RATE-DISTORTION BASED PATH SELECTION FOR VIDEO STREAMING OVER WIRELESS AD-HOC NETWORKS

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ABSTRACT

In wireless ad-hoc networks with low bandwidth, high bit error, and node mobility, the quality of streaming video is highly dependent on the quality of routing paths. Most of existing ad-hoc routing algorithms select the path according to network parameters. However, the selected path may not be the best path for video applications. This paper proposed a rate-distortion based (RD) path selection algorithm for video streaming over wireless networks. The video distortion on application layer is used as path metric. On each link, the rate-distortion due to transmission error and congestion is estimated using queuing theory. The algorithm selects the path with the minimum expected rate-distortion as the routing path. Extensive experiments are carried out over NS-2 simulation environment. Simulation results demonstrate that RD routing algorithm can improve the quality of video streaming significantly as compared to the conventional shortest-path routing algorithm.

Index Terms— video streaming, wireless ad-hoc networks, rate-distortion, path selection, routing

1. INTRODUCTION

Recently, there has been considerable interest in supporting video streaming over wireless ad hoc networks. The main challenges stem from mobility of nodes, time-varying nature of wireless channel, and error-prone communications. To ensure various multimedia applications with the necessary QoS, one critical issue is how to select a qualified path. The quality of a received video is highly dependent on the quality of the path in terms of loss, delay, and jitter. An efficient path selection algorithm should take account in not only network status on network layers, but also video distortion on application layers.

Prior routing researches mainly use network performance metrics. The metric most commonly be used by existing ad hoc routing protocols is hop counts. A typical routing algorithm, DSR(Dynamic Source Routing)[1] protocol, selects the path according to pre-determined metrics, such as hop counts, delay, et. However, the shortest path maybe not the best path for video applications. Minimizing the hop-count maximizes the distance traveled by each hop. It likely results to minimizing the signal strength and maximizing the loss ratio in physical links. For bandwidth-consume and delay-sensitive video applications, a path with high loss ratio and narrow bandwidth degrades video quality in receivers. One approach fixing this problem is to find a new routing metric for path selection, such as ETX metric[2]. The ETX(Expected Transmissions Count) metric measures the expected transmission times to send a unicast packet across a link. The reason it works is MAC layer would retransmission packets when sender didn't receive ACK message. So the transmission times can be estimated by using link loss probability. However, this metric does not explicitly consider delay constraints in video applications.

Some researches have proposed rate-distortion based end-to-end path selection strategies. They model rate distortion as function of network parameters, such as delay and loss ratio. Mao et al. [3] propose a heuristic approach based on genetic algorithms to solve the path selection problem in wireless ad hoc networks. It assumes the probability of packet loss and delay of end-to-end path is given. Wei et al. [4] propose a path selection algorithm based on end-to-end packet loss probability. There are some assumptions for these solutions: the network is static, and we have accurate information about the status of each end-to-end path. However, topology is always changing over time and channel conditions are time-varying in wireless multi-hop networks. It is also not practical to know path characteristics of the entire network in real time.

In this paper, we propose a rate-distortion based (RD) routing algorithm for video streaming over wireless ad-hoc networks. The rate-distortion is used as routing metric. The distortion on each node is estimated by the expected loss probability generated in MAC layer and network congestion. Each link along the path is assigned to a weight associated with the rate-distortion introduced by the node. RD routing

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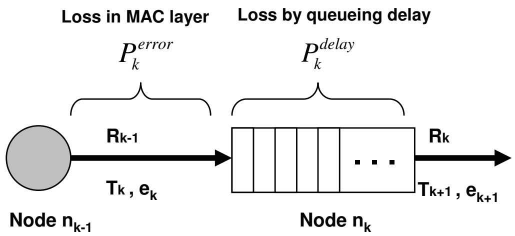


Fig. 1. Packet Loss Model

algorithm selects the path with the minimum sum of rate distortion as the routing path.

This paper makes following main contributions: First, it proposed a new path metric, rate-distortion, instead of conventional network performance metrics (i.e. hop-count, loss probability, and delay) for video routing. Second, the rate-distortion is estimated by using the network prediction models, not network measurements. Compared to existing path selection algorithms, RD routing can not only find the best path for video applications, but also work well in dynamic networks.

The paper in Section 2 gives the rate-distortion prediction model, and congestion analysis using queuing theory. Section 3 describes the algorithm of RD routing protocol. The experiment and algorithm evaluation is described in section 4, and Section 5 concludes the paper.

2. DISTORTION ESTIMATE

We model a multi-hop wireless network as a directed graph $\mathcal{G}(\mathcal{N}, \mathcal{L})$, where $\mathcal{N}$ is the set of vertices, representing mobile nodes n, and $\mathscr{L}$ is the set of wireless links l. The path between the video server and the client can be expressed $\mathcal{P}$. Assumed a path consists of m nodes, the nodes along the path is $\mathcal{P}_{\mathcal{N}} = \{n_1, n_2, ..., n_m\}$. The links along the path $\mathcal{P}$ can be denotes as $\mathcal{P}_{\mathcal{L}} = \{l_{1,2}, l_{2,3}, ..., l_{m-1,m}\}$. We can characterize the link $l_{k-1,k}$ by following parameters: R_{k-1} denotes the input video bit rate of the link. The packet error probability of the link is denoted as e_k. The physical layer throughput of the link is T_k.

In our model, packet loss is generated by two reasons: channel error, and queuing loss, as in fig.(1). In IEEE 802.11a/b/g standard, MAC layer handles wireless channel error by retransmitting error packet. If the number of retransmissions exceeded the preset limits, the packet would be dropped. This kind of loss probability is denoted as P_k^{error}. Queuing loss is due to queuing delay in nodes. If the queuing delay of packets at the node queue exceeds the desired delay constraint, we would drop the packets. It is also named as network congestion. This kind of loss probability is denoted as P_k^{delay}.

There are three steps to estimate the video distortion D_k introduced by node k. First, we should estimate the packet error probability in MAC layer. Second, we should estimate the packet loss probability because of network congestion. Last, we use a rate-distortion model to calculate the rate distortion of node.

2.1. Rate-Distortion Model

In [5], Stuhlmuller proposed an empirical rate-distortion model for a hybrid motion compensated video encoder. For a video sequence encoded at a target coding rate R, the average delivery distortion D consists of the encoding distortion at the encoder (D^{enc}), the distortion due to congestion (D^{delay}), and distortion due to channel error loss (D^{error}). That is:

$$\begin{aligned} D &= D^{enc} + D^{delay} + D^{error} \\ &= (D_0 + \tfrac{\omega}{R-R_0}) + \kappa(1 - P^{error})P^{delay} + \kappa P^{error} \end{aligned} \tag{1}$$

where D_0, ω, R_0, κ are constants for a specific video codec and video sequence. Since the encoding distortion is only generated at the encoder, the distortion introduced by relay nodes is mainly due to the last two parts: queuing loss P^{delay}, and channel error loss P^{error}.

2.2. Wireless Channel and MAC Layer

The transmission rate and packet error rate for a wireless link can be determined based on a specific choice of modulation and coding scheme in wireless channel. To describe the channel conditions, we assume that each wireless link is memoryless packet erasure channel. For a given modulation and coding scheme, the effective physical layer throughput and the packet error rate can be approximated with sigmoid function as in [6].

For a wireless link between node n_{k-1} and n_k, the signal to interference noise ratio(SINR) is denoted as $SINR_k$. According to sigmoid function [6], the packet error probability in physical layer can be expressed as:

$$e_k = \frac{1}{1 + e^{\varsigma(SINR_k - \delta)}} \tag{2}$$

where ς and δ are constants related to channel modulation and code scheme.

The IEEE 802.11a/b/g standard requires that transmitter should contend again for the medium to retransmit the packet if a physical error occurred. An acknowledgement (ACK) frame would be sent by the receiver upon successfully reception of a data frame. It is only after receiving an ACK frame correctly that the transmitter assumes successfully delivery of the corresponding data. In the standard, a data frame is discarded by the transmitters MAC after a certain number of unsuccessful transmission attempts π. The expected packet loss probability in MAC layer due to retransmission error can be expressed as:

$$P^{error} = 1 - \sum_{i=1}^{\pi} e_k^{i-1}(1 - e_k) \tag{3}$$

2.3. Congestion Analysis with Queuing Theory

To estimated the packet loss probabilities generated by network congestion, we predict the expected queuing delay $E[W_k]$ and packet loss probabilities P^{delay} using queuing theory. In network congestion, packet queue in a relay node can be modeled as a M/G/1 queues[7]. Arrival traffic at each node is assumed to be a Poisson process. Each packet will be retransmitted until it is either successfully received or discarded because its retry times exceed the retransmission limit. The time that a node processes a packet is determined by the physical transmission rate and error probability of the wireless link to the next node. As an example, let us consider the node n_k, Its process time X_k is a function of physical characterize on link $n_{k,k+1}$. So the service time for a packet on a node can be formulated as a geometric distribution.

The packet arrival probability on node n_k is related to the video rate output from node R_{k-1} and the packet loss probability on link $l_{k-1,k}$. From equation (3), we know the packet arrival probability on node n_k is:

$$\lambda_k = R_{k-1}(1 - P_k^{error}) \tag{4}$$

The estimated packet process time on node n_k consists of two parts: the estimated transmission time if packet delivered successfully, the retry time if packet is discarded at last. L represents the average length of video packet. The estimated packet process time $E[X]$ at queue of node n_k is:

$$E[X_k] = \sum_{i=1}^{\pi} \frac{L}{T_{k+1}} i e_{k+1}^{i-1}(1 - e_{k+1}) + \frac{L}{T_{k+1}} \pi e_{k+1}^{\pi} \tag{5}$$

The second moment of the packet process time $E[X_k^2]$ is:

$$E[X_k^2] = \sum_{i=1}^{\pi} (\frac{L}{T_{k+1}} i)^2 e_{k+1}^{i-1}(1 - e_{k+1}) + (\frac{L}{T_{k+1}} \pi)^2 e_{k+1}^{\pi} \tag{6}$$

Consider a single-server queuing system where packet arrive according to a Poisson process with rate λ_k, the packet process time have a general distribution. The estimated process time is $E[X]$, and the second moment of process time is$E[X^2]$. By the Pollaczek-Khinchin(P-K) formula [7], the expected delay time $E[W_k]$ at node n_k is:

$$E[W_k] = E[X_k] + \frac{\lambda_k E[X_k^2]}{2(1 - \lambda_k E[X_k])} \tag{7}$$

The probability of packet loss due to network congestion can be estimated using the tail distribution of delay[8]. We assume that the delay deadline for a video packet is Δ. The packet passed through all nodes from n_0 to n_k along a path. If the accumulative delay exceeded Δ, the packet will be discarded. The condition of packet loss due to congestion can be expressed as:

$$W_k + \sum_{i=0}^{k-1} E[W_i] > \Delta \tag{8}$$

According to the approximation formulate for waiting time tail probabilities[8], the packet loss probability due to network congestion can be expressed as:

$$\begin{aligned} P_k^{delay} &= Pr(W_k > \Delta - \sum_{i=0}^{k-1} E[W_i]) \\ &\approx \lambda_k E[X_k] e^{\frac{-\lambda_k E[X_k](\Delta - \sum_{i=0}^{k-1} E[W_i])}{E[W_k]}} \end{aligned} \tag{9}$$

The output video rate of node n_k can be expressed as:

$$R_k = R_{k-1}(1 - P_k^{error})(1 - P_k^{delay}) \tag{10}$$

3. RATE-DISTORTION BASED ROUTING

To minimize the video distortion over multi-hop wireless networks, we proposed a rate-distortion based path selection algorithm to choose the best path for wireless video streaming. Each link in the path is assigned to a weight in video distortion calculated by the node in the receiver end. The path metric is the sum of all links' weight along the path. RD routing algorithms select the path with the minimum sum as the routing path. According to equation (1), (3), (9), we can calculate each link's weight by this equation:

$$D_k = \kappa P_k^{error} + \kappa(1 - P_k^{error}) P_k^{delay} \tag{11}$$

We implement RD routing algorithm in DSR[1] routing protocol. DSR is a source routing protocol proposed for mobile ad hoc networks, where intermediate node do not need to maintain up-to-date routing information for forwarding a packet. Each packet carries the end-to-end path in its header. It is an on-demand protocol where route discovery process is perform only when there is data to be sent. We extender DSR in the following ways:

First, we modify the data receiving function in MAC layer to measure SINR value. Nodes firstly measure the SINR value of the input links. Through exchanging the value with all neighbors, nodes learn the SINR value of the output links. With equation (2) and (3), we can calculate the physical loss probability e_k on the link between node n_{k-1} and n_k, the physical loss probability e_{k+1} and throughput T_{k+1} on the link between node n_{k-1} and n_k.

Second, we modify the packet header to carry following information: the output video rate(R_k), the accumulative delay from the source to the current node $\sum_{i=0}^{k} E[W_i]$, and the rate-distortion(D_k) on the node. The first two data are renewed on each node. The rate-distortion value is recorded in packet header, and used for path selection.

4. EXPERIMENT

We compare our RD routing algorithm with the shortest-path(SP) routing algorithm. The typical SP routing algorithm

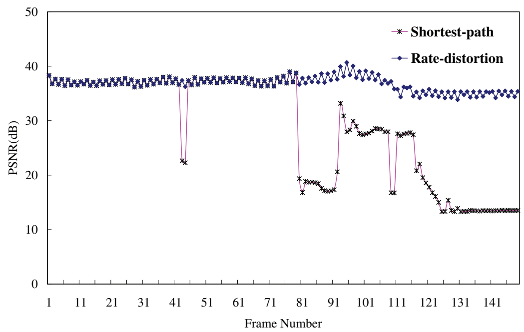
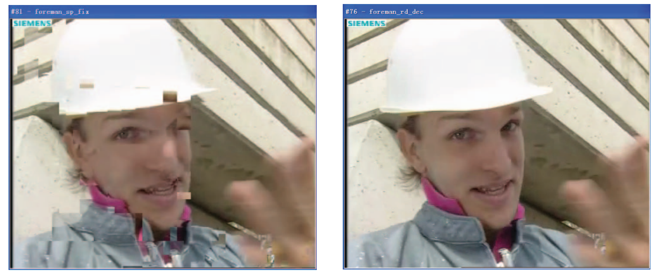


Fig. 2. PSNRs of Received Frames



(a) SP Routing (b) RD Routing

Fig. 3. Decoded Frame in Receiver

uses hop-count as the routing metric. We use a simulation model based on Ns-2 [9], and focus on the case of static wireless ad hoc networks. The IEEE 802.11 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. We simulate a 16 node wireless ad hoc network within a 1000*1000 m2 area. The video source node is located at the left-top corner, and the sink is located at the right-down corner.

The video sequences ”Foreman” are encoded using H.264 video coding standard(JM 14.2). The test video sequences is CIF(352*288) format at a temporal resolution of 15 frames per second. The average bit rate of the video is about 240.35kbps. We have investigated the impact of RD Routing algorithms in average video distortion. In order to illustrate its effect on individual video frames, we transmit encoded video on the selected path found by SP routing, and RD Routing schemes respectively. We plot the PSNRs of decodes frames in Fig. 2. It can be observed that most of frames sent on RD Routing paths have much higher PSNR values than those sent on SP routing paths. Such significant gains are due to the fact that the application layer video quality is optimized by the video distortion metric in RD Routing approach.

We also present decoded frame 76 in Fig. 3b and Fig. 3a, obtained by the RD Routing and SP routing separately. Clearly, the decoded frame in Fig. 3b has a much better visual quality than the other. Since the packet loss probability is so high in SP routing, many frames in SP Routing can not be recovered correctly. It results that visual effects of SP routing is much less than RD routing.

5. CONCLUSION

This paper proposed a rate-distortion based routing algorithm for finding the best path for video streaming over wireless ad-hoc networks. Using video distortion as path metrics, the scheme can select the path with minimum distortion. The rate-distortion is estimated on each node by using queue theory. We carried out extensive experiments in NS2 simulation environment. The experiment results evaluate our scheme. Some aspects of RD routing algorithm could be improved in the future: multi-path selection for multiple stream; packet schedule strategy to improve video quality; and optimized routing in interference environment.

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