Retransmission-Aware Queuing and Routing for Video Streaming in Wireless Mesh Networks

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Abstract— **The dynamic and shared nature of wireless medium imposes an adverse barrier to supporting QoS for video streaming applications in wireless networks. In this paper, we investigate a case study of video streaming in a wireless mesh network to obtain important observations on the factors which impact video quality in multihop wireless mesh networks. Based on our analysis of the case study, we propose the solutions for enhancing video streaming experience in wireless mesh networks from a cross-layer perspective which leverage the information across network (routing) layer and link (MAC) layer. The MAC layer retransmission count is exploited to guide the interface queue management for video packets. In addition, this retransmission count is also used as a metric to construct a retransmission-aware QoS routing scheme for video streams. In our approach, the upper layers are aware of the dynamic network status via retransmission count, so timely QoS decision can be made to enhance video quality effectively. Simulation results demonstrate the proposed solutions improve video streaming quality significantly compared with the existing schemes.**

I. Introduction

With significant advances in wireless mesh networking technologies [1], content-rich multimedia services are increasingly expected to be deployed in these networks. Traditional data applications are best-effort and no QoS is supported, while multimedia applications need to maintain a certain level of QoS to satisfy user experience requirements. However, the shared medium and limited resources make it difficult to design efficient QoS solutions for multimedia applications in wireless networks. Concurrent transmissions close to each other contend for limited resources, causing severe interference problems. In addition, wireless links are dynamic and fragile, so link failures happen frequently, which increases the complexity of QoS provisioning. All these characteristics have a great impact on the performance of resource-consuming multimedia applications in wireless mesh networks.

Most existing link layer and network layer protocols are not adequate to support QoS for multimedia applications. In the MAC layer, it has been shown that distributed QoS mechanisms are difficult for IEEE 802.11 [2]. Many existing buffer management schemes do not consider the QoS requirements of multimedia applications. Traditional routing protocols strive for the shortest path but do not explicitly support QoS. A prominent feature of wireless mesh networks is that there are generally multiple routes between a single source-destination pair, which benefits QoS routing schemes to find better routes with less interference.

Video is the most representative and complex form of multimedia, which has stringent QoS requirements. In this paper, we are concerned with the important problem of QoS provisioning for video streaming applications in wireless mesh networks. To clearly understand the factors impacting video streaming quality, we design and investigate a case study that provides us with important observations, allowing us to identify the issues which degrade video quality in wireless mesh networks. Interface queue overflow in a highly congested network environment causes packet drops. Sharing routes with best-effort traffic without QoS protection makes video streams compete with best-effort traffic on the same route which exacerbates packet losses.

Based on the analysis of the case study, we present the retransmission-aware queuing scheme and QoS routing scheme. The MAC layer average retransmission counts are exploited to guide the buffer management and the route discovery. By explicitly provisioning QoS for video traffic, our schemes enhance video streaming quality substantially.

The rest of the paper is organized as follows. In Section II, we investigate the major factors impacting the video quality in a case study. Based on the case study results, we propose our retransmission-aware QoS solutions in Section III and IV. In Section V, the performance of proposed schemes for video streaming in a random network is evaluated to demonstrate their effectiveness. We briefly discuss the related work in Section VI and conclude the paper in Section VII.

II. A Case Study

A. Network Topology and Traffic Pattern

In this section, we examine video streaming performance in a grid wireless mesh network where the network topology and traffic are well defined and can be easily controlled. We add 25 nodes in a 800m$\times$800m square area with equal 200m horizontal and vertical spacing (as shown in Figure 1). The transmission range is 250m. This grid network has the key features of a wireless mesh network: all nodes are connected to each other via multihop links and multiple paths exist between the source and the destination.

Table I lists the characteristics of the traffic we inject into the network. We create a congested network scenario common to the bandwidth-consuming video applications. For the video streams, we use the standard QCIF (176 $\times$ 144) "foreman" clip (400 frames in raw YUV format). It is compressed using FFMPEG [3] into a MPEG4 stream (25 frames per second, 10 frames in a Group Of Pictures). The packet size for video streams is 1000 bytes. Each video stream has 570 packets. The CBR flows consist of 512-byte UDP packets. All simulations are done with the NS2 simulator [4].

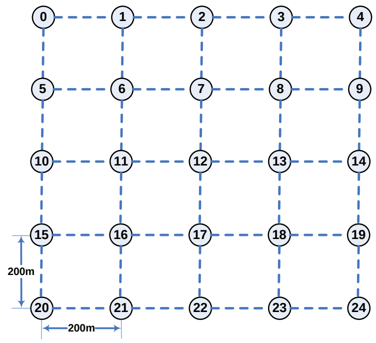


Fig. 1. A Grid Wireless Mesh Network

TABLE I
4 FLOWS IN A 5×5 GRID NETWORK

	CBR1	CBR2	Video1	Video2
Rate (Kbps)	200	200	150	150
Duration (s)	0-40	5-40	10-26	15-31
Source-Destination	10-14	16-8	10-14	16-8

Compared to other routing protocols, AODV is more effective at higher network loads [5][6] and on-demand route discovery of AODV reduces the routing overhead. These two features are desirable for multimedia applications as they generally consume more network resources, so we use AODV as a baseline in our simulations.

B. Case Study Analysis

We use Peak Signal-to-Noise Ratio (PSNR), the most widely used objective video quality metric. It is defined as a function of the mean squared error (MSE) between all pixels of the decoded video frame and the original version. The PSNRs of two video streams are shown in Figure 2. From the curves we see that after the stream2 starts, video quality of both streams degrades significantly, especially for the stream1.

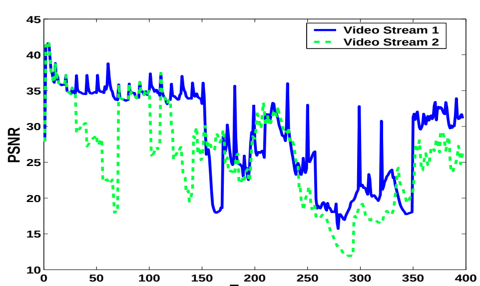


Fig. 2. PSNRs of Two Video Streams in A Grid Network

Analyzing the video packet trace, we find that the stream1 takes the path (10→11→12→13→14) and later changes to (10→5→6→7→12→13→14) due to the rerouting caused by a link failure. The stream2 takes the path (16→11→6→7→8). 51 packets are lost in the stream1; 62 packets are lost in the stream2. Analysis of the packet trace provides us clear insight of what impacts the video quality. Among the 51 lost packets of the stream1, 26 packets are dropped due to the interface queue overflow. 1 packet is lost due to reaching the MAC layer retransmission limit, so the link is deemed to be broken and the failure feedback triggers the routing layer to purge 7 packets in the queue. All 62 packets lost in the stream2 are due to the interface queue overflow.

Taking a closer look at the individual lost packets, we find that for the stream1 all interface queue overflow is seen on link 11→12. For the overflow of the stream2, 26 packets are lost on 11→6, and 36 packets on 16→11 (after the stream1 changes its route). Node 11 is the key node of both paths, so it has the highest load and most congestion, leading to frequent link failures and interface queue overflow.

One more link failure is caused by a CBR flow1 packet (reaching the retransmission limit). The failure triggers rerouting of the CBR flow1, which in turn changes the route of the video stream1 (video stream1 and CBR flow1 share the same route). The link failure feedback also causes 17 additional video packets of the stream1 purged from the queue.

From the results we find that conventional routing and queuing schemes do not consider the QoS requirements of video streams and treat them equally with best-effort traffic, so video quality is not guaranteed. Video streams have to compete with best-effort traffic at the interface queue, and share the same routes. In order to support QoS for video streams,

- At individual nodes, queue management should have higher priority for video packets so video streams can have better chance to satisfy their QoS requirements.
- We need a QoS routing scheme to discover paths offering high video quality. It must avoid highly loaded or congested nodes/links.

To make QoS decision at the higher layers (routing and the interface queue), we need a metric that is closely relevant to the network conditions. In our study, we observe that retransmission count is a good indicator of the network utilization status. The feedback of MAC layer retransmission counts can help the upper layers aware of the load distribution in the network, and provide better QoS support for video streams.

In Table II, we summarize the MAC layer retransmission statistics of video traffic in our case study. All high retransmission counts (4 through 6) occur on link 10→11. These statistics are fairly consistent with the results of packet losses, so the retransmission count in the MAC layer is a useful metric for the upper layers.

TABLE II
MAC LAYER RETRANSMISSION STATISTICS OF TWO VIDEO STREAMS

Retxs	Video Stream1	Video Stream2
1	**153**, (10→11, 68), (13→14, 27), (11→12, 21), (12→13, 15), (5→6, 12), (6→7, 5), (7→12, 5)	**76**, (16→11, 27), (6→7, 24), (11→6, 20), (7→8, 5)
2	**27**, (10→11, 21), (13→14, 2), (5→6, 2), (6→7, 1), (10→5, 1)	**2**, (16→11, 2)
3	**6**, (10→11, 5), (5→6, 1)	**0**
4	**6**, (10→11, 6)	**0**
5	**4**, (10→11, 4)	**0**
6	**1**, (10→11, 1)	**0**

III. Retransmission-Aware Queue Management

In the case study we found that many video packets are dropped due to the interface queue overflow. Conventional queuing schemes do not support QoS for video streams and treat packets from all traffic equally. A drop-tail priority queue is used for AODV where queuing follows the FIFO rule and the priority is given to the routing packets. When buffering video packets into the queue, we leverage the information from the MAC layer along with the queue length to make the queuing decision. Here we use the retransmission counts at the MAC layer, as we studied in the previous section.

To obtain the MAC layer retransmission counts, each node maintains a table of retransmission counts for its neighbors. When a packet is retransmitted, the node records the retransmission count for that packet to the destination node. For each neighbor, we set a sliding window of 5 consecutive samples of the retransmission counts. The actual retransmission count used by the upper layers is the moving average of these 5 samples which smoothes the transient change of the retransmission counts.

We use the average MAC layer retransmission count and the queue length to estimate the network status and predict the future queue utilization. The idea is similar to RED [7], a congestion avoidance mechanism to mark or drop packets based on the queue status. However RED does not work well in wireless networks where the primary issue is the interference in a node's neighborhood [8]. We use EWMA (exponentially weighted moving average) to estimate the average queue length:

$$\overline{Q}(t+1) = \alpha \cdot Q + (1-\alpha) \cdot \overline{Q}(t)$$

where $\overline{Q}$ is the queue length estimation and Q is the current queue length when a new packet is passed into the queue.

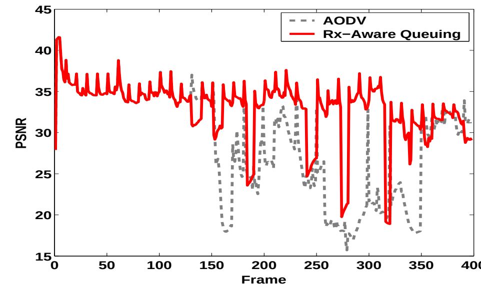
We drop best-effort packets to make room for future video packets even if the queue is not full. When a video packet needs to be queued, we add this video packet into the queue, and drop a best-effort packet with the probability P_{drop}:

$$P_{drop} = \omega \cdot \frac{\overline{R}}{R_{max}} + (1-\omega) \cdot \frac{\overline{Q}}{Q_{max}}$$

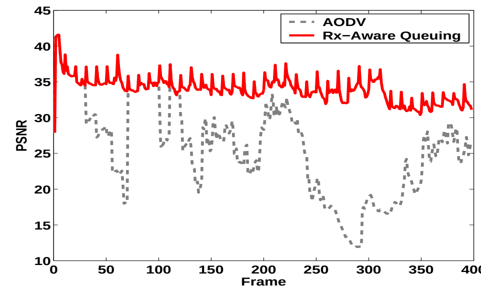
where $\overline{R}$ is the average retransmission count, and R_{max} is the retransmission limit. Q_{max} is the queue capacity. ω is the weight for retransmission count and queue length.

A high P_{drop} indicates a node is highly congested so we need to protect the video packets. We do not guarantee buffering every video packet, but it has better opportunity to be queued when a node is heavily loaded. Figure 3 shows the results when we implement the video packet queuing based on the probabilistic dropping. Video quality of both streams has been enhanced significantly. The curve of the video stream1 still suffers severe drops, so the queue overflow still exists, but it is expected as we cannot queue video packets when the queue is full. In our results both α and ω are set to 0.5.

Queue management for video packets is a local solution to enhance video quality in the sense that each node individually



(a) PSNR Comparison for Video Stream 1



(b) PSNR Comparison for Video Stream 2

Fig. 3. Video Quality Enhancement by Rx-Aware Queuing

considers QoS demands. It does not know the status of other nodes from a global network perspective. To address this limitation, we consider a QoS routing scheme to discover routes specifically for video streams focusing on streaming quality.

IV. Retransmission-Aware Routing

In the previous section, we present a QoS queuing scheme for video streams at each node. Clearly there are two problems we need to address from a global network point of view:

- Video streams share routes with best-effort traffic without any consideration for QoS requirements.
- Shortest-path routing schemes repeatedly use congested nodes and links, causing heavy loads, frequent link failures and interface queue overflow.

Therefore, we need to reconstruct a QoS based routing scheme. Most of conventional routing schemes follow the philosophy of "shortest path", where hop count is the metric to determine the best route. They are easy to design and implement, but in wireless networks the shared nature of the medium tends to make the shortest path become the bottleneck in many cases since all traffic competes for this path. Consequently, more link failures are seen on the shortest path. In addition, without explicit QoS support in those routing schemes, video traffic and best-effort traffic may have to share paths, which may adversely affect the video quality.

Based on these observations, we propose a retransmission-aware QoS routing scheme, based on AODV, that focuses on video quality. In our scheme, video streams do not share routes with best-effort traffic. Video sources run a separate QoS route discovery to find a less congested route which offers better video quality. The MAC layer retransmission count is used as the routing metric to leverage the cross-layer information.

When the video source sends out a route request, it includes the retransmission counts of its neighbors. After an intermediate node receives a route request, it checks if it is one of the neighbors of the sending node. It it is, then it adds the retransmission count of the link into the route request it will broadcast. Going forward, the route requests accumulate the retransmission counts of the links on its route from the source to the destination. We determine the quality of a route by calculating the average of retransmission counts of its links. In our routing scheme, we allow both the intermediate nodes and the destination to accept multiple route requests with the same broadcast ID from different paths (AODV drops all subsequent route requests other than the first one), so "detour" routes can be found which actually are less loaded and offer good video quality. When an intermediate node receives two or more route requests, if the average route retransmission count in the incoming route request improves compared to the current one or it is the same but the hop count is less, then the reverse path is updated, and the route request is forwarded. Otherwise, the route request is dropped and not further forwarded. Route request propagations with excessive number of hops are dropped to avoid taking detour but exceeding delay requirements. When the destination receives a route request, it compares the average route retransmission count in the route request with the one in its record. If it is less, the destination will send out a route reply. Otherwise, the destination just drops the route request. When an intermediate node receives a route reply, it constructs the path to the destination accordingly. The source may keep receiving route replies with better quality (lower average route retransmission count). Eventually, the source sends packets using the best route found in the route discovery process.

Since the network condition is considered when discovering new routes, "hot spots" with large interference are avoided, resulting in load balancing and high network utilization.

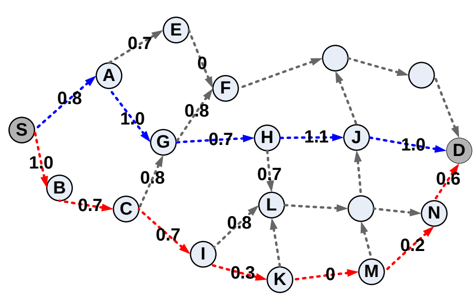
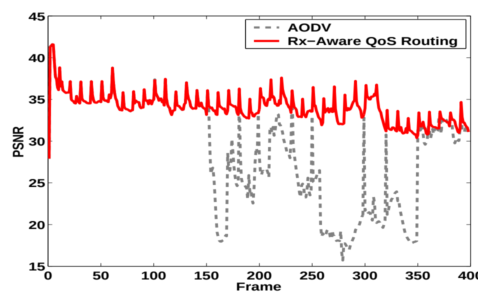
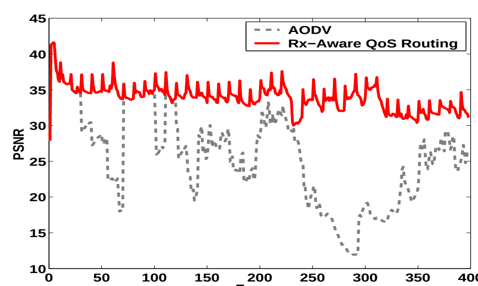


Fig. 4. A Example of Retransmission-Aware QoS Routing

Figure 4 illustrates the retransmission-aware QoS route discovery process. The source S needs to establish a video streaming session to the destination D. First, S broadcasts a route request to its neighbors carrying the average retransmission counts to those neighbors. When nodes A and B receive the route request, they find their retransmission counts (0.8 and 1.0 respectively) from the source S, add it to the route request, and forward it to their neighbors. At node G, it receives the first route request from the path S→A→G with an average route retransmission count 0.9. Later it receives another route request from the path S→B→C→G with an average route retransmission count 0.83. Although the hop count for this partial route is 3, it has a lower average route retransmission count (0.83 versus 0.9). The reverse path at G is updated from G→A→S to G→C→B→S. The route request is forwarded with this update. At node F, it receives the first route request from node G and later receives another route request from node E. Two partial routes have the same hop count, but the second one carries a lower average route retransmission count so it updates the reverse path and is forwarded. A different case occurs at node L: the first route request from the path S→A→G→H→L has the same hop count and average route retransmission count as the second route request from the path S→B→C→I→L, so the second one is simply dropped, no reverse path updated. Eventually the destination node D receives the first route request from node J and a shortest path S→A→G→H→J→D is established. Later another route request is received at D with a higher hop count but much lower average route retransmission count (S→B→C→I→K→M→N→D). So it is less congested and offers better video quality. The video streaming session will be established on this path.



(a) PSNR Comparison for Video Stream 1



(b) PSNR Comparison for Video Stream 2

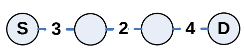
Fig. 5. Video Quality Enhancement by Retransmission-Aware Routing

In Figure 5 we present the results of applying retransmission-aware routing to the video streams in the case study. Clearly, the video quality is enhanced substantially compared to AODV. There is no packet loss for the stream1 and only 1 packet loss for the stream2. Both streams take non-shortest paths which however have a lower level of congestion, so offer better video quality.

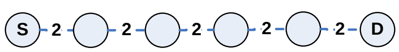
V. Performance Evaluation

In this section, we evaluate the performance of our retransmission-aware schemes for video streaming in wireless mesh networks. In addition to the simulation results of the case study, we also investigate a more general random network scenario where we compare our approach with AODV and the ETX [9] (expected transmission count), a high-throughput path metric for multihop wireless routing.

The link ETX is calculated from the forward and reverse delivery ratios. These two ratios are estimated based on the periodical broadcast probes that could cause extra overhead traffic especially in dense mesh networks. In the grid network of our case study, even without any data traffic about 10% of the periodical probes (every 0.5 second) are collided and lost, which may reduce the accuracy of ETX estimation. Our approach uses the retransmission information of realtime data packets, so no overhead is involved. The ETX of a route is the sum of the ETX of each link in the route. It may favor a shorter route over a "detour" but better quality route. Figure 6 is an example where a 3-hop chain (a) has an ETX of 9 but a 5-hop chain (b) has an ETX of 10. The bottleneck link delivery ratio for (a) is 0.25 while it is 0.5 for (b). Two more hops would cause extra delay for (b), but considering the highly lossy links on (a), they may incur additional delay and degrade the route quality. Within the delay budget, a good-quality but longer route should be acceptable which is the important feature of our retransmission-aware routing scheme.



(a) ETX = 9



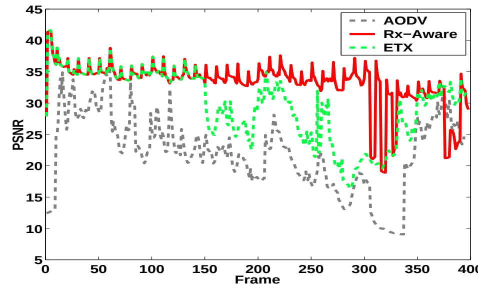
(b) ETX = 10

Fig. 6. ETX does not favor a detour route.

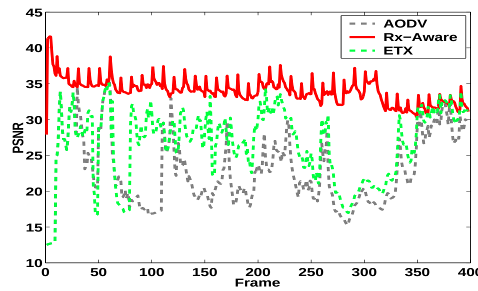
TABLE III
5 Flows in a 100-node Random Network

Flows	CBR1	CBR2	CBR3	Video1	Video2
Rate(Kbps)	100	100	100	150	150
Duration(s)	0-50	5-50	10-50	25-41	30-46

In our network setting, 100 nodes are randomly placed in a 1000×1000 square area. The simulation duration is 50 seconds. We add 5 flows into the network. The details of the traffic pattern are listed in Table III. The PSNR comparison in Figure 7 shows that the proposed retransmission-aware schemes improve the video quality quite effectively. The PSNR values of our schemes are much higher than the QoS-agnostic conventional scheme, and also higher than the ETX based approach. More visual results are presented in Figure 8 and 9 where we compare the decoded images of two video streams. The images produced by AODV are barely recognizable while our schemes offer much clearer images. ETX gives much better image quality than AODV, but it is still blurry compared with the images of our approach.

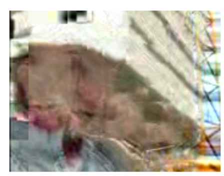


(a) PSNR Comparison for Video Stream 1

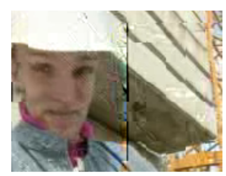


(b) PSNR Comparison for Video Stream 2

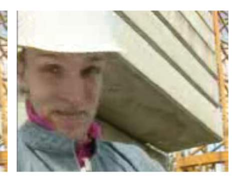
Fig. 7. Video Quality Enhancement in a 100-node Random Network



(a) AODV

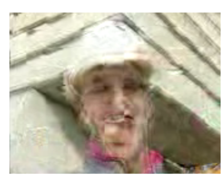


(b) ETX

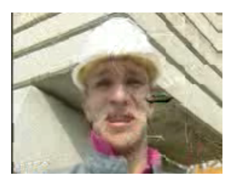


(c) Rx-Aware

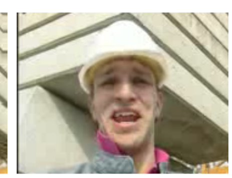
Fig. 8. Decoded Images of Frame 275 in Video Stream 1



(a) AODV



(b) ETX



(c) Rx-Aware

Fig. 9. Decoded Images of Frame 156 in Video Stream 2

The improved video quality is not at the expense of the best-effort traffic. The throughput performance of the CBR flows is not degraded as shown in Table IV. Our retransmission-aware approach helps video sessions being established on less loaded paths, avoiding heavy interference which also benefits the best-effort traffic. In Table V, we compare the end-to-end delay statistics generated by three solutions. Our approach helps video streams achieve much lower delay which is very important for enhancing user experience of video streaming. The delay of CBR flows is substantially reduced as well.

TABLE IV

AVERAGE THROUGHPUT (KBPS) OF 3 CBR FLOWS

Flows	CBR1	CBR2	CBR3
AODV	107	113	95
ETX	106	104	103
Rx-Aware	108	111	106

TABLE V

AVERAGE DELAY (MS) OF 5 FLOWS

Flows	CBR1	CBR2	CBR3	Video1	Video2
AODV	781	247	1339	947	976
ETX	329	39	128	515	573
Rx-Aware	426	189	44	75	105

VI. RELATED WORK

Video streaming in wireless mesh networks has been receiving great attention [10] in the research community. To support QoS provisioning for video applications in wireless networks, cross-layer design which exploits the lower layer information has been widely considered as an effective and efficient solution [11][12].

QoS schemes based on IEEE802.11e [13] were proposed in [14][15]. Mastronarde *et al.*[14] proposed a synergistic optimization algorithm for control parameters at each node, across the protocol layers as well as end-to-end. Their optimization is based on HCCA mode of IEEE802.11e (providing a contention-free TXOP interval) and an overlay network infrastructure available to convey real-time network information. In highly dynamic wireless mesh networks, these two assumptions may not hold true. In [15], the proposed cross-layer design maps video packets to appropriate link layer access categories according to their information significance. This content-aware categorization prioritizes important video packets (I frame) to improve video quality. However in heavily loaded networks, packet losses are often caused by the congestion of concurrent transmissions from other nodes.

The impact of retransmissions on multimedia transmission over WLANs was evaluated in [16]. A heuristic for cooperative retransmission between the sender and neighbors that overhear the transmission was proposed [17] to decrease latency. However, both efforts focused on single-hop networks. For multihop wireless mesh networks, an optimization framework for video streaming over multihop mesh network was proposed in [18] by considering the modulation rate (PHY layer), retransmission limit (MAC layer), routing (network layer), and packet scheduling (application layer). ETX [9], as we discussed in the previous section, was proposed as a routing metric for multihop wireless networks. This scheme however has large messaging overhead and system complexity issues.

Interference-aware routing was investigated in [19] and [20]. Both proposals employed the conflict graph based model to characterize the interference. Our work differs in that we use runtime information (retransmission counts of data packets) to identify the effect of interference in a node's transmitting neighborhood.

VII. CONCLUSION

In this paper, we study video streaming performance in multihop wireless mesh networks. Based on the investigation of a case study, we identify the major factors that degrade the video streaming quality. We propose the retransmission-aware queuing and QoS routing schemes to address the issues exposed in the case study. The extensive simulation results show the significant increases of the average PSNR values over the existing solutions, justifying the effectiveness of the proposed cross-layer approach for enhancing video streaming quality in wireless mesh networks.

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