Practical design of a proxy agent to facilitate adaptive video streaming service across wired/wireless networks

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ABSTRACT

Thanks to the growing of the wireless networks, the video streaming application becomes a ubiquitous joyful service. In a wireless communication network environment, the service traffic spans across the wired and wireless domains. In this article, we propose a practical design of a proxy agent – SPONGE (Stream Pooler Over a Network Graded Environment) sitting between the wireless User Equipments (UEs) and the video streaming server to facilitate the adaptive video streaming service across wired/wireless networks. To make the wireless streaming service more efficient, an input video session would be encoded as multiple qualities of video streams so that UEs with a similar receiving condition can share streams with the same service quality via SPONGE. SPONGE can alleviate the direct load on the original stream broadcasting server. Meanwhile, it can make each UE get an adaptive streaming service according to the network conditions of the UE by a reduced network condition feedback latency. Our theoretical analysis and simulation results show that SPONGE can help wireless streaming users get a smooth and better playback quality by a quick and accurate reaction to the network condition.

1. Introduction

The recent growth of the wireless technologies revolutionizes people’s lives. Many wireless networks are springing up in the past decade. Juicing up wireless technologies makes interesting multimedia services become ubiquitous, especially for the wireless streaming service. In a wireless communication network environment, the quality of service is largely affected by various network characteristics, such as a limited channel bandwidth and a variant transmission rate. Therefore, many wireless multimedia applications have encountered new challenging issues while crossing wired and wireless networks. Based on above, we sketch a proxy agent – SPONGE (Stream Pooler Over a Network Graded Environment), which is located between the streaming server and UEs to pool the different qualities of video streams, to alleviate the direct load on the streaming server. Since wireless networks are largely affected by various characteristics, UEs’ access statuses may vary dramatically compared to wired networks. Therefore, all client UEs can be graded regarding their network access statuses and be classified into several Video Stream Groups (VSGs) to share a same quality of video stream. Moreover, since SPONGE can obtain UEs’ statuses rapidly, adaptive qualities of video streams can be delivered to UEs timely according to the feedbacks. On the other hand, SPONGE can monitor and reflect the wired network status back to the streaming server so as to adjust the circulated video streams in the wired network. For example, the wired network may encounter the traffic congestion so that SPONGE needs to inform the video streaming server to cut down the video stream with the highest quality for saving the wired network bandwidth. Our theoretical analysis and simulation results show that SPONGE can help wireless streaming users get a smooth and better playback quality by a quick and accurate reaction to the network condition.

The rest of this paper is organized as follows. Section 2 illustrates some related works about wireless streaming techniques. Section 3 describes the architectural overview about SPONGE and related system components. Section 4 depicts the operation algorithms on SPONGE. In Section 5, we discuss the theoretical analysis about our proposed scheme. In Section 6, we make analytical comparisons of different streaming service models and depict the simulation results for the streaming services across wired/wireless networks with and without SPONGE. Concluding remarks are finally drawn in Section 7.

2. Related works

A revolutionized wireless Internet service mainly comprises three parts: content providers, network operators and end users (Leu, 2008). Content providers deliver the content through the wired network (generally, Internet) and the wireless network...
The live video streaming service is even contributing to offer joyful information just in time, such as live sports and news. It is expected to be among the most important applications in the developing and future generation networks and is also an important key to attract and keep customers to increase profits for content providers and network operators. Ideally, the multicasting technology can realize the video streaming service. However, it is hard to be deployed in a public IP service network. Meanwhile, since the video streaming service runs across wired and wireless networks, the Quality of Service (QoS) is not easy to be controlled. Such an issue can be mended by the following strategies: controlling the network congestion to maintain the service quality (Floyd et al., 2000), optimizing a rate-distortion streaming (Chou and Miao, 2006), and adding more error correction packets to reduce the frame retransmission (Lee et al., 2001). Basically, these improvements can ameliorate QoS by means of the receiving status feedback from the end users to the streaming server. However, the end-to-end feedback can not reflect the individual conditions of the wired and wireless networks. With the additional assistance of the statistic feedback by an agent sitting between the wired and wireless domains (Cheung et al., 2005), the streaming server can therefore recognize the respective statuses of the wired and wireless networks. Radio Network Feedback (RNF) is used to adapt its source bit rate to a varying WCDMA radio link by a streaming server (Chemiakina et al., 2003) and adaptive streaming is proposed to deliver content at a quality level that requires a rate not exceeding the currently available transmission rate by RTCP feedbacks (Frojd et al., 2006). There are various techniques for adapting the transmission rate of an application while maintaining the perceived quality at the receiver at acceptable levels (Chakareski and Frossard, 2007; Yu et al., 2003; Cha et al., 2006; Chang et al., 2007; Jammeh et al., 2008; Ozcelebi et al., 2007; Kampmann and Plum, 2006; Turner and Ross, 2003; Lei and Georganas, 2005; Wien et al., 2007; Mayer-Patel and Gotz, 2007).

### 3. Architectural overview about SPONGE

The general adaptive streaming service architecture across wired/wireless networks is shown in Fig. 1.

The transmission quality for each UE varies and fluctuates in a wireless environment. In general, CQI (Channel Quality Indicator), RSSI (Received Signal Strength Indication), SNR (Signal Noise Ratio) can be used to measure the channel quality from the physical layer viewpoint. The packet receiving rate, packet lost rate, packet dispersion can be used to measure the transmission quality from the network layer viewpoint. The client-end playback buffer condition and PSNR (Peak Signal to Noise Ratio) can be used to measure the playback quality from the application layer viewpoint. All above-mentioned indicators at different layers can be taken into consideration as feedback parameters in a cross-layer feedback-based video streaming system. To keep the feedback process simple, the stream buffer condition at the UE site can be used as a comprehensive feedback indicator. Meanwhile, the feedback process from the UEs to the server across the wired and wireless networks is time-consuming. If the feedback latency can be shortened, the adaptive streaming service can be fine-tuned more quickly according to the individual network conditions. On the other hand, a public streaming service is normally realized by multiple unicast streaming instead of the multicasting ones over IP. The streaming server generates as many unicast streams as the requested users no matter whether the receiving conditions of some UEs may be similar. To make the service more efficient, an input video session can be encoded as multiple qualities of streams so that some UEs with a similar receiving condition can share the same quality of video streams. In this article, we propose a skeleton about a proxy agent – SPONGE to make UEs quickly obtain adaptive video streams according to their varying receiving condition in a wireless circumstance and achieve a better playback quality.

#### 3.1. Architectural overview

In our proposed service architecture, there are three major components – Video Streaming Server (VSS), SPONGE and end UEs. Normally, the video streaming server and SPONGE are connected by the wired network (Internet) whereas SPONGE and UEs are linked together through wireless networks (like UMTS, HSDPA). The service architectural overview is shown as in Fig. 2.
First, the raw video is input to the VSS first. Then VSS converts the video session into multiple qualities of video streams as demanded from SPONGE. Initially, VSS would generate one basic level quality of video stream for service. After a while, some UEs may ask VSS to generate more different qualities of video streams for service via SPONGE based on their access capabilities.

SPONGE pools these multiple qualities of video streams and delivers them to UEs according to UEs’ packet receiving conditions which are used to classify UEs into different Video Stream Group (VSG) under a wireless network. Under the control of SPONGE, UEs in the same VSG would get a same quality of video stream.

Classified video streams are received and then played back on UEs.

To reflect varying packet receiving conditions on UEs in a wireless environment, UEs request to switch up or down to a new VSG toward SPONGE based on the stream receiving and stream buffer consuming conditions at the UE site. Consequently, SPONGE tunes the UEs’ belonging groups to make UEs with a similar receiving condition able to share a same quality of video stream. Since the tuning interaction happens between SPONGE and UEs, the video stream adaption time can be shortened.

SPONGE monitors the wired network traffic toward VSS to adjust video streams sent from the VSS. If some VSG is empty, SPONGE informs VSS to cancel sending the corresponding shared streams. On the other hand, if a new VSG is formed and no such a quality of streams exists in SPONGE, SPONGE must notice VSS to generate a new quality of video stream for the new VSG.

3.2. System components

The proposed system can be analyzed in more details by the three major components shown in Fig. 3. Fig. 3 also depicts an example including some classified UEs belonging to different VSGs which are related to different qualities of video streams.

(1) Video Streaming Server (VSS): Video Streaming Server is in charge of converting the input video into multiple qualities of video streams as well as adjusting the output circulated video streams based on the wired network status and VSG statuses that are replied from SPONGE. There are two sub-components:

- Multiple Qualities of Video Stream Generator (MQVSG): MQVSG is responsible for producing multiple qualities of video streams for a raw input video session and generates one basic tier of video stream for service in the beginning.
- Multiple Qualities of Video Streams Controller: (MQVSC): MQVSC obtains the wired network condition feedbacks from SPONGE and informs MQVSG to adjust the output video streams for meeting the wired network condition, cancel the unused video streams for saving the wired network bandwidth, or generate one new quality of video stream as SPONGE demands.

(2) SPONGE: SPONGE between VSS and UEs pools different qualities of video streams from VSS and delivers these video streams to the wireless UEs. SPONGE also classifies UEs into several graded network access groups based on UEs’ packet receiving conditions and accepts UEs’ requests to switch UEs up or down among these groups. That means SPONGE can adjust the members in different stream quality groups according to their access conditions. Meanwhile, since SPONGE bridges the VSS and UEs by a wired connection and a wireless connection respectively, SPONGE is also designed to patrol the traffic condition in the wired network. The congestion management policy for the wired network is changeable. One of the possible rules is to maximize the participation of UEs within the limited wired backbone bandwidth. That means if the traffic is busy or congested in the wired network, the video stream with a highest video quality which consumes a larger bandwidth may be sacrificed to keep most of in-service UEs stably running or accommodate more requests from more UEs which demand a new stream with a lower video quality. There are three sub-components inside SPONGE:

- Stream Pooler (SP): SP pools different qualities of video streams from VSS.
Group Tuner (GT): GT manages UE members in each VSG by referring to UEs’ packet receiving conditions and UE’s up- or down-switch requests. Meanwhile, GT would inform VSS to create a new quality of stream or cancel a existing unused stream.

Wired Network Status Monitor (WNSM): WNSM reflects the wired network status toward VSS. If the network is busy or congested, WNSM may notice VSS to cancel generating and delivering the video stream with a highest video quality.

(3) UE:
All received video streams are played back on UEs for users. Each UE belongs to different VSGs. To better fit the dynamic wireless environment, UEs request toward SPONGE to switch them up or down to a different VSG based on the packet receiving condition and video stream buffer consuming condition at the UE site.

4. Processing algorithms on SPONGE

We illustrate the processing algorithms as below:

4.1. At sponge side

The following Video Stream Group Tuning algorithm runs at SPONGE side. SPONGE interacts with UEs according their requests by referring to UEs’ packet receiving conditions.

```plaintext
// Sk: the k-level quality of video stream; the video quality for Sk+1 is better than the one for Sk
// Reference_Table: an array to maintain the reference counts for different qualities of video streams in SPONGE
Video Stream Group Tuning:

While_Begin
  Switch (Request_From_UE)
    // If UE in VSGk
  Case Up_Switch:
    If Sk doesn’t exist then
      Issues a request to the streaming server to generate Sk+1;
      Generates VSGk+1
      Moves UE from VSGk to VSGk+1
      Increases Reference_Table[Sk+1] by one
      Decreases Reference_Table[Sk] by one
      If Reference_Table[Sk] is zero
        Issue a request to VSS to cancel Sk

  Case Down_Switch:
    If Sk-1 doesn’t exist then
      Issues a request to server to generate Sk-1
      Generates VSGk-1
      Moves UE from VSGk to VSGk-1
      Increases Reference_Table[Sk-1] by one
      Decreases Reference_Table[Sk] by one
      If Reference_Table[Sk] is zero
        Issue a request to VSS to cancel Sk

  Case Join_Session:
    Adds UE in VSG1
    Increases Reference_Table[S1] by one

  Case Leave_Session:
    Removes UE in VSGk
    If Reference_Table[Sk] is not zero
      Decreases Reference_Table[Sk] by one

End If
End If

While_End
```

4.2. At UE side

The Join, Leave, Playback Buffer Checking and Feedback algorithms run at UEs. First, each UE joins the VSG with a lowest quality and gradually be promoted. That’s because most of UEs may not only run the video streaming playback program but even some other programs, which may already utilize some network resources, before activating the video streaming playback program. Therefore, UEs start to join the group in a modest way to prevent
from effecting other existing applications on UEs and then gradually switch up based on their receiving conditions.

// Threshold_up_switch: a duration threshold for a UE to switch up to a higher VSG. If the playback time for one UE in its current VSG can stably last more than this threshold, this UE can be promoted to get a higher quality of stream.

// Threshold_down_switch: a duration threshold for a UE to switch down to a lower VSG. If the playback time for one UE in its current VSG can stably last more than this threshold, this UE would be degraded to get a lower quality of stream.

// T_stable: another duration threshold for a UE to switch down to a lower VSG. If the duration for a UE to stably play back a newly switched quality of stream is less than this threshold, this UE would be degraded to get a lower quality of stream.

Join:
UE issues a Join_Session request toward SPONGE

Leave:
UE issues a Leave_Session request toward SPONGE

Playback Buffer Checking and Feedback:
While Begin
  // Up Switch
  If the duration for stably playing the current quality of stream lasts more than Threshold_up_switch then
  UE issues an Up Switch request toward SPONGE
  End If
  // Down Switch
  If (the duration for stably playing streams in the remainder buffer is less than Threshold_down_switch) then
  (the duration for stably playing the newly switched quality of stream only lasts less than T_stable) then
  UE issues a Down Switch request toward SPONGE
  End If
End While

5. Theoretical analysis

In this section, we try to analyze the average throughput for stream delivery and the buffer size variation for playback sustainability on UE when a UE encounters a degraded channel quality with or without the assistance of SPONGE. We deduct the quantitative comparison result by referring to the following notations.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q</td>
<td>the data size of the video stream</td>
</tr>
<tr>
<td>R_{wireless}</td>
<td>the data transmission rate in the wireless channel</td>
</tr>
<tr>
<td>R_{wired}</td>
<td>the data transmission rate in the wired network</td>
</tr>
<tr>
<td>D</td>
<td>the transmission time of streaming data without SPONGE</td>
</tr>
<tr>
<td>D'</td>
<td>the transmission time of streaming data with SPONGE</td>
</tr>
<tr>
<td>\gamma_{average}</td>
<td>the average throughput on UE without SPONGE</td>
</tr>
<tr>
<td>\gamma'_{average}</td>
<td>the average throughput on UE with SPONGE</td>
</tr>
<tr>
<td>\mu(s)</td>
<td>the packet receiving rate on UE at time s</td>
</tr>
<tr>
<td>\mu'(s)</td>
<td>the reduced packet receiving rate on UE at time s</td>
</tr>
<tr>
<td>d</td>
<td>the start time to consume a lower quality of stream after stream switching down without SPONGE</td>
</tr>
<tr>
<td>d'</td>
<td>the start time to consume a lower quality of stream after stream switching down with SPONGE</td>
</tr>
</tbody>
</table>

5.1. Average throughput analysis for stream delivery

With the support of SPONGE, if one UE’s channel quality degrades so that the UE only can sustain a lower quality of stream, this UE can request the new stream directly from SPONGE (assuming the new stream already resides in SPONGE).

According to (1) and (2) (the comparison exhibited in Fig. 4),

\[ D = \left( \frac{Q}{R_{wireless}} + \frac{Q}{R_{wired}} \right) \]

\[ D' = \frac{Q}{R_{wireless}} \]

we can find that SPONGE can shorten the transmission time for the new requested stream (in short, \( D > D' \)).

As Fig. 5 shows, we assume that one UE faces a degraded channel condition so that the UE have a worse packet receiving condition. That means the UE has a degraded data receiving rate from \( \lambda \) down to \( \lambda' \) after the UE’s receiving condition gets worse at time \( t \). We define the definite integral \( \int_{t}^{t+d} \mu(s)ds \) as the received packet volume during \( t1 \) to \( t2 \) with a packet receiving rate \( \lambda \) on UE. On the other hand, the reaction time \( (d) \) to start to consume a lower quality of stream with a lower packet consuming rate \( (\mu') \) from a higher packet consuming rate \( (\mu) \) without SPONGE is more than the one \( (d') \) with SPONGE since \( D > D' \). We also define the definite integral \( \int_{t}^{t+d'} \mu(s)ds \) as the consumed packet volume during \( t1 \) to \( t2 \) with a packet consuming rate \( \mu \) on UE. To prevent from the buffer underflow, the stream switching delay must be shortened as possible.

\[ \frac{n \cdot D}{n} > 1 \cdot D + (n - 1) \cdot D' \]

We can obtain

\[ \frac{n \cdot D}{n} > 1 \cdot D + (n - 1) \cdot D' \]

That means the average transmission cost is lower with the assistance of SPONGE by (3). This inference also reveals that the more users share the media stream, the more efficiency can be achieved. The additional effort to fill the vacant stream in SPONGE may be ignored as lots of subsequent users share the new stream. Nevertheless, the worst case is if a UE requests a new video stream which does not exist in SPONGE and no other UEs share the same stream, a wasted effort of searching an unexisted stream in SPONGE before requesting the wanted video stream toward the VSS would always result in a longer transmission time for the new requested stream.

On the other hand, we can evaluate the average throughput comparison by

\[ \frac{\gamma_{average}}{D} = \frac{1}{R_{wireless} + R_{wired}} \]

In short, \( \gamma'_{average} > \gamma_{average} \). That means the average throughput can be raised with the support of SPONGE.

5.2. Buffer size variation analysis for playback sustainability

As Fig. 5 shows, we assume that one UE faces a degraded channel condition so that the UE have a worse packet receiving condition. That means the UE has a degraded data receiving rate from \( \lambda \) down to \( \lambda' \) after the UE’s receiving condition gets worse at time \( t \). We define the definite integral \( \int_{t}^{t+d} \mu(s)ds \) as the received packet volume during \( t1 \) to \( t2 \) with a packet receiving rate \( \lambda \) on UE. On the other hand, the reaction time \( (d) \) to start to consume a lower quality of stream with a lower packet consuming rate \( (\mu') \) from a higher packet consuming rate \( (\mu) \) without SPONGE is more than the one \( (d') \) with SPONGE since \( D > D' \). We also define the definite integral \( \int_{t}^{t+d'} \mu(s)ds \) as the consumed packet volume during \( t1 \) to \( t2 \) with a packet consuming rate \( \mu \) on UE. To prevent from the buffer underflow, the stream switching delay must be shortened as possible.
so as to deliver the new stream timely to UEs for compensating the effect of the changed channel condition.

By observing the Fig. 5, the UE can start to consume the lower quality of stream after the new stream is delivered to the UE and UE has used up the higher quality of stream in the buffer. Finally, the UE would achieve another steady state with a lower packet consuming rate. We can evaluate the buffer size variation comparison by (5) while stream switching down.

$$\Delta B_{\text{UE}} = \int_t^{t+d} \lambda'(s)ds - \int_t^{t+d} \mu(s)ds$$

$$= \int_t^{t+d} \lambda'(s)ds - \int_t^{t+d} \mu(s)ds - \int_t^{t+d} \mu(s)ds$$

$$< \int_t^{t+d} \lambda'(s)ds - \int_t^{t+d} \mu(s)ds - \int_t^{t+d} \mu(s)ds = \Delta B_{\text{UE}}$$
In short, $\Delta B_{ul} > \Delta B_{ub}$, we can find that more stream data could be kept in the UE's buffer to avoid the buffer underflow if having the support of SPONGE. Therefore, the adaptive video streaming architecture with the support of SPONGE can have better playback sustainability.

6. Analytical comparison and simulation results

6.1. Analytical comparisons of different streaming service models

The major differences between the streaming services across wired/wireless networks with and without SPONGE are depicted in Table 1.

With an intermediate node (SPONGE or proxy) to relay video streams to the end users, a two-hop streaming service can maximize the reusability of video stream so as to save network traffic in the network. Moreover, a SPONGE-based solution can have a quicker response and a shorter feedback latency for UEs in an ever-changing wireless environment compared to a proxy-based solution. SPONGE also can reduce the probability of buffer underflow at UE sites while playing back the received streams. Although the SPONGE solution needs to build an additional hardware in each collaborative network operator for the streaming service, a low-cost hardware should be sufficient to carry out the operations of SPONGE. Such an inexpensive investment can achieve a higher quality of user experience and a good service reputation.

Fig. 6. (a) Network topology for performance evaluation; (b) performance evaluation from the buffer size variation viewpoint; (c) performance evaluation from the throughput viewpoint.
6.2. Simulation results of streaming services with and without SPONGE

We conduct a simulation to evaluate the system performance by NS2 with Enhanced UMTS Radio Access Network extensions (EURANE). The network topology for performance evaluation is shown in Fig. 6a and the related settings are as follows.

- Pre-buffering time on UE: 2 s
- Thresholddown_switch: 1.7 s
- Thresholdup_switch: 10 s
- Tstable: 1 s
- Five levels qualities of video streams: 160 kbps, 320 kbps, 480 kbps, 600 kbps, 720 kbps

Fig. 6. (continued)

Fig. 7. Average transmission time for the new requested stream based on different sharing degrees.
• Five VSGs for the above video streams
• Five existing UEs belonging to the above VSGs + 1 new join UE
• Monitoring duration: 0–108 s

We observe the performance on the new join UE from the viewpoints of the buffer size variation and the throughput with and without SPONGE in Fig. 6b and c.

1. In the beginning (in Fig. 6b), the UE starts to buffer the video streams for playback.
2. During 0–30 s, the stream packet consuming rate on UE is far behind the stream packet receiving rate. That means the UE’s receiving capability may be underestimated. Therefore, the UE is gradually tuned into an upper VSG to get a better quality of video stream.
3. About approaching 33 s, the stream packet receiving rate goes above the receiving capability bounded by the channel condition. Therefore, the content in the buffer was consumed a lot suddenly before the UE’s belonging group was tuned back to a moderate one. That is because if the receiving capability is overestimated, it would result in losing most of the incoming stream packets.
4. About approaching 35 s, with the assistance from SPONGE, the buffer consuming condition would be controlled back to a steady state earlier than the one without SPONGE. The buffer control is paramount for the live streaming service since it may result in a jerky playback.
5. After around 37 s (in Fig. 6c), the UE goes back to join a VSG which can match the packet receiving condition. Since the UE with SPONGE can have a quicker reaction to the physical receiving condition, it would stay in a VSG with a better quality of video stream (320 kbps) compared to the one (160 kbps) without SPONGE under a sustainable channel quality.
6. At around 55 s, the channel quality for the UE becomes good abruptly so that the throughput can be raised suddenly. The sudden channel quality change is a natural property in a wireless environment. However, the throughput up-rising did not last long enough to switch the UE to an upper VSG. Due to the unstable channel quality, the throughput goes back to a normal level at around 320 kbps soon. During our simulation, there are some similar situations at some discrete points, such as at 55, 78 s. Notwithstanding a sudden fluctuation and a suddenly longer delay jitter may appear at these scattered points, such an abnormal phenomenon would not affect the overall performance of SPONGE.

As the result shows, with the assistance from SPONGE, UE can react to the varying condition more rapidly and have better playback sustainability.

To estimate the benefit of the stream sharing in SPONGE, the average transmission time for the new requested stream based on different numbers of UEs sharing the same stream is shown in Fig. 7. Inevitably, if only one UE requests a new video stream which does not exist in SPONGE and no other UEs share the same stream, a wasted effort of searching an unexisted stream in SPONGE causes a longer transmission time and degrades the service performance. However, the average transmission time can be lowered as the sharing degree increases.

7. Conclusion

Video streaming service is deemed as one of the most important applications in the developing and future generation networks. As the diversified wireless technologies are springing up in our life, the video streaming service becomes a ubiquitous joyful service. However, carrying out the streaming service across wired/wireless networks faces the hurdle of the QoS control since the access capabilities at the user sites are varying. Therefore, adaptive streaming scheme is a good solution to achieve a smooth playback quality at the end user equipment site. In this article, we aim to propose a practical design of a proxy agent – SPONGE to provide an adaptive streaming service across wired/wireless networks by grading UEs into different access groups according to UEs’ different access capabilities. SPONGE can adapt the suitable qualities of video streams for the grouped UEs. Our simulation results show that SPONGE can react to network condition accurately and quickly so as to have a smooth and better playback quality at the end user site across wired/wireless networks.

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