Time-constrained Packet Scheduling Optimization for Video Streaming in Wireless Ad-hoc Networks

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Abstract— **Packet schedule is effective to improve the quality of video streaming over time-varying wireless ad-hoc networks. In this paper, we propose a time-constrained packet scheduling algorithm, which minimizes the video distortion by allocating transmission opportunities to packets under the constraint of playback delay. The problem is formulated in a constrained convex optimization framework and solved with Lagrangian method. The packet loss probabilities and transmission time in IEEE802.11 wireless channel are predicted by using a Markov Chain model. The experiments in NS-2 simulator validate that the algorithm achieves a significant improvement on the quality of streaming.**

I. Introduction

Recently, there have been considerable interests in supporting video streaming in wireless mesh networks(WMN). However, the natures of wireless multi-hop networks, such as lack of infrastructure, low bandwidth, high bit error rates and stringent delay constraints, make it a great challenge to offer the necessary quality of service (QoS) for multimedia applications. Random packet losses may have unpredictable effects on the quality of reconstruction video at the receiver. Thus, it is necessary to employ proper video packet selection and scheduling method to improve the quality of service (Qos).

There has been considerable researches on adapting the video representation to the channel variations. Many have focused on the framework for rate-distortion (RDO) optimized [1], [2], [3] streaming. However, to the best of our knowledge, R-D optimized packet scheduling in considering the video delay requirements in wireless ad-hoc networks, as studied in this paper, has not been investigated before. The work of Chou et al. [1] presents a general framework for R-D optimized streaming. To find optimal retransmission strategies for different packets, Chou used an iterative descent algorithm in a Lagrangian framework to solve the minimal Lagrangian problem. Unfortunately, the framework assumes the network parameters are static, and does not take account of the end-to-end delay requirements of video packets.

Some researches focus on delay sensitive schedule. The packets are assigned to different priorities by their delay, and these with the earliest deadline (EDF) [4] are sent first. In this case, the jitter time in the receiver's buffer is minimized, and as a result, we achieve minimum required buffer size at the receiver. However, they do not explore the difference between contents. For example, the video with many motion frames would consume more bandwidth. In addition, they also ignore the dependency relationship between video packets. The packets in a Intra-coded (I) frame are more important than that in a inter-coded frame (B).

In this work, we propose and evaluate the time-constrained optimized packet scheduling algorithm (TCO-PS) for video streaming over wireless multi-hop networks. Packets are assigned to different transmission opportunities under the delay constraints of video decoders, to guarantee that these successfully received packets are able to maximize the quality of reconstruction video at the receiver end. We formulate the problem in a constrained convex optimization framework, which minimizes the sum of the expected distortions under the condition of delay constraints. The distortion of packet is measured by using the packet dependency model. The packet loss probabilities and transmission time in IEEE 802.11 wireless channel are predicted by using a Markov Chain model, which takes the effects of interference and contention into account. Packets are scheduled according to the optimal solutions on each node along the routing path. Extensive experiments are carried out in NS-2 [5] simulation models. We compare the proposed scheme with the random packet scheduling and priority-based packet scheduling schemes. The performance of the three schemes are examined under various network scenarios. The experimental results illustrate that the proposed algorithm achieves a significant improvement on the quality of video streaming over wireless ad-hoc networks.

The main contributions of this work are as follows. First, we formulate the packet scheduling problem in a time-constrained optimization framework, which minimizes the distortion by tradeoff between the packet distortion and expected delay. Second, we proactively schedule packets by predicting the delay in wireless ad-hoc networks, while conventional priority based methods drop packets only when there is not enough network resource. The proposed algorithm uses a Markov Chain model to predict network status, which takes account of the interference and contention in wireless channel.

The rest of the paper is organized as follows. In section 2, we introduce the packet distortion model and Markov model of wireless channel. In section 3, we formulate the packet scheduling problem in a time-constrained optimization framework, and give the solution to find the optimal allocations for transmission opportunities. Performance evaluation and comparison are described in section 4. Finally, Section 5 concludes the paper.

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II. Preliminaries

In this section, we cover various preliminaries, including rate-distortion model for packets, and characterization of IEEE 802.11 wireless channel. Both have great effects on our packet scheduling algorithm.

A. Incremental Distortion Model

In our algorithm, packets are weighted by their importance for the distortion of reconstruction video on the receiver end [1]. PSNR distortion is measured if the packet is not delivered to the receiver on time. Here, we assume each frame is capsulated into one or more packets, whose size are no more than 1024 bytes. Any loss of them will result to the whole frame corrupt. The importance of packet is equal to that of the frame which the packet belongs to. Due to error propagation, which is caused by the predictive nature of motion-compensation encoding scheme, the PSNR associated with subsequent frames is also related to the corrupt frame [2]. Hence, the distortion of one packets is the sum of all PSNR distortion value measured in the subsequent frames.

$$d_i = \sum_j \triangle d_j \qquad \text{i} <= \text{j} \tag{1}$$

where i, j is the frame index. $\triangle d_j$ is the increase in PSNR distortion associated with frame j given frame i is lost.

B. Channel Contention Model of IEEE 802.11

The IEEE 802.11 multi-access mechanism[6] is used in medium access control (MAC) layer. A transmitter should contend for shared wireless channel before transmission. The IEEE 802.11 multi-access mechanism (i.e. DCF without RTS/CTS) requires that the transmitter should contend for the medium when the channel is sensed idle for more than a distributed inter-frame time space (DIFS). In a successful transmission attempt, the transmitter first waits for a time $DIFS$, and then chooses a back-off time. When the back-off time count down to zero, the packet is transmitted with H time. Then an ACK message is responded by the receiver with the time ACK, after a period of time called short inter-frame space($SIFS$). In a failed transmission attempt, there is no ACK message, and the transmitter need not wait for a SIFS time. Hence, if we ignore the back-off time, the packet transmission time in a successful delivery T_s and that in a failed attempt T_c can be expressed as:

$$\begin{aligned} T_s &= DIFS + H + SIFS + ACK \\ T_c &= DIFS + H \end{aligned} \tag{2}$$

We use a discrete-time Markov chain [7] to model the back-off mechanism. Let $s(i)$ be the stochastic process presenting the back-off stage for a given node, where $i \in (1, m)$ is called back-off stage. Each packet collides with constant and independent probability p. A new packet starts with back-off stage 1. When an collision occurs at back-off stage i, the back-off stage increases. While a successful transmission occurs with probability $1 - p$, the process stops. Finally, when the back-off stage reaches the maximum transmission limits m, the packet would be discarded and the stochastic process stops. The Markov chain is depicted in Fig. 1.

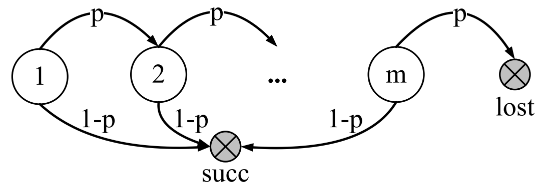


Fig. 1. Markov Chain Model for Back-off Mechanism

In stage i, the size of contention window is $2^{i-1}W$. By the model in Fig. 1, the probability of stage i is $(1-p)p^{i-1}$. while in the last stage m, the probability is $(1-p)p^{m-1}+p^m$. Hence, we can get the expected size $E[S]$ of contention window as:

$$\begin{aligned} E[S] &= \sum_{i=1}^{m} 2^{i-1}W(1-p)p^{i-1} + 2^{m-1}Wp^m \\ &= \frac{1-p-p(2p)^{m-1}}{1-2p}W \end{aligned} \tag{3}$$

The duration of stage i is a random time between $(0, 2^{i-1}W - 1)$. Then the expected back-off time is $E[S]/2$. Hence, the average back-off time T_b can be expressed as:

$$E[T_b] = \frac{(1-p^m)(1-p-p(2p)^{m-1})}{2(1-p)(1-2p)}W \tag{4}$$

If a packet is received successfully in the stage i, it has $i - 1$ unsuccessful transmission attempts, and one successful transmission. Hence, the expected transmission time for a packet can be expressed as:

$$\begin{aligned} E[T_x] &= \sum_{i=1}^{m} ((i-1)T_c + T_s)p^{i-1}(1-p) + mT_c p^m \\ &= \frac{p(1-p^m)}{1-p}T_c + (1-p^m)T_s \end{aligned} \tag{5}$$

The time to process a packet is the sum of the back-off duration and transmission duration. According to Eqn. (4) and (5), we can express the expected time T to process a packet in the IEEE 802.11 channel as:

$$\begin{aligned} T &= \frac{(1-p^m)(1-p-p(2p)^{m-1})}{2(1-p)(1-2p)}W \\ &\quad + \frac{p(1-p^m)}{1-p}T_c + (1-p^m)T_s \end{aligned} \tag{6}$$

From the Markov chain model, we also know that the packet loss occurs only after m times of unsuccessful transmission attempts. Then the packet loss probability P, which is caused by interference or channel contention in MAC layer, can be expressed as:

$$P = p^m \tag{7}$$

III. Time-constrained Optimization

We seek a optimized packet scheduling algorithm that, for given any video stream, has the minimum expected distortion under a delay constraint, over a multi-access shared wireless channel with contention and interference. We allocate the different transmission opportunities to packets in network layer, according to their R-D importance and the delay constraints. More important packets would be allocated to more opportunities so that they can reach the receiver in time. Even there are losses in MAC layer, the important packets would be retransmitted in network layer. While other minor packets are allocated to less opportunities, or even more there is no opportunity for some packets to be transmitted. Hence, we formula the packet scheduling problem to a constrained optimal problem, which trade-off expected distortion and transmission opportunities. By using Lagrange optimal algorithm, we can find an optimal packet scheduling solution.

A. Expected Distortion and Delay

Consider there are L packets waiting for transmission, we are interested in finding the best packet schedules by allocating the transmission opportunities. Assume that the packet l, for $l = 1, ..., L$, has been allocated a transmission limit x_l. The packet would be always retransmitted until the transmission successes, or the attempts reach the limit x_l. The sender needs to decide the transmission limits $x_1, ..., x_L$ for each packet before transmission, such that the expected transmission time does not exceed the delay constraint for video packets.

The distortion of reconstruction video on the receiver is caused by packet losses. For packet l, it would either reach the receiver, or be discarded after x_l transmission attempts. The importance of packet is represented with the distortion $\triangle d_l$, which is calculated according to Eqn. (8). Hence, the expected distortion on the receiver can be expressed as:

$$D = \sum_{l=1}^{L} \triangle d_l p^{x_l} \tag{8}$$

The transmission duration for all packets in the buffer is the sum of transmission time of each packet. According to Eqn. (6), we know the expected time to process a packet is T. Hence, we can express the total transmission duration K as the follows:

$$K = \sum_{l=1}^{L} x_l T \tag{9}$$

B. Optimization for Time-constrained Packet Scheduling

We denote the delay constraint as $\triangle T$. If a video packet is not successfully received by the destination in $\triangle T$, the packet is useless for the decoder even if it is received lately. Hence, we can assume that the total transmission time for packets waiting in the buffer should be less than $\triangle T$.

The packet scheduling problem is equal to find the optimal solution for transmission limit vector $\pi = (x_1, x_2, ..., x_L)$, which is the allocated transmission opportunities of packets in the buffer. We are interested in minimizing the overall expected distortion on the receiver for the optimal vector π^*, subject to a constraint on the total transmission time. Hence, the packet scheduling problem can be formulated in a constrained optimization problem as follow:

$$\begin{array}{lll} \text{Minimize:} & & \\ & D(\pi) & = \sum_{l=1}^{L} \triangle d_l P^{x_l} \\ \text{subject to:} & & \\ & K(\pi) & \leq \triangle T \\ & x_l & \geq 0 \end{array} \tag{10}$$

Obviously, This is a nonlinear inequality-constrained optimization problem [8]. We use the method of Lagrange multipliers to generate the conditions of minimization. A Lagrangian function J is created by adding the constraint K, which is multiplied by an unknown new variable, λ, to the objective function D.

$$J = \arg\ \min_{\pi} D(\pi) + \lambda K(\pi) \tag{11}$$

By finding a convex set of points satisfied to this unconstrained optimization equation, we can find the solution to problem (10). This can be accomplished with dynamic programming, such as the knapsack algorithm.

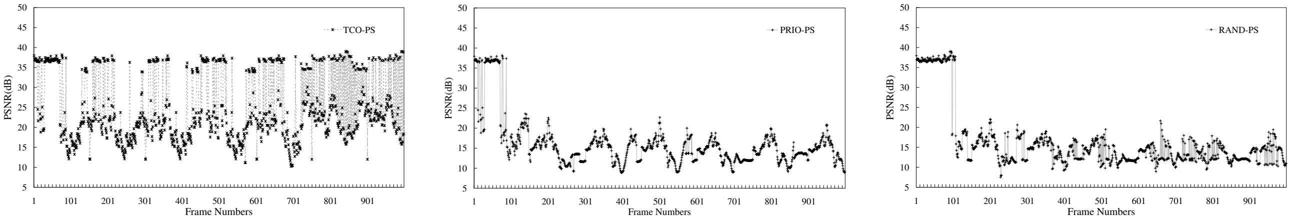
IV. Performance Evaluation

In this section, we use NS-2 [5] simulation model to examine the performance of the proposed scheme over a wide range of network scenarios. Sixteen nodes are randomly scattered in a $1000 * 1000m^2$ area. The IEEE 802.11 protocol [6] for wireless LANs is used as the MAC layer. The data rate of the wireless channel is 2Mbps with a radio range of 250 meters. The interference range is 550 meters. If two or more senders are within this range, the packet collision occurs. Among the 16 nodes, one is randomly chosen as the video source and another node is chosen as the video sink.

The video sequence "Foreman" is encoded using JM 14 of the JVT/H.264 video compression standard [9]. The test video sequences is CIF(352*288) format with a temporal resolution of 10 frames per second. We set the GOP size to 15 with the structure "IBBPBBP...". The sequences is encoded to various bit rate from 20kbps to 300kbps. The video length is 1000 frames. Each frame is capsulated into one or more packets, whose size are no more than 1024 bytes. A playback buffer with 5s is used to absorb the jitter in receiver packets.

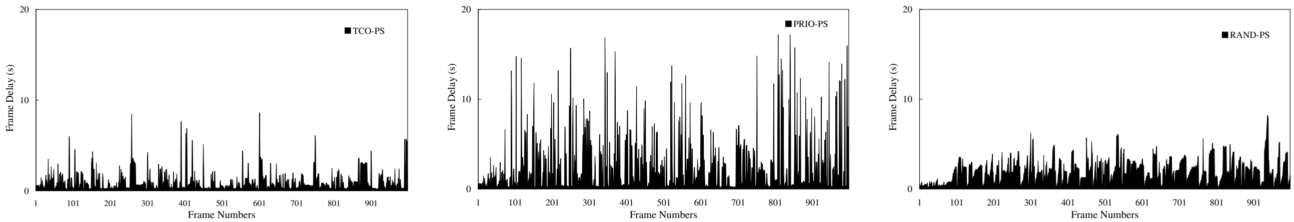
The proposed time-constrained optimized packet scheduling scheme is denoted as TCO-PS in the following experiments. As a basis of comparison, we introduce two conventional packet scheduling strategies: the earliest deadline first scheme and rate-distortion based scheme. The earliest deadline first scheme, denoted as RAND-PS, randomly drops packets when the transmission buffer is overflowed. It ignores the difference between video frames. The rate-distortion based scheduling scheme, denoted as PRIOR-PS, discards packets by packet importance in the order of I, P and B frames.

First, we examine the quality of received video. Fig. 2 plots the PSNR traces of the three schemes respectively. The average PSNR of TCO is about 32dB, which is much higher than others. It means that the proposed algorithm is able to achieve a better performance at the same topology and video source. Before network congestion occurs, nodes



(a) TCO-PS (b) PRIO-PS (c) RAND-PS

Fig. 2. PSNR of received frames using the three packet scheduling schemes.



(a) TCO-PS (b) PRIO-PS (c) RAND-PS

Fig. 3. Delay of received frames using the three packet scheduling schemes.

proactively discard the packets whose end-to-end delay already exceeds the limitation. Hence, the quality of received video using the proposed algorithm recovers quickly, as illustrated in Fig. 2 (a). However, PRIO-PS and RAND-PS suffer from massive packet losses when congestion occurs, which result in significant quality degradations.

The delay of received frames is illustrated in Fig. 3. The average delay in Fig. 3 (a) is about 1 second, while that of other two schemes is larger than 3 seconds. The proposed scheme discards overtime packets, and release network resources to the rest packets. While in PRIO-PS scheme, the packets with higher priority are retransmitted again and again, which results that the peak delay in Fig. 3 (b) is the largest. Since RAND-PS scheme deliver the packets with the earliest deadline first, the variance of delay in Fig. 3 (c) is the smallest.

V. Conclusions

As the time-varying nature of wireless channel and error sensitivity of compressed video data, it is a great challenge to guarantee video streaming QoS over wireless ad-hoc networks. In this paper, we proposed a time-constrained optimized packet scheduling algorithm, which schedules packets with different transmission opportunities, to promise that these successfully received packets are able to maximize the quality of reconstructed video. The number of transmission is constrained by the delay requirements of video decoder. Then the problem is formulated in a constrained convex optimization framework. The priority of packet is measured by using the packet dependency model, which estimates the distortion on all related frames. We also use a Markov chain model to predict the packet collision and processing time in MAC layer, which takes account of the effect of interference and channel attention in IEEE 802.11 wireless channel. Extensive experiments are carried out on NS-2 simulation models. The experimental results illustrate that the proposed algorithm achieves a significant improvement on the quality of video streaming over wireless ad-hoc networks.

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