Quality of Experience Oriented Video Streaming in Challenged Wireless Networks: Analysis, Protocol Design and Case Study

Tom H. Luan, Sanying Li, Mahdi Asefi, Xuemin (Sherman) Shen (Fellow, IEEE),
Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON N2L 3G1, Canada
{hluan,s68li,masefi,xshen}@bbcr.uwaterloo.ca

1. Introduction

The networked video streaming has achieved tremendous success in the past decade. It has already become the killer Internet application. As reported in [1], 183 million U.S. Internet users watched 40.9 billion online videos in one month. Youtube, the most popular video sharing site, features over 40 million videos and attracts around 20 million subscriptions per month. On the other hand, the last decade has witnessed the equally exciting evolution and explosive adoption of various mobile portable devices, such as smartphones, tablet PCs and laptops. This makes efficient wireless video streaming to the heterogeneous and mobile devices ever more important and demanding.

With the limited network connectivity and high mobility, mobile devises are often connected through the challenged wireless networks, such as Delay Tolerant Networks (DTNs), Mobile Ad-hoc Networks (MANETs) and cognitive radio networks. These networks are characterized by the *network heterogeneity*, *frequent network partition*, and *dramatically changing networking conditions*. Video streaming in such environments inevitably suffers from the intensively changing throughput, long packet delay and severe packet losses, making traditional video systems and protocols operate poorly. In this paper we focus on the design of Quality of Experience (QoE) oriented video streaming system over the challenged wireless networks. To this end, we first develop an analytical framework to characterize the QoE of users, represented by the network performance metrics. Based on the developed model, we introduce a cross-layer design framework to build the QoE-oriented video streaming system over the challenged wireless networks. Lastly, we showcase the implementation of the proposed cross-layer framework in the vehicular networks and cognitive radio networks.

2. QoE-oriented Video Streaming

We consider a typical packetized video streaming as shown in Fig. 1. The encoded video clips are cached at media servers and streamed to remote mobile users using the UDP/IP protocol stack through the challenged wireless networks, such as DTN and MANET. Churned by the dynamic and uncertain network connectivity and performance, video playback tends to suffer from frequent playback interruptions and annoying delays once the playback halts. We thus model the QoE of users from the perspective of video playback smoothness and experience. In specific, we evaluate the QoE of users through two metrics: (1) start-up delay, i.e., delay when user subscribes to watch the video until the video playback starts, and (2) probability of playback frozen, i.e., the probability that playback halts during the video playout.

We evaluate the two QoE metrics by analyzing the playout buffer at the receivers. Specifically, to combat the network dynamics, a typical way is by deploying a playout buffer at the receiver, as shown in Fig.1. To eliminate the effects of variable arrival delays (or delay jitters), the playout buffer postpones the start of video playback by a short period (start-up delay), and buffers the downloaded video packets in a local cache until a certain threshold is reached.

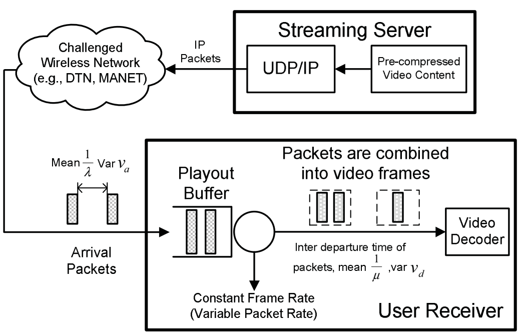

Figure1 Playout Buffer at the Receiver

Therefore, as long as the playout buffer is kept nonempty during the video presentation, the playback can always sustain. In other words, provided the network download performance, the QoE of end users is closely related to the evolution of the playout buffer over time.

Let λ and v_a denote the mean value and variance of the packet download rate, respectively. Let μ and v_d denote the mean value and variance of the video playback rate, respectively. Let *D* denote the start-up delay, which accounts the duration starting when the playback halts until the playback restarts when the number of the buffered packets reaches a threshold *b*. Let *P* denote the probability of playback frozen once the playback initiates. We model the playback buffer as a G/G/1 queue. As described in [1], assuming that $\lambda \le \mu$ and the playout buffer size is infinite, the start-up delay can be represented by the cumulative density function as

$$\Pr(D \le t) = \Phi\left(\frac{x-\lambda t}{\sqrt{\lambda^3 v_a t}}\right) - \exp\left(\frac{2b}{\lambda^2 v_a}\right)\Phi\left(\frac{x-2b-\lambda t}{\sqrt{\lambda^3 v_a t}}\right), \quad (1)$$

where $\Phi(\cdot)$ is the standard normal distribution. The probability of playback frozen *P* is

$$P = \exp\left(-\frac{2b}{\lambda^3 v_a + \mu^3 v_d}(\lambda-\mu)\right). \quad (2)$$

From (1) and (2), decreasing the network variations v_a would monotonically reduce the average start-up delay and probability of playback frozen. Increasing the playback threshold *b* will reduce the probability of playback frozen but enlarge the average start-up delay.

Based on relationship between the network performance metrics (mean value and variations of download rate) and the QoE metrics, as characterized by (1) and (2), the goal of the QoE-oriented video streaming is to optimize the network formation to attain the best user perceived video quality,

$$\max \sum_i U_i(D_i, P_i) \quad (3)$$
$$\text{Subject to } (\lambda_i, v_i) \sim \Omega$$

In (3), the utility $U_i(\cdot)$ represents the satisfaction of user *i*; it is a decreasing function of the start-up delay D_i and probability of playback frozen P_i of user *i*. The objective of (3) is thus to maximize the integrated user satisfaction in the system. The decision variables in (3) are λ_i and v_i, i.e., the mean value and variance of the download rate of each user. Ω denotes the feasible network solutions to enable user *i* to download at (λ_i, v_i). In practice, Ω is embodied by the constraint of networks, like the physical constraints of transmission rate, flow conservation and network resource allocation, etc. In what follows, we show the implementation of (3) in vehicular networks and cognitive radio networks, respectively.

3. QoE-oriented Video Streaming in Vehicular Networks

The newly emerged vehicular networks [3, 4] enable vehicles on the road to communicate among each other in proximity, namely Vehicle-to-Vehicle (V2V) communication, and to access the Internet through roadside infrastructure, namely Vehicle-to-Infrastructure (V2I) communication. Due to the limited coverage of infrastructure, Internet video streaming to the highly mobile vehicles typically involves both the V2I communication and the multi-hop V2V relays from the gateway to the destination vehicles. The intermittent connectivity of the video streaming path paired by the severe interference among vehicles make the smooth video streaming a very challenging task.

In [5], we have developed a QoE-oriented video stream routing protocol steaming from the cross-layer design framework in (3). Given the video playback rate (μ and v_d) and playback threshold *b*, we design the optimal packet retransmissions to attain the best QoE. In specific, due to the volatile wireless channel, coupled with the interference and contentions among vehicles in proximity, packet delivery to vehicles may suffer from severe packet losses. The retransmissions are used to correct the errors. This, however, prolongs the packet delivery and may lead to the underflow of playout buffer, which results in the frozen of video playback. In [5], we model the impact of packet retransmissions on the video download rate (λ_i, v_i) to each user and the resultant QoE (*D*, *P*) of users according to (1) and (2). The optimal retransmissions are designed based on (3) with the constraints subject to the tolerable QoE of users, i.e., upper bounded start-up delay and probability of frozen.

4. Smooth Video Delivery in Cognitive Radio Networks

The Cognitive Radio (CR) networks allow a group of CR users to dynamically access the idle spectrums when spectrums are not used by the licensed users; the CR users are dictated to vacate the channels instantaneously once the licensed users are online [6]. By doing so, the wasted spectrum can be recycled to improve the spectrum utilization. However, as CR users need to keep switching channels to avoid the possible interference to the licensed users, paired with mutual contention among CR users, the download of CR users tend to be turbulent and unstable, which poses significant challenges to the high-quality video streaming in CR networks [7].

To provide smooth video delivery to CR users in the dynamic system, we propose an adaptive channel spectrum allocation scheme in [8] based on the cross-layer framework (3). In specific, we consider two groups of users coexisting in the system, video users and best effort users. The former downloads the inelastic video traffic from the network, and the latter downloads elastic data traffic. Therefore, the two groups of users have distinct QoS requirements. The video users demand relatively static download rate to support the smooth video playback characterized by QoE; whereas the best effort users require lower bounded download rate to enable on-top applications. Based on the instantaneous channel status and different QoS requirements of users, we adaptively allocate the channel spectrums to users, which affects their download rates. Therefore, video users are rendered with different QoE which can be evaluated by (1) and (2). By feeding this to (3), the spectrum allocation is configured to maximize the integrated utility of all CR users. Fig. 2 plots the resultant video frozen probability of video users when the proposed algorithm is applied, compared with the random and greedy channel allocations. As we can see, the proposed scheme can achieve much lower video frozen probability compared to traditional heuristics.

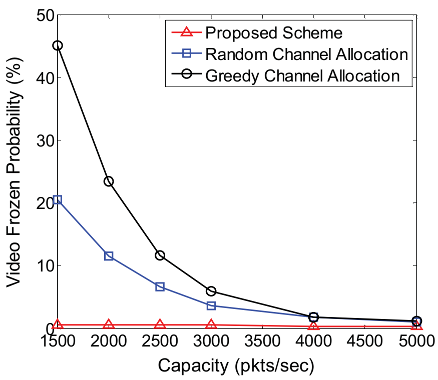

Figure 2 Video frozen probability with different channel allocation schemes in CR network

5. Conclusion

With the enhanced communication capability and fast mobility of wireless devices, the intermittent wireless connectivity yet high-rate during connection will occur more frequently in the near future. To enable the smooth video delivery over such challenged wireless networks needs to address the network dynamics. In this paper, we have provided a QoE-oriented video streaming framework as an effort on this issue. We first develop an analytical framework to characterize the QoE of users, represented by the network performance metrics. We then formulate the video streaming as a cross-layer design problem. Using the video streaming in vehicular networks and cognitive radio networks as examples, respectively, we have shown how the proposed framework can be used in the real-world design. In the future, we intend to test the proposed algorithms in the real-world environment.

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