABORATIVE MULTI-USER VIDEO STREAMMING OVER POWER CONSTRAINED WIRELESS DOWNLINK

[1,3]Zhu Li, [2,3]Jianwei Huang, and [3]Aggelos K. Katsaggelos

[1]Multimedia Research Lab (MRL), Motorola Labs, Schaumburg, Illinois, USA
[2]Dept of Electrical Engineering, Princeton University, Princeton, New Jersey, USA
[3]Dept of Electrical Engineering & Computer Science, Northwestern University, Evanston, Illinois, USA

ABSTRACT

Video streaming is becoming an important application in wireless communications. In a typical scenario, a base station needs to serve multiple video users with a total transmitting power constraint. How to make appropriate video coding decisions and allocate limited transmitting power among users to achieve optimal total utility is an important problem. In this paper we develop a pricing based downlink power allocation scheme with collaborative video summarization among users. The scheme exploits the multi-user diversity in channel states and utility-resource tradeoff characteristics in video contents to achieve better resource utilization. The computational burden can be distributed among video sources and base station. Simulation results demonstrate the effectiveness of the proposed algorithm.

1. INTRODUCTION

Serving mobile users with wireless video contents has been one of the driving forces in video coding and wireless communication research. Many efforts have been made trying to achieve better video quality and more efficient communication resource utilization in wireless video communication, e.g., [6, 9, 11, 12].

The demand for video quality needs to be reconciled with the limited communication resources, especially for the currently deployed wideband wireless network, where the practical achievable data rate for video users is still very low. The video coding decisions need to be carefully coordinated with the communication resource allocations to achieve better efficiency.

Pricing has been recently used in allocating resources in wireless networks. Examples of related literature include power allocation in CDMA uplink transmissions [7] and downlink transmissions [2, 10], as well as spectrum sharing models in licensed radio bands [1]. However, most previous work focus on either voice users or rate adaptive data users, and the developed techniques do not apply directly to the case of multimedia communications as considered here.

Under limited communication resource, the optimal video coding problem is very challenging, especially in the low bit rate case as we consider here. Instead of sending all video frames with severe quantization distortions as most previous work did, a better way of solution is through video summarization, [3, 4], i.e., select a subset of video frames that best represent the sequence, and encode them at a higher quality than what is possible under a content-blind rate control scheme. We have developed a summarization based solution for the interference-limited uplink problem for a low bit rate case in [5].

In the down link wireless video problem with total transmission power constraint, video sources need to make frame selections and coding decisions, base station needs to allocate powers among users such that the total end-to-end user utility is maximized under the power constraint. In this paper, we develop a two-tier algorithm to achieve this. First, video sources and base station collaboratively find an optimal *average* power allocation for a sliding time window on video contents, with distributed video summarization and pricing. Then base station computes the actual transmit power for each user over the sliding window with content aware joint scheduling.

The paper is organized as follows. In Section 2, we develop the pricing based video summarization and power allocation algorithm that achieves the socially optimal solution. In Section 3, we discuss the packet scheduling problem and develop a water-filling power scheduling solution. Simulation results are presented in Section 4, and we draw conclusion remarks and outline our future work in Section 5.

2. PRICING AND VIDEO SUMMARIZATION FOR POWER ALLOCATION

In a scenario where multiple video traffics are served in a wireless downlink with a total power constraint, instead of provisioning a constant bit rate channel for each user, which is rather wasteful, multi-user diversity in channel states and video contents can be exploited. The goal is to determine the transmitting power function, $P_j(t)$, of each user j, for a time segment, $[0, T]$, such that the total user utility as function of the received video quality is maximized. The first step is to compute the average power allocations among video users. This *base station problem* is expressed as,

$$\max_{P_1,P_2,\cdots,P_n} \sum_{j=1}^{n} U_j(P_j), s.t. \sum_{j=1}^{n} P_j \le P_{\max}, P_j \ge 0 \quad (1)$$

where n is the total number of video users, U_j is the utility function for user j, reflecting the utility derived from the video quality received by consuming transmitting power at level P_j during the time segment. The utility function is assumed to be continuous, increasing and strictly concave. P_{max} is the total down link power constraint for the video traffic in the current window. The value of P_{max} may change over time to reflect the voice traffic load on the base station. The optimal solution to Eq. (1) can be found by maximizing the Lagrangian,

$$J(\lambda) = \max_{P_1,P_2,\cdots,P_n} \sum_{j=1}^{n} U_j(P_j) - \lambda(\sum_{j=1}^{n} P_j - P_{\max}), \quad (2)$$

for some optimal non-negative λ. The optimization in Eq. (2) can be achieved in a distributed, iterative fashion by charging each video source a price for its power consumption, λ^i, in iteration i, and let each user solve for the *video source problem*,

$$P_j^i = \max_{P_j} U_j(P_j) - \lambda^i P_j. \quad (3)$$

The utility U_j in this case is defined on the video summarization quality. Let a video segment of n frames be denoted by $V=\{f_0, f_1, \ldots, f_{n-1}\}$, and its video summary of m frames by $S=\{f_{l_0}, f_{l_1}, \cdots, f_{l_{m-1}}\}$, where $m \le n$. At the receiver side, reconstruct the sequence as $V_S' = \{f_0', f_1', \cdots f_{n-1}'\}$ 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,

$$D(S) = \frac{1}{n}\sum_{k=0}^{n-1} d(f_k, f_k'). \quad (4)$$

Therefore, the optimization problem in Eq. (3) can be transformed into the problem of summarization with a price on power,

$$S_j^*(\lambda^i) = \arg\min_{S_j}\left(D(S_j) + \lambda^i P(S_j, W, h_j)\right). \quad (5)$$

λ^i is the power price in current ith iteration. $P(S_j, W, h_j)$ is computed as the average power needed to transmit all video summary frames with bandwidth W and channel state h_j within the current time window. Eq. (5) can be solved with a Dynamic Programming (DP) approach at video sources; more details can be found in our energy efficient video summarization work in [4].

At the base station, the resulting power requests from video sources for the current price are collected, and the new price is computed through a price tatonnement process,

$$\lambda^{i+1} = \max\{0,\ \lambda^i + \alpha[\sum_j P(S_j^*(\lambda^i), W, h_j) - P_{\max}]\} \quad (6)$$

In Eq. (6), if the requested power level is larger than the constraint, the price for power is revised up in the next iteration, and vice versa for the case when requested power is below the constraint. A proof of the convergence of the price iterations can be found in [8]. In practice, the iteration stops after the total power request is within certain error range of P_{max}. Notice that the computation burden for computing the optimal power levels in Eqs. (5) and (6) are distributed among base station and video sources.

The resulting power level allocations $\{P_j^*\}$ are just indications of the resource consumption level for delivering certain level of utility for each user. The actual transmitting power schedule for each user is computed as explained in Section 3.

3. JOINT POWER SCHEDULING WITH WATER FILLING

The pricing scheme allocates power among video traffics assuming a constant transmitting power, P_j^* for the given segment of time. In practice, since video summary frame packets have different packet sizes and delivery deadlines, the power function of each user, $P_j(t)$, is not a constant in time. An energy-efficient packet scheduler is developed next to deliver all packets on time with the total power constraint $P(t)=\sum_j P_j(t) \le P_{max}$ for all values of t belongs to $[0, T]$.

First, we sort the packets of all users in increasing order of delivery deadlines. For the k-th packet belonging to user j, we denote the packet size, packet arrival time, and deliver deadline as, $\{B_k^j,\ t_k^j,\ T_k^j\}$, where $t_k^j < T_k^j$. The scheduler needs to compute a transmitting power function for each user, $P_j(t)$, over the given time window, such that both the total power constraint and individual video packet delivery deadline requirements are met.

Then the scheduling is performed using a greedy water-filling power allocation algorithm. Let $P(t)$ be the committed total power function for processed packets so far, then to schedule packet k (from user j), with parameter $\{B_k^j, t_k^j, T_k^j\}$, we look at $P(t)$ in time $[t_k^j, T_k^j]$, and search on a water filling level L, such that the power function available for transmitting packet k is,

$$P_k^j(t;L) = \begin{Bmatrix} L - P(t), & t \in [t_k^j, T_k^j] \\ 0, & else \end{Bmatrix}. \quad (7)$$

The downlink capacity as a function of water filling level L for user j in $[t_k^j, T_k^j]$ can be computed as,

$$B(L) = W\int_{t_k}^{T_k} \log(1 + \frac{h_j P_k^j(t;L)}{WN_0^j}) - \log(1 + \frac{h_j P_j(t)}{WN_0^j}) dt, \quad (8)$$

where h_j is the channel state for user j, $P_j(t)$ is the committed power profile for user j before scheduling the current packet k, and N_0^j is the background noise density of user j. A fast bi-section search on L can find the correct filling level L_k^* that gives $B(L^*)=B_k^j$. The process is illustrated in Fig. 1, where $P_k^j(t;L)$ is the shaded area bounded by $P(t)$ and L, between t_k^j and T_k^j.

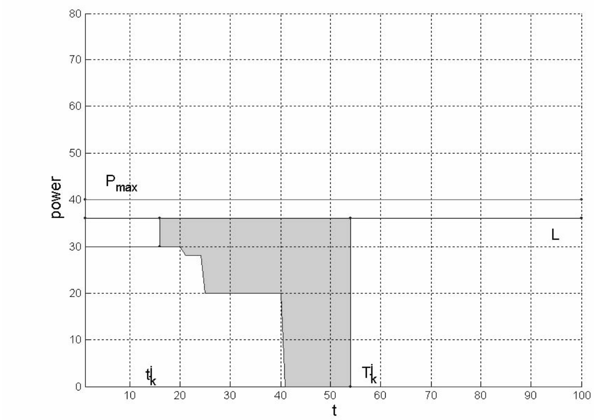


Figure 1. Water filling scheduling example

The algorithm schedules each packet in the order of delivery deadlines, until the last packet's power function is computed. Then each user's transmitting power function is computed as,

$$P_j(t) = \sum_{k \in K_j} P_k^j(t; L_k^*) , \qquad (9)$$

where K_j denotes the set of packets from user j. Notice that although the resulting $P_j(t)$'s may not be constant functions, the scheduling tries to utilize as much power as possible within the total power.

4. SIMULATION RESULTS

To demonstrate the effectiveness of our proposed algorithm, we consider an example with 4 different video clips with different content activity levels, and simulate the pricing controlled distributed summarization and packet scheduling.

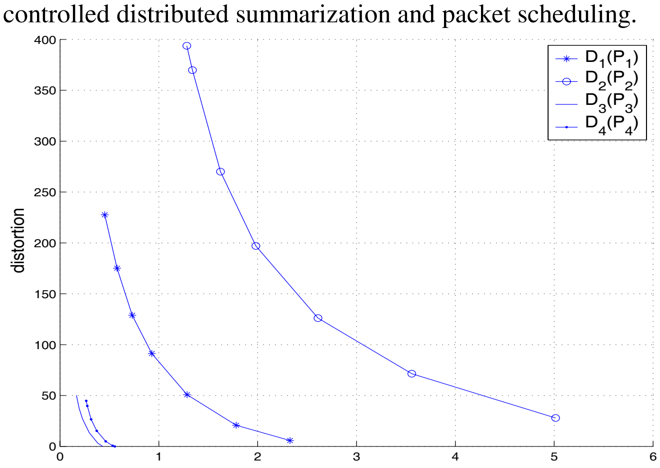


Figure 2. Utility-average power functions for different clips

Clips 1, 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. The channel gains are also different, given as, H=[0.75, 1.00, 0.80, 0.65]. This choice of channel states and content covers a wide range of activity levels and reflects diversity in marginal utility w.r.t. to transmitting power consumptions which are illustrated in Fig. 2. At the summarization-power allocation phase, a total transmitting power threshold of $P_{max}=2.4$ is given, and the optimal price is found as $\lambda^*=101.45$ through the tatonnement process.

The resulting video summary distortions are plotted below in Fig. 3. The vertical arrows indicate video summary frame locations in the sequence. Notice that the distortion is zero at summary frame locations. The optimal price gives the best trade-off 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 *20.1*, *43.3*, *8.1* and *9.4* kbps, respectively.

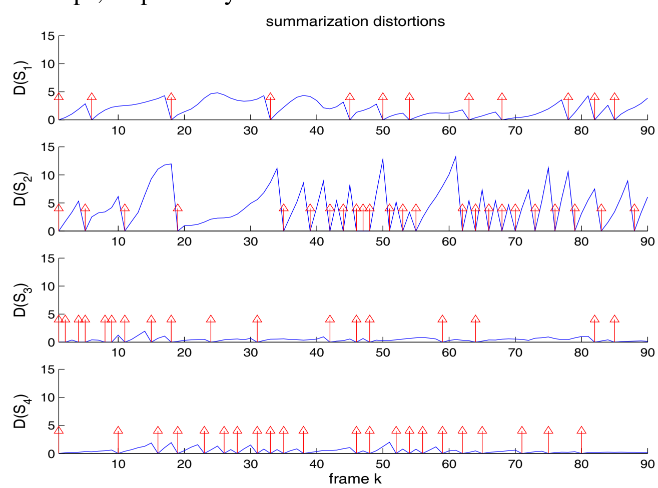
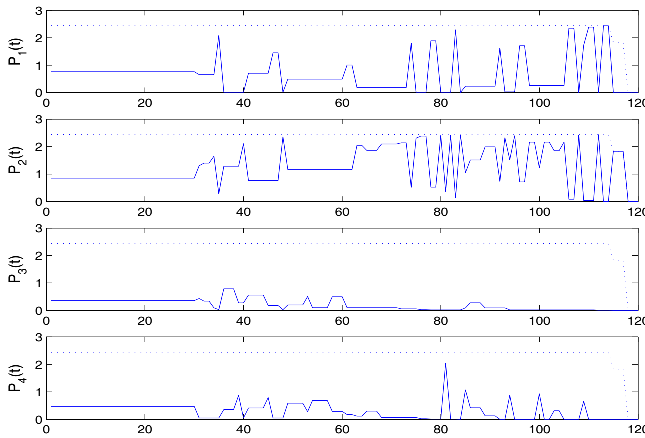


Figure 3. Resulting video summary distortion for P_{max}=2.4

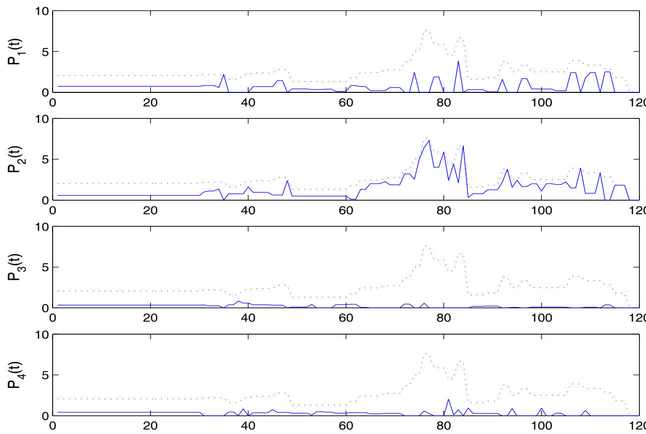
With an initial delay of *1* sec, the joint water-filing scheduler achieves a total power limit of $P_{max}=2.45$. There is a slight loss of power efficiency through the summarization and power allocation phase that only considers the average transmitting power.

The power allocation results, $P_1(t)$~$P_4(t)$, for the video summaries generated in Fig. 3 are shown in Fig. 4a. The dotted line is the total power function $P(t)$. Notice that each user's power function is not constant at all but the total power function is rather flat and achieves efficient utilization of the power resource. As a comparison, the results based on the single user earliest deadline first serve (EDFS) scheduling are plotted in Fig. 4b, which leads to a maximum power of P_{max}=7.56.

The computational complexity of the pricing solution is distributed among video sources and the base station. The amount of information need to be communicated for the pricing scheme is kept to a minimum.



(a) Joint water-filling scheduling



(b) Single user based scheduling

Figure 4. Packets scheduling results

The pricing operating curve for the total distortion and power constraint P_{max} with summarization-pricing scheme for the 4 clips is also plotted in Fig. 5.

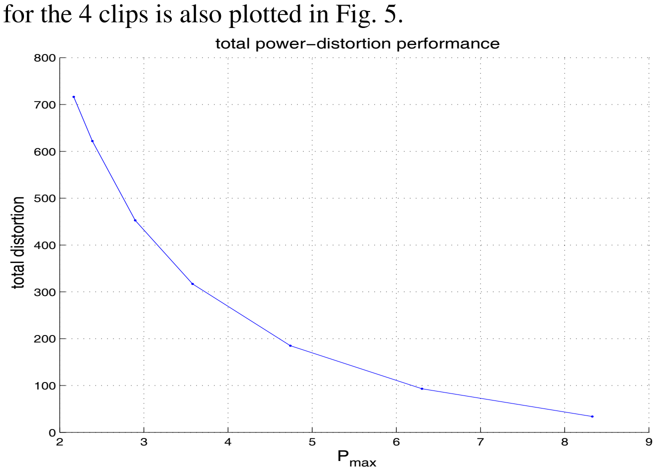


Figure 5. Total distortion-power constraint plot

5. CONCLUSION AND FUTURE WORK

In this paper, we developed a two-tier, distributed, pricing based power allocation and scheduling scheme for downlink video transmissions to achieve efficient communication resource utilization. Video summarization is performed on the video sources to achieve good end-to-end video quality at low bit rates. The solution maximizes the total utility among users for the given power constraint. Simulation results demonstrate the effectiveness of the algorithm. The computational burden is distributed among base station and source nodes. It is suitable for deployment with current wireless infrastructure to serve downlink video streaming with mixed voice/video traffic.

In the future, we plan to further improve the scheduling algorithm by considering delay tolerance and delay induced distortion modeling. Also bit stream extraction for scalable video coding will be considered in addition to summarization scheme.

REFERENCES

[1] J. Huang, R. Berry, M. L. Honig, "Auction-based Spectrum Sharing", Allerton Conference of Communication, Computing and Control, Sept. 2004

[2] J. W. Lee, R. R. Mazumdar, and N. B. Shroff, "Downlink power allocation for multi-class CDMA wireless networks", INFOCOM'2002, N.Y., Jun. 2002.

[3] Z. Li, A. Katsaggelos, G. Schuster and B. Gandhi, "Rate-Distortion Optimal Video Summary Generation", *IEEE Trans. on Image Processing*, vol. 14, no. 10, October, 2005.

[4] Z. Li, F. Zhai, and A. K. Katsaggelos, "Video Summarization for Energy Efficient Wireless Streaming", *Proceedings of SPIE Visual Communication and Image Processing* (VCIP), Beijing, China, 2005.

[5] Z. Li, Q. Cheng, A. K. Katsaggelos, and F. Ishtiaq, "Video Summarization and Transmission Power Adaptation for Very Low Bit Rate Multiuser Wireless Uplink Video Communication", *IEEE Int'l Workshop on Multimedia Signal Processing* (MMSP), Shanghai, Oct. 2005.

[6] I.-M. Kim, and H-M. Kim, "Transmit power optimization for video transmission over slowly-varying Rayleigh-fading channels in CDMA systems", *IEEE Trans. on Wireless Comm.*, pp.1411-1415, vol.3(5), Sept. 2004.

[7] C. Saraydar, N. Mandayam, and D. Goodman, "Efficient Power Control via Pricing in Wireless Data Networks", *IEEE Trans. On Wireless Communications,* Vol. 50 (2), Feb., 2002

[8] R. Srikant, *The Mathematics of Internet Congestion Control*, Birkhauser, Boston, 2004.

[9] Q. Zhang, Z. Ji, W. Zhu, and Y.-Q. Zhang, "Power-minized bit allocation for video communication over wireless channels", *IEEE Trans. on Circuits & System for Video Tech*, vol.12(6), June, 2002.

[10] P. Zhang, S. Jordan, P. Liu, M. L. Honig, "Power control of voice users using pricing in wireless networks", *ITCom'01*, 2001

[11] Q.Zhang, W. Zhu, and Y.-Q. Zhang, "Channel-adaptive resource allocation for scalable video transmission over 3G wireless network", *IEEE Trans. on Circuits & System for Video Tech*, vol.14, no.8, Aug, 2004.

[12] S. Zhao, Z. Xiong, and X. Wang, "Joint error control and power allocation for video transmission over CDMA networks with multiuser detection", *IEEE Trans. on Circuits & System for Video Tech*, vol.12(6), June, 2002.