Performance Evaluation of Video Streaming in Multihop Wireless Mesh Networks

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ABSTRACT

Supporting multimedia services in wireless mesh networks is receiving more attention from the research community. While wired networks have mature infrastructure and protocols providing QoS for multimedia, supporting multimedia in multihop wireless mesh networks faces greater technical challenges. The unreliable nature and shared media of multihop communications make the deployment of multimedia applications in wireless mesh networks a difficult task. To identify and understand the issues and problems of providing multimedia in multihop wireless mesh networks, we take video streaming as an example, setting up a real testbed to conduct extensive experiments in various scenarios and analyze its performance. In contrast to simulation or network-layer statistics based studies, our investigation is directly focused on video quality in multihop scenarios. The results better represent real networks and reveal interesting aspects of video performance in multihop wireless mesh networks, which we believe is helpful in designing efficient QoS solutions for multimedia services in the wireless mesh networks.

1. INTRODUCTION

Wireless mesh networking has made significant advances in both research and practice in recent years. In addition to traditional data services, content-rich multimedia applications (such as video-conferencing, VoD or VoIP) are increasingly being deployed in this type of networks. However, multimedia services need QoS support to maintain user satisfaction, which is fairly difficult in multihop wireless mesh networks where dynamic environments cause fragile links and high packet loss ratios, having a great adverse impact on quality of multimedia. More importantly, shared media severely limit resource availability, especially in multihop scenarios. Interference among concurrent transmitting links (either on a multihop path or multiple paths in proximity) complicates supporting resource-consuming multimedia applications. Hence, QoS schemes for wired networks are not directly applicable. New solutions incorporating special characteristics of wireless mesh networks need to be developed.

As a complex form of networked multimedia, video transmission, particularly in interactive applications, has stringent QoS requirements to maintain high quality for user's perception. To support video applications in wireless mesh networks, one must have a deep understanding about their performance under dynamic and multihop network conditions. In this paper, we take video streaming as an example of multimedia services and evaluate its performance in a multihop wireless mesh network testbed. Extensive experimental performance study for video applications in multihop wireless mesh networks is rarely reported in literature.

Prior work was mostly based on simulations that make over-simplified assumptions and overlook many details. In many studies, only network-layer statistics (such as throughput, delay and loss) or single-hop scenarios were investigated. However, those metrics are not directly related to user-perceived video quality, which is the most important application layer metric. In addition, multihop communications are more prevailing and difficult in wireless mesh networks. We take an experimental approach based on a real multihop wireless mesh testbed to study the performance of video streaming, with a direct focus on video quality as well as traditional network-layer statistics. We analyze the video performance in a real multihop wireless environment as it is very important to identify potential problems and design solutions to support QoS for video applications in wireless mesh networks.

Supporting multimedia services in wireless mesh networks is an active research topic. Performance evaluation study for video applications is reported in several papers. Sun *et al.* [1] investigated the media traffic performance in mesh networks. They evaluated the performance of both video and voice traffic through multihop wireless paths. However, their testbed ran in an ad-hoc mode and focused on network layer statistics. Nodes in ad-hoc mode maintain communications in a peer-to-peer fashion. It does not fully harvest the benefits of infrastructure wireless mesh networks in which a gateway/access point (AP) node manages and coordinates a group of client nodes and provides access to the backbone Internet. In practical deployments, AP-client mode is more efficient.

The performance of video streaming with background traffic over IEEE 802.11 WLANs was studied in [2]. The experimental comparison of wired versus wireless video streaming over IEEE 802.11 WLANs was presented in [3]. Both papers only addressed the cases of single hop WLANs, not multihop scenarios which is the inherent nature of wireless mesh networks. In addition, their evaluation targets were still network layer performance, not user-perceived video quality.

The rest of the paper is organized as follows. Section 2 gives the hardware and software details of our testbed. We present our study on basic video performance in Section 3. Performance tradeoffs are discussed in Section 4. Video performance under various parameter settings is demonstrated in Section 5. Potential techniques for enhancing video streaming quality are introduced in Section 6. Section 7 summarizes and concludes the paper.

2. WIRELESS MESH TESTBED

2.1 Hardware

The testbed topology for our experiments is shown in Figure 1, which is a small but typical wireless mesh network in a regular

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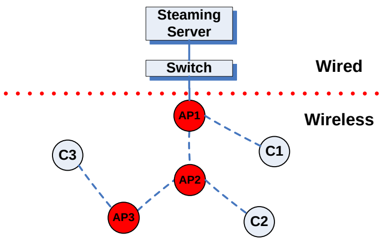


Figure 1: A wireless mesh testbed

lab room (7m×7m). AP1, AP2 and AP3 are three access points (Soekris boards [4]). A streaming server is connected to AP1 via a switch. Three clients (laptops) C1, C2 and C3 are associated with their corresponding access points. In the nomenclature of IEEE 802.11s [5], AP1 is a mesh portal connected to the wired backbone. AP2 is an access point as well as a mesh point, which relays packets for AP3. AP3 is a pure access point. WDS (Wireless Distribution System) [6] links are employed to achieve inter-access point communications. Although the topology considered here is simple and small, it has most of the variants and characteristics of a typical multihop wireless mesh network. To avoid interference from IEEE 802.11b/g networks, IEEE 802.11a is used in all tests with a channel rate 6 Mbps.

2.2 Software

All nodes in the network are equipped with the Linux kernel 2.6.22 and madwifi Atheros driver [6]. VideoLAN [7] server and client are applied to stream video. A NTP server [8] is setup on the streaming server. APs and clients periodically synchronize their local time with the NTP server. A 2000-frame *highway* video clip is used in the evaluation. It is coded into MPEG4 streams using *ffmpeg* [9] with a frame rate of 25 fps (it lasts for 80 seconds). UDP/RTP is used for the streaming protocol.

Video quality is highly related to subjective human perception, which is difficult to be characterized by conventional statistics such as delay, loss ratio and throughput. MOS (Mean Opinion Score) is a subjective measure to provide a numerical indication of the perceived quality of received media. In many cases, it is too expensive and often biased. Therefore, we apply another widely used objective metric–PSNR (Peak Signal-to-Noise Ratio).

3. BASIC PERFORMANCE

In this section, we evaluate the video streaming performance with basic settings in the presence of interference, either from other video flows or best-effort traffic. We intend to understand the impacts of interference on video performance, which is the major source of quality degradation.

3.1 Impact of Interference

An important characteristic of wireless mesh networks is the use of shared media. Open-air communications allow interference among concurrent transmissions to degrade the network performance significantly. Interference may exist among different flows, or network links on a single multi-hop flow, termed as inter-flow and intra-flow interference respectively.

3.1.1 Inter-flow Interference

We study the inter-flow interference between two flows from the Server via AP1 to C1 (1-hop), and from the Server via AP1, AP2 and AP3 to C3 (3-hop). The coding rate of both flows is 1500 Kbps.

We first stream two flows simultaneously from the Server to two clients. Next we stream only one (3-hop) flow from AP1 to C3. We demonstrate the interference of the 1-hop flow on the 3-hop flow. In Figure 2 we compare the PSNR values in these two cases. Clearly the interference from the 1-hop flow severely degrades the video quality of the 3-hop flow (1-hop flow itself also suffers low video quality). When streaming the 3-hop flow only without inter-flow interference from the 1-hop flow, its PSNR values are constantly much higher. Network statistics in Figure 3 give similar results. Without interference, the 3-hop flow only has few packet losses while interference from the 1-hop flow causes a much higher loss ratio.

Table 1: Average network statistics of the 3 links of the 3-hop flow in the presence of inter-flow interference from the 1-hop flow.

Link	Thr.	Loss	Delay	Jitter
AP1-AP2	1296	0.1837	166.6	6.426
AP2-AP3	1299	0.00011704	24.4	5.878
AP3-C3	1298	0	19.6	4.065

To better understand the impact of inter-flow interference, we take a closer look at the network statistics of individual links of the 3-hop flow as shown in Table 1. [1] We can see that the link AP1-AP2 is the bottleneck link that has the highest loss ratio. This is to be expected as this link is the closest to the 1-hop flow (from AP1 to C1). Link AP2-AP3 and link AP3-C3 only have a few packet losses as most of the contention happens on link AP1-AP2.

3.1.2 Intra-flow Interference

We investigate the intra-flow interference in three individual experiments. A flow from the Server via AP1 to C1 (1 hop), from the Server via AP1 and AP2 to C2 (2 hops), or from the Server via AP1, AP2 and AP3 to C3 (3 hops) is separately streamed in these three experiments. The coding rate of three flows is 2500 Kbps.

The results are shown in Figures 4 and 5. Interference among the links degrades the video quality in the 2-hop and 3-hop flows. The 3-hop flow has the worst performance, with an average loss ratio of 36.83% and delay of 617.6ms which makes the video barely recognizable. 6 Mbps channel rate is sufficient for the 1-hop flow, so it enjoys lossless transmission and the highest video quality (PSNR values).

One important observation is that the video quality (PSNR) is not directly related to network layer metrics. When the same flow goes through a 2-hop path, compared with the 1-hop path, there is a slight decrease in throughput and sporadic losses (mostly around 20s and a slot of 40-60s). However, PSNR values drop significantly after the loss events occur and keep propagating. Video is compressed based on motion prediction and compensation, so this error propagation effect is typical and impacts video performance.

3.2 Impact of Best-effort Traffic

QoS provisioning is necessary for multimedia applications. However, there exists a large volume of best-effort traffic which may not require QoS support, but will affect the performance of multimedia traffic. In this section, we study the impact of best-effort traffic (TCP or UDP based) on video streaming applications.

All tests are performed in a 3-hop scenario. In both TCP and UDP cases, a video flow coded at the rate of 1000 Kbps is streamed from the Server via AP1, AP2 and AP3 to C3. A best-effort flow (TCP or UDP) is injected from C1 to C2 via AP1 and AP2 20 seconds after the video streaming starts and lasts for 40 seconds. The rate of the UDP flow is 1000 Kbps. The results are shown in Figures 6 and 7. We find that both TCP and UDP flows degrade video performance, but with the different amount of impact. Because of the congestion control in TCP, the interference caused by the TCP flow is moderate compared with the UDP flow. The increases in loss ratio and delay are much less in the case of the TCP flow than the UDP flow. The average PSNR value drop due to the UDP flow (9.6 dB) is larger than the TCP flow (4.4 dB).

We further study the impact of best-effort flows on individual links of the video flow. Network statistics of individual links of best-effort flows are also compared. The results with the TCP flow

[1] Throughout the paper, we use the following abbreviations and units in all tables: Thr. for throughput in Kbps; Loss for loss ratio; Avg P. for Average PSNR in dB. Delay and jitter are in millisecond.

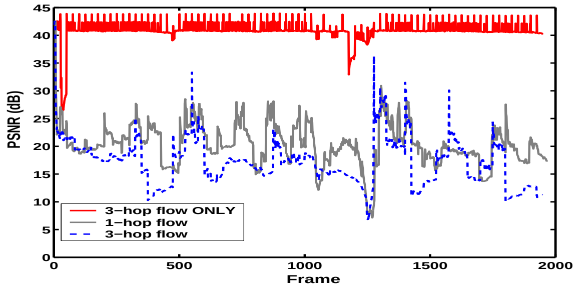
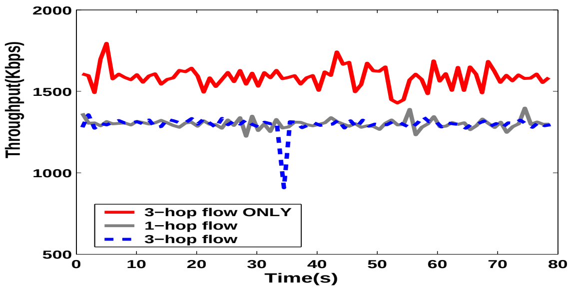
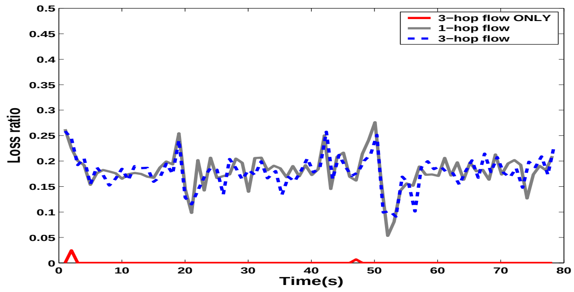


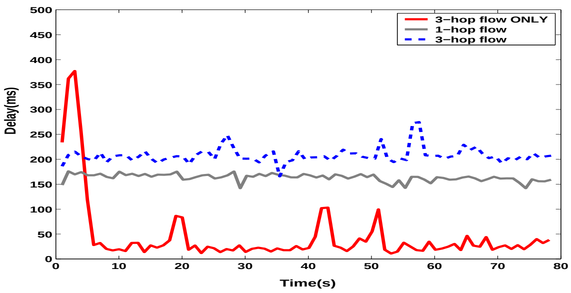
Figure 2: PSNR comparison—with and without inter-flow interference: when streaming with inter-flow interference, both 1-hop and 3-hop flows are streamed simultaneously; when streaming without inter-flow interference, ONLY 3-hop flow is streamed.



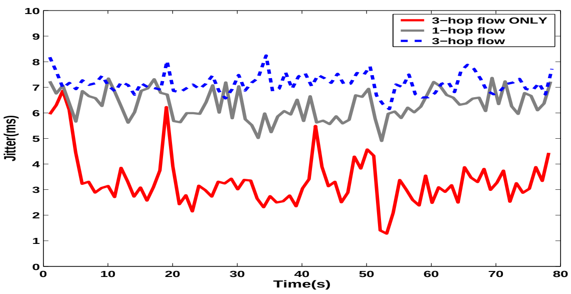
(a) Throughput.



(b) Loss.



(c) Delay.



(d) Jitter.

Figure 3: End-to-end network statistics comparison—with and without inter-flow interference: when streaming with inter-flow interference, both 1-hop and 3-hop flows are streamed simultaneously; when streaming without inter-flow interference, ONLY 3-hop flow is streamed.

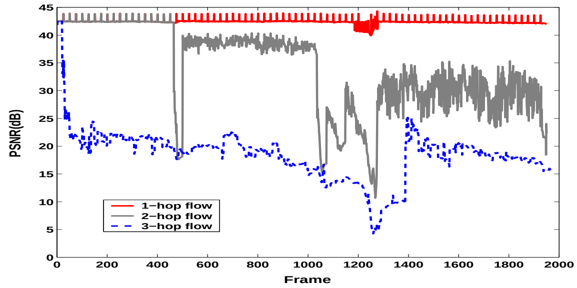
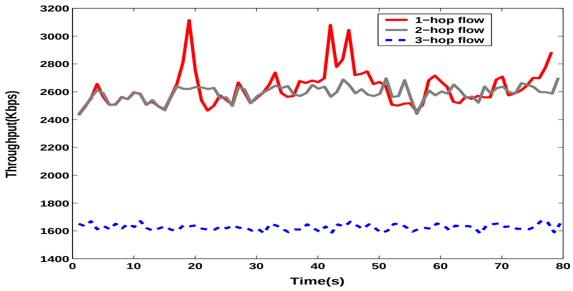
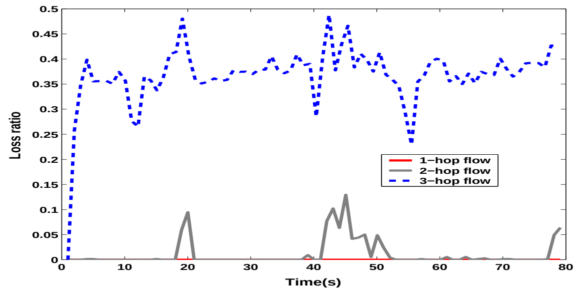


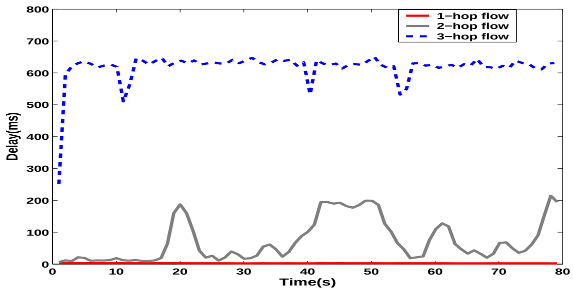
Figure 4: PSNR comparison—the same flow streamed on paths with different number of hops: when streaming on a 1-hop path, there is no intra-flow interference; when streaming on a 2-hop or 3-hop path, there is intra-flow interference.



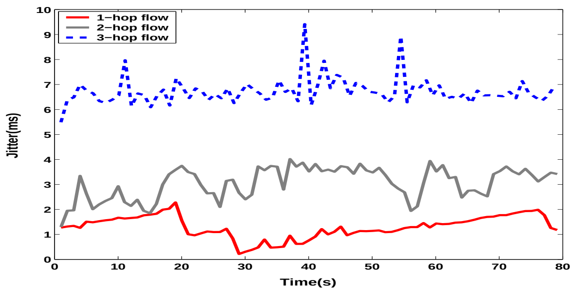
(a) Throughput.



(b) Loss.



(c) Delay.



(d) Jitter.

Figure 5: End-to-end network statistics comparison—the same flow streamed on paths with different number of hops: when streaming on a 1-hop path, there is no intra-flow interference; when streaming on a 2-hop or 3-hop path, there is intra-flow interference.

Table 2: Average network statistics of 3 links of the video flow in the presence of interference from the TCP flow.

Link	Thr.	Loss	Delay	Jitter
AP1-AP2	1075	0.0007244	27.53	5.101
AP2-AP3	1066	0.008156	89.37	6.398
AP3-C3	1067	0.0000531	22.83	5.025

Table 3: Average network statistics of 3 links of the TCP flow.

Link	Thr.	Delay	Jitter
C1-AP1	547	19.88	10.592
AP1-AP2	548	20.04	6.670
AP2-C2	528	173.03	11.344

Table 4: Average network statistics of 3 links of the video flow in the presence of inteference from the UDP flow.

Link	Thr.	Loss	Delay	Jitter
AP1-AP2	1007	0.06355	131.4	5.179
AP2-AP3	920	0.09376	167.9	8.870
AP3-C3	920	0.00007181	21.1	5.109

Table 5: Average network statistics of 3 links of the UDP flow.

Link	Thr.	Loss	Delay	Jitter
C1-AP1	988	1.9628e-004	15.2	5.126
AP1-AP2	987	9.5786e-005	56.1	5.822
AP2-C2	569	0.4199	486.3	18.448

are shown in Tables 2 (individual links of the video flow) and 3 (individual links of the TCP flow); the results with the UDP flow are shown in Tables 4 (individual links of the video flow) and 5 (individual links of the UDP flow). From Tables 2 and 4 we can see that for the video flow, link AP2-AP3 suffers large intra-flow interference from the link AP1-AP2 and AP3-C3 as well as large inter-flow interference from the best-effort flows. Thus it is the bottleneck link which has the highest loss ratio and end-to-end delay. Link AP3-C3 is the least affected by interference, and hence it has the best quality. Link AP1-AP2 has relatively higher quality with TCP than UDP. It is again explained by TCP's congestion control capability, which throttles the flow rate and causes much less interference on this link than UDP. For the link statistics of the TCP and UDP flows, link AP2-C2 is the bottleneck that incurs the most interference from the video links and other links on the same TCP or UDP flow. In addition, link AP2-C2 of the UDP flow has higher delay and jitter than those of the TCP flow.

4. PERFORMANCE TRADEOFFS

4.1 Tradeoff Between Rate and Quality

Table 6: Comparison among flows with different coding rates.

Coding rate	Avg P.	Thr.	Loss	Delay	Jitter
1500Kbps	40.74	1588	0.0004032	44.9	3.342
2000Kbps	23.50	1706	0.1817	292.8	6.186
2500Kbps	15.92	1702	0.3436	306.3	6.874

Interference and unreliable communication media in wireless mesh networks make higher rates of video streams not necessarily desirable. In this experiment, we study the tradeoff between video coding rate and the achieved video quality. We stream a video flow from the Server via AP1, AP2 and AP3 to C3, varying the rate from 1500 Kbps to 2000 Kbps and 2500 Kbps. From the results in Table 6 we find that the 1500 Kbps flow has the lowest rate and throughput, but it has the best video quality and network performance. Interference (particularly intra-flow interference in this case) explains the large performance gaps. Clearly, high rates do not necessarily imply high video quality in wireless mesh networks.

4.2 Capacity of Supporting Multiple Streams

In wireless mesh networks, the capacity for supporting multiple streams on different paths is different due to inter-flow and intra-

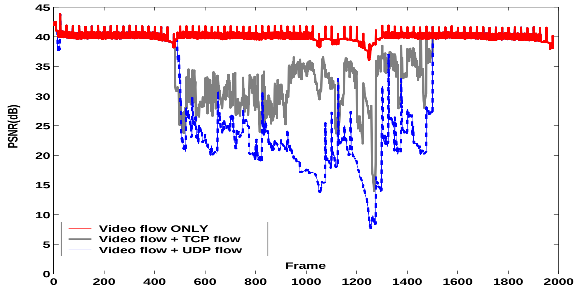
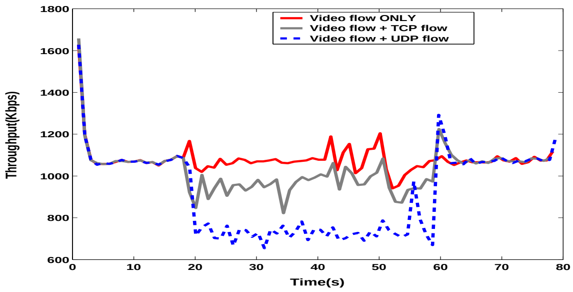
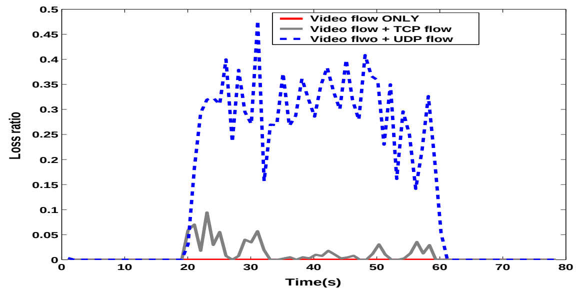


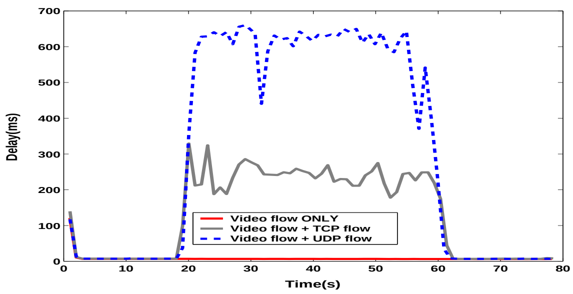
Figure 6: PSNR comparison of the same video flow: when streaming the video flow ONLY; when streaming the video flow with the TCP flow; when streaming the video flow with the UDP flow.



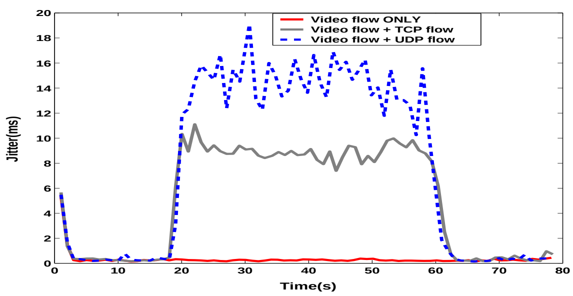
(a) Throughput.



(b) Loss.



(c) Delay.



(d) Jitter.

Figure 7: End-to-end network statistics comparison of the same video flow: when streaming the video flow ONLY; when streaming the video flow with the TCP flow; when streaming the video flow with the UDP flow.

flow interference. In this test, we demonstrate this capacity of paths with different number of hops. We stream multiple video flows coded with the rate of 1000 Kbps on a 1-hop, 2-hop or 3-hop path respectively. In general, video quality (PSNR values) degrades with increasing number of streams (Figure 8). However, to support the same number of streams, a path with a fewer number of hops can offer higher video quality (higher average PSNR values for each stream). Network statistics in Figure 9 give the underlying explanations of this capacity difference. The insight behind these results again is that interference in multihop scenarios significantly worsens the video performance.

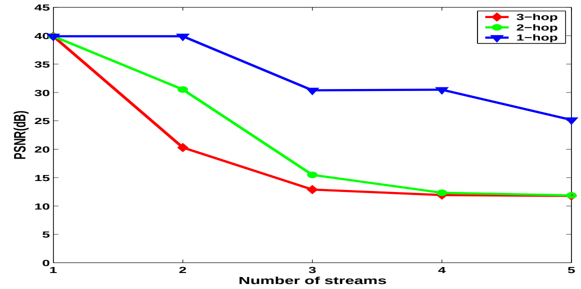


Figure 8: PSNR comparison—average PSNR of each stream: support multiple streams on paths with different number of hops.

5. PERFORMANCE VARIATIONS

In this section, we investigate the video performance variations by tuning parameter settings. The video coding rate in the following experiments is 2000 Kbps.

5.1 RTS/CTS

In this experiment, we study the impact of RTS/CTS on video quality. The results in Table 7 show that enabling RTS/CTS does not significantly improve the video performance. Both the video quality and the network level statistics are similar. When RTS/CTS is disabled, network statistics have slightly less variations. RTS/CTS packet exchange adds more overhead and thus causes more contention and interference.

Table 7: Comparison with different RTS/CTS settings.

RTS/CTS	Avg P.	Thr.	Loss	Delay	Jitter
Enabled	22.72	1692	0.1850	453.7	6.067
Disabled	22.71	1696	0.1845	457.2	6.001

5.2 Buffer Size

In this experiment, we study the impact of UDP buffer size of VideoLAN on the video quality. We vary it from 0ms to 300ms and 1000ms. From the results in Table 8 we can see that the UDP buffer does not have significant impact on the video quality. The average PSNR increases only slightly with a higher buffer size. When we take a closer look at the PSNR values, we find that buffering has more impact on the initial stage of streaming. With larger buffer size, initial PSNR values are much higher. Since buffer size is a decoder parameter at the receiver, it does not affect the networking layer statistics.

Table 8: PSNR comparison with different UDP buffer size.

Buffer size (ms)	0	300	1000
Avg PSNR	23.27	23.75	24.15

5.3 UDP Packetization

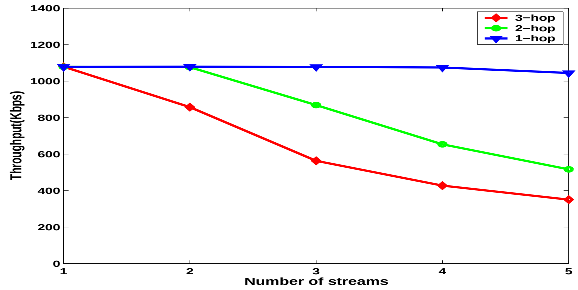
In this experiment, we study the impact of UDP packet size on video quality. We use 500B, 1000B and 2000B of packet sizes. The results in Table 9 show that a smaller packet size incurs more transmission overhead and collisions (interference), hence the flow with 500B UDP packets has the worst video quality and highest loss ratio. However the downside of a larger UDP packet size is that it causes higher delay and jitter.

Table 9: Comparison with different UDP packet size.

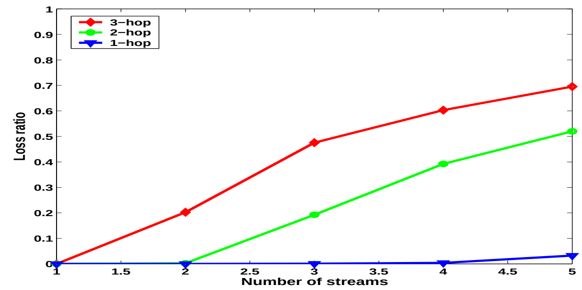
UDP pkt size	Avg P.	Thr.	Loss	Delay	Jitter
500B	13.87	1400	0.3479	207.3	3.077
1000B	19.13	1544	0.2618	376.3	4.473
2000B	19.80	1549	0.2525	456.2	6.528

5.4 MAC Layer Fragmentation

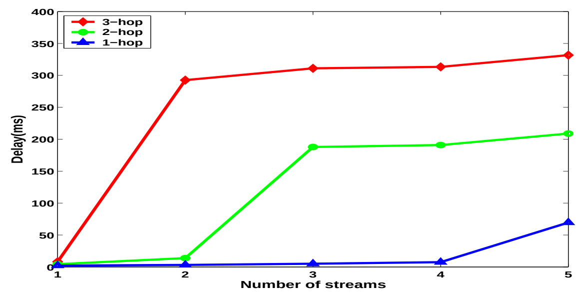
In this experiment, we study the impact of MAC layer fragmentation on video quality. We set it as 512B, 1024B and 1500B respectively. The results are shown in Table 10. Similar to the experiment of UDP packetization, the smaller MAC frame fragmentation produces higher video quality (PSNR values) and lower loss ratio. On the other hand, larger fragmentation incurs higher delay and jitter.



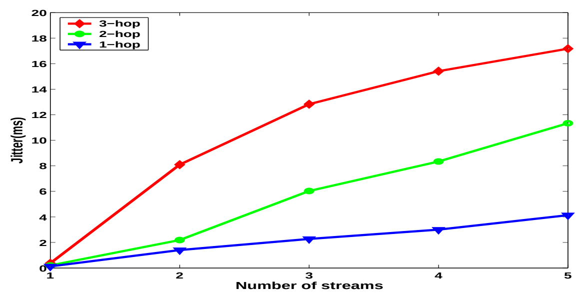
(a) Throughput.



(b) Loss.



(c) Delay.



(d) Jitter.

Figure 9: End-to-end network statistics comparison—average values of each stream: support multiple streams on paths with different number of hops.

Table 10: Comparison with different MAC fragmentation.

MAC pkt size	Avg P.	Thr.	Loss	Delay	Jitter
512B	14.84	1486	0.2886	134.4	5.249
1024B	17.30	1551	0.2575	184.7	5.112
1500B	23.35	1687	0.1808	492.7	6.295

From the above two experiments with various packet size at transport and MAC layers, we find that it is very important to do proper packetization at various layers to achieve optimal performance. A video frame is normally large and has to be segmented into multiple packets. We need to carefully maintain a tradeoff between quality and delay. When generalized into other multimedia applications, such as VoIP which is delay-sensitive and consists of many small packets, this consideration is even more important.

6. PERFORMANCE ENHANCEMENTS

In this section, we explore the enhancement techniques in wireless mesh networks to improve the video quality.

6.1 Gain with Multichannel and Multiradio

Multichannel and multiradio can significantly reduce interference among nodes. Our experimental results clearly show that even with two radios we can achieve substantial gain in video quality. We compare the streaming of a 2500Kbps flow from the Server via AP1, AP2 and AP3 to C3 in both single-radio and two-radio scenarios. In the two-radio scenario, AP2 and AP3 operate on two radios with two different channels. Link AP1-AP2, link AP2-AP3 and link AP3-C3 are on three orthogonal channels.

The comparison is made in Table 11. Channel diversity of links allows interference-free concurrent transmissions, which reduces loss ratio (only few packet losses), delay and jitter substantially. Consequently, much higher throughput is achieved, which in turn make higher video quality (PSNR values) possible.

Table 11: Comparison between single-radio and two-radios.

Radio	Avg P.	Thr.	Loss	Delay	Jitter
1	18.39	1626	0.3683	617.6	6.725
2	42.35	2625	0.00001669	7.5	1.283

6.2 Basic QoS Support with IEEE 802.11e

Madwifi driver supports IEEE 802.11e [10], which provides basic QoS features to IEEE 802.11 networks by differentiating traffic into four AC (Access Categories)—voice, video, best effort, and background. Traffic in each category has a predefined priority when competing for channel access.

We investigate the performance gain in video streaming by applying IEEE 802.11e QoS support. In both experiments with or without QoS extension, we first send a 1500 Kbps UDP flow from AP1 to C3 via AP2 and AP3. After 5 seconds, we stream a 1000 Kbps video flow from the Server to C3 via AP1, AP2 and AP3. In the experiment with QoS support, we set the priority of the UDP flow as AC_BE (best-effort traffic) and the video flow as AC_VI (video traffic). Table 12 summarizes the average results of the experiments. We find that QoS prioritization significantly improves the video quality (29.62 dB with QoS support versus 21.90 dB without QoS). The basis of this enhancement is the substantially reduced loss ratio and delay of the video stream. However, due to the shared nature of the wireless media, the improved video quality is at the expense of the deteriorating UDP flow (higher loss ratio and larger end-to-end delay). Therefore, avoiding the starvation of best-effort traffic when designing QoS schemes is an important issue. We also tested with a TCP flow in the same experimental setting. The quality improvement is marginal. Unlike UDP traffic, congestion control in TCP reduces transmission rate. Thus the prioritization mechanism does not have as much impact as with the UDP traffic.

Table 12: Comparison between w/ and w/o IEEE 802.11e.

	Avg P.	Thr.	Loss	Delay	Jitter
Video flow w/ 802.11e	29.62	996	0.02071	48.0	8.499
Video flow w/o 802.11e	21.90	764	0.2529	358.7	9.167
UDP flow w/ 802.11e	——	851	0.4142	1162.0	17.30
UDP flow w/o 802.11e	——	1066	0.2249	321.7	6.28

7. CONCLUSIONS

We evaluate the system performance of video streaming in a multihop wireless mesh testbed. Compared to prior work, our results in multihop scenarios better represent real system and network issues and directly targeted on video quality which is the application layer metric. While many of our broad conclusions hold true in wired networks, this is the first study to consider the specific performance tuning that needs to be done for maintaining video quality in multihop wireless mesh networks. The results expose many insights about the video streaming in wireless mesh networks:

- Video has its special characteristics. Perceptual quality of video is not always directly related to networking layer statistics. Lower layer solutions must consider application layer performance metric.
- Interference adversely degrades video performance. Both inter- and intra- flow interference have a great impact on video quality. This is particularly true in wireless multihop scenarios.
- In a multihop wireless mesh network, the tradeoff between streaming rate and video quality needs to be considered carefully. High rates do not necessarily bring high video quality. Multihop interference complicates this issue.
- To obtain higher video quality, we need to intelligently tune various parameters, which has important impact on network performance as well as video quality. For instance, RTS/CTS does not really help much to improve video quality. Small packet size reduces delay but worsens quality significantly.
- Emerging enabling techniques show great potential in improving video quality in wireless mesh networks. Multichannel/multiradio creates interference-free transmissions and produces video reception with higher quality. IEEE 802.11e gives multimedia traffic higher priority and enhances their quality.

We believe that our study is beneficial for network design and implementation (such as routing, QoS provisioning) in multihop wireless mesh networks for multimedia applications. Our results provide insights in potential problems and solutions for supporting video streaming in wireless mesh networks. Our experience in building a multihop testbed and performance measurement may be helpful for other researchers in their experimental studies as well as to network administrators in tuning their deployments.

8. REFERENCES

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