Video to Go: The Effects of Mobility on Streaming Media in a CDMA2000 1xEV-DO Network

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ABSTRACT

This paper experimentally examines the performance of streaming media applications over a CDMA2000 1xEV-DO network. The performance of streaming in a cellular network is tested across three different levels of mobility, two applications, and the two transport layer protocols, TCP and UDP. Findings of this study are that streaming applications are impacted more by sources of interference such as high-rise buildings than by increased velocity. Also, when the mobile client is stationary, high data rates and high video quality are consistently achieved. We also find that for the streaming applications considered, UDP streams outperform TCP streams, consistently achieving higher bandwidth.

Keywords: Wireless multimedia, Video Streaming, Wireless WANs, Code Division Multiple Access (CDMA), third generation (3G)

1. INTRODUCTION

The development of the third generation (3G) wireless wide area networking systems such as CDMA2000 in North America and UMTS in Europe has laid the foundation for ubiquitous access to Internet-based services. Among the Internet services expected to propel further growth of cellular technology, multimedia streaming services such as live broadcasting and video-on-demand are at the forefront.

As 3G systems are deployed, it is expected that the support built into these systems for high speed, TCP/IP packet switching over radio frequency (RF) links will facilitate deployment of new, high data rate, multimedia streaming services in Wireless Wide Area Networks (WWANs). In this context, this paper studies the performance of commercial streaming media applications over a CDMA2000[16] 1xEV-DO network.

Streaming media applications have requirements that distinguish them from other types of TCP/IP traffic. Most applications, such as e-mail and Web traffic, are not very sensitive to network conditions such as delay and bandwidth. They are, however, very sensitive to lost or corrupted packets. In contrast, streaming media is very sensitive to network characteristics such as delay and bandwidth and may, in some cases, be able to tolerate lost or corrupted packets. These unique requirements, combined with their popularity, make streaming media applications interesting and relevant to examine in a mobile environment.

There are many unique challenges to audio and video streaming applications in WWANs. RF links in cellular environments are highly fragile and are often impacted by multipath fading, scattering, shadowing, interference and cell hand-offs. These properties impose several limitations on data delivery in WWANs that can impact multimedia streaming applications. One of the main challenges faced in cellular networks that is not encountered in 802.11 Wireless Local Area Networks (WLANs) is extremely high mobility, where the user may move up to 100 km/h. Effects of high mobility can include increased packet loss rates, as well as high and variable delays in content delivery that can severely impact the performance of most currently deployed streaming media applications.

In recent years, several studies have explored the properties of cellular networks.[2–5, 8, 10, 12, 13, 15] Some of these studies focussed on multimedia applications.[3–5, 8, 10, 12, 13] Experimental evaluation of multimedia streaming in EV-DO networks, however, has been limited.[10] In this respect, the performance evaluation carried out in this

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study is unique. The experiments presented in this paper examine various mobility conditions, from stationary to high mobility, to better understand the effects of mobility on streaming media. Experiments are also carried out to evaluate the impacts of application layer and transport layer protocols on mobile streaming media.

Key observations of this study are as follows. When network conditions are relatively constant, even at high velocities, streaming applications perform well. In contrast, when there are sources of interference, streaming performance can be highly variable. UDP streams consistently perform better than TCP streams, achieving higher bandwidth and playing out streams with higher encoding rates. HelixServer generally performs better than Windows Media Server in the EV-DO network. The HelixServer is able to maintain higher bandwidth and more consistent frame rates.

The remainder of this paper is structured as follows. Section 2 presents background on CDMA2000 and previous work on characterizing streaming media in 3G mobile environments. The methodology of our study is presented in Section 3. An evaluation of streaming performance across various mobility levels is presented in Section 4. The impacts of varying the application layer and transport protocols used for streaming are examined in Section 5 and Section 6, respectively. Conclusions and directions for future work are summarized in Section 7.

2. BACKGROUND

2.1. CDMA2000

The cdmaOne and CDMA2000 systems are among the most widespread cellular network architectures in the world. These systems are widely deployed in North America and the Asia Pacific Region, and are also deployed in some parts of Europe, Middle East, Africa, and South America.

The cdmaOne is a second generation (2G) system. Upgrades that transform cdmaOne to a third generation (3G) system are standardized by the Third Generation Partnership Project 2 (3GPP2), and collectively referred to as CDMA2000.[16] Developments by 3GPP2 include CDMA2000 1xRTT (considered 2.5G), CDMA2000 1xEV-DO, and CDMA2000 1xEV-DV. In this paper, we experimented with a commercially deployed CDMA2000 1xEV-DO (Evolution Data Optimized) network.

A distinguishing feature of CDMA2000 1xEV-DO is that it provides a high speed radio channel dedicated to packet switched data transfer. This makes CDMA2000 1xEV-DO ideal for deploying high-speed Internet-based applications such as video-on-demand services. CDMA2000 1xEV-DO provides a maximum downlink data rate of 2.4 Mbps with Revision 0 (Rev. 0) and 3.1 Mbps with Rev. 1 (deployed in Japan and Korea). The maximum uplink data rates are 153.3 Kbps and 1.8 Mbps in Rev. 0 and Rev. 1, respectively. Our experiments are conducted with a network interface card that supports Rev. 0.

2.2. Streaming in Wireless Networks

The effects of mobility on streaming in WLANs has been considered in several studies (e.g.[1,7,11]). However, there are few studies that empirically study the effects of mobility on streaming media in 3G cellular networks,[12,13] and even fewer that consider the effects of mobility in EV-DO networks.[10]

Measurements of streaming media in a European Universal Mobile Telecommunications System (UMTS) network are made by Chesterfield *et al.*[4,5] The authors analyze the performance of streaming media over GPRS and UMTS networks. They also develop an application which uses link aggregation to improve streaming performance over cellular links. However, the work by Chesterfield *et al.* does not place an emphasis on the effects of mobility on streaming media as is done in our work.

Similar to our work, Lundan and Curcio[13] examine the performance of streaming over a UMTS 3G network. The authors examine several characteristics of mobile streaming media including start-up delay and bitrates. The maximum bitrate encoding used by Lundan and Curcio is 384 Kbps, whereas in our study the maximum bitrate is 768 Kbps, enabling us to further examine the limits of streaming over 3G networks.

The effects of mobility between WLANs and a CDMA2000 1xRTT network is examined by Li *et al.*[12] In this work, the authors present a framework for clients to move between a cellular network and a WLAN environment. Our work is distinct from the work by Li *et al.* in that we focus our investigation on mobility within a cellular network. Also, our experiments are with the newer CDMA2000 1xEV-DO technology.

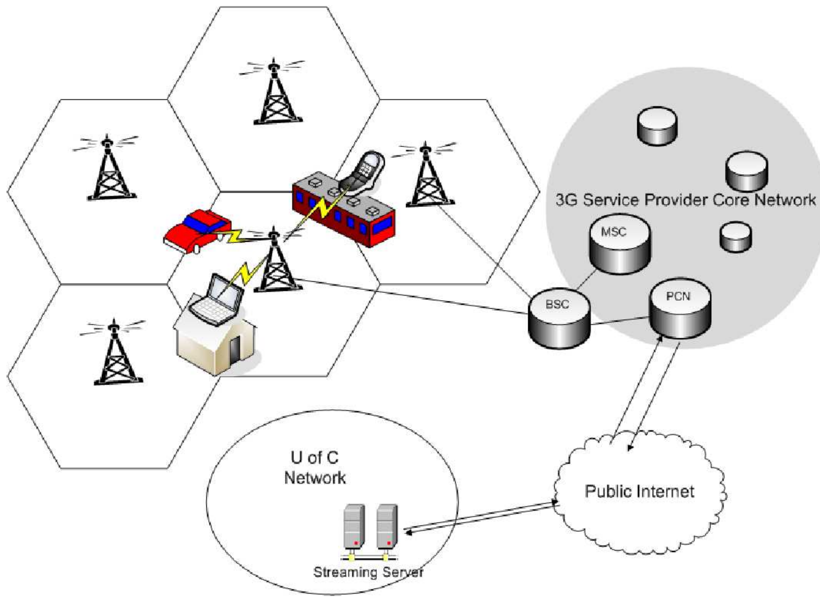


Figure 1. Experiment set-up to evaluate streaming performance

More recently, Claypool *et al.*[6] carried out measurements of the general performance of a CDMA2000 1xEV-DO network. They focus their study on network characteristics, such as delay, throughput and bandwidth that may impact many currently deployed applications. Although streaming is considered in their study, the authors do not explicitly consider the impacts of the network properties on stream characteristics such as frame rate. Also, the authors do not consider the impacts of mobility on streaming media as is done in our study.

3. METHODOLOGY

This section describes the measurement methodologies used to characterize the performance of streaming media over an EV-DO network. Software and hardware set-up as well as the various experiments carried out are summarized.

3.1. Experimental Framework

To characterize the performance of streaming media over an EV-DO network, a procedure for connecting to a server and streaming the media had to be developed. A key challenge in this study was finding a platform that could not only connect to an EV-DO network, but would also have the computing power to run various monitoring tools and record statistics from the streaming sessions. Because most commonly available mobile platforms were not able to run the required measurement applications, a laptop was used instead. A wireless card that is able to connect to EV-DO base stations is used to connect the laptop to the Internet. The base stations are connected to the service provider's core network, which is then connected to the public Internet. Streaming servers for the experiments were set-up at the University of Calgary. The experimental framework used in our study is illustrated in Figure 1. Our work considers two popular streaming servers, namely Microsoft's Windows Media Server (2003) and RealNetworks' HelixServer (version 11.0.2.2358) [*], both transport protocols, and various mobility conditions.

A 4-minute long sample video clip was encoded using the multiple bit rate encoding format provided by each vendor; SureStream[9] in the case of HelixServer and Intelligent Streaming[14] for Windows Media Server. Multiple bitrate encoding formats are used by commercial streaming software to improve video quality experienced by streaming clients. This is accomplished by encoding multiple bitrates of a video clip into a single media object.

[*] http://www.realnetworks.com/products/discreteserver/index.html

If available bandwidth changes during playback, the rate at which the client receives the video is dynamically adjusted by the streaming server to allow better use of the available bandwidth. This property is especially advantageous in our study because if the connection quality degrades, the server can dynamically reduce the quality at which it sends the media, rather than potentially having to terminate the streaming session. The video used in this study was encoded at the following rates for HelixServer: 34 Kbps, 100 Kbps, 225 Kbps, 350 Kbps, 450 Kbps, and 700 Kbps. For Windows Media Server the video was encoded at: 58 Kbps, 109 Kbps, 148 Kbps, 282 Kbps, 340 Kbps, 548 Kbps, and 764 Kbps. All of these bitrates include video as well as audio components of the media file. Since there is some overhead when sending the video, bandwidth required to receive the stream is actually higher than the encoded bit rate. For example, to receive a stream of 700 Kbps a bandwidth of 768 Kbps is required.

The performance of the streaming session was monitored using multiple software tools. In particular, we made use of the RealTracker program[17] for monitoring bandwidth, jitter, frame rate, frame loss, and frame drops of the RealPlayer streams. To monitor characteristics of the Windows Media streams, MediaTracker[14] was used. Each characteristic of streaming media performance is sampled every 0.5 seconds with MediaTracker or every second with RealTracker; distributions of these samples are examined to draw conclusions about the performance of media streaming under various conditions.

3.2. Mobility Patterns

To understand the effects of mobility on streaming media performance, three different mobility conditions are considered. The conditions include *office* where the user does not move at all, *city* where the user moves at approximately 30-60 km/h, and *highway* in which the user moves at approximately 100 km/h.

The first mobility condition examined in this study is the office condition. In these tests, the mobile device is stationary. These tests were carried out on the seventh floor of the ICT building at the University of Calgary. This simulates conditions users may encounter when using a handheld device to access the Internet in an office environment.

Using mobile devices on city transit is also examined. These experiments were carried out on Calgary Transit's light rail transit C-Train system. The C-Train environment poses many challenges to streaming on EV-DO networks, in particular tunnels and shadowing effects of high-rise buildings are examined in this study.

The highway condition where the user moves at 100 km/h was carried out in a rural highway environment. In this environment there were very few buildings or other tall objects that would interfere with the data transfer over the RF link. The highway mainly serves to test the bounds on streaming media performance in very high mobility situations. A relevant application of the highway condition would be video-on-demand systems that may be built into automobiles, high-speed trains, or busses to entertain passengers on long trips.

3.3. Experiments

Using both the Windows Media Server and HelixServer, experiments were performed to evaluate the effects of mobility on streaming media. Tests were done with both TCP and UDP under high and moderate mobility conditions using the Windows Media Server. With the HelixServer, all three mobility conditions were examined. However, only UDP experiments with the HelixServer are considered in this paper. When attempting to perform the aforementioned experiments using the HelixServer with TCP, several problems were encountered. Specifically, SureStream did not adapt its sending rate to TCP transport on the 3G connection and as a result, video playback was only possible for 1-2 seconds at a time. This problem is discussed further in Section 5.

Experiments were carried out in 7 different scenarios. Each experiment was repeated until 4 successful trials were observed, where a successful trial constitutes full playback of the movie from start to finish. The number of repetitions and experiments carried out was limited by data transfer limits imposed by our EV-DO provider.

In our experiments it was observed that streaming media over 3G can be highly unpredictable in city and highway situations. Connections were frequently lost, and the quality of the streaming media depended heavily on proximity to base stations as well as the presence of objects that may interfere with the connection, such as high-rise buildings. However, when there were few sources of interference and adequate network coverage, even in the highest mobility condition, a relatively reliable connection was possible.

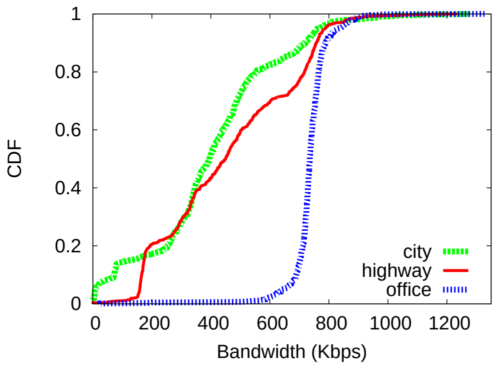


Figure 2. CDF of observed bandwidth (HelixServer using UDP transport)

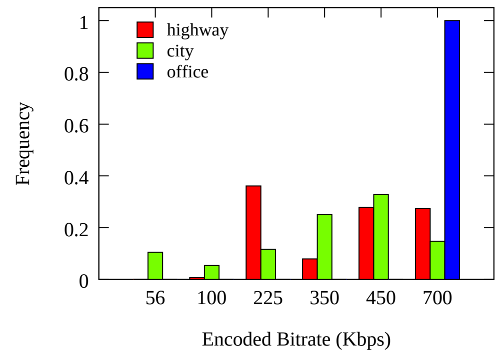


Figure 3. Histogram of encoded bitrate (HelixServer using UDP transport)

4. THE EFFECTS OF MOBILITY ON STREAMING

This section presents results from measurements of streaming performance using HelixServer at the application layer and UDP at the transport layer, across the three mobility patterns described above. The three mobility patterns are compared using bandwidth, encoded bitrate, jitter, and frame rate to determine the effects of mobility on streaming applications.

4.1. Bandwidth

In our tests of mobility, we observe that bandwidth is the characteristic impacted most by varying the mobility pattern. Figure 2 shows the CDF of bandwidth observed at each second of all 4 repetitions for each mobility experiment. When the streaming client is stationary, bandwidths between 600 Kbps and 800 Kbps are consistently achieved. When mobility is introduced, the amount of bandwidth achieved exhibits high variability. In our experiments we find that the highway condition out-performs the city condition. The poor performance of the city scenario may be attributed to sources of interference encountered in the core of a city, that were not present in the rural highway environment used in the highway tests.

On the highway, bandwidths of above 194 Kbps are experienced 80% of the time. Also, 49% of the time bandwidths between 200 Kbps and 600 Kbps are achieved in the highway scenario. In contrast, 65% of the time in the city, the client experiences bandwidths between 200 Kbps and 600 Kbps. We also found that 30% of the time the streaming client in the highway scenario has bandwidth greater than 600 Kbps whereas in the city, bandwidths of over 600 Kbps are observed less than 20% of the time.

Encoded bitrate in each mobility scenario is examined to evaluate the quality of video received by clients with varying degrees of mobility. Figure 3 shows a histogram of the encoded bitrate at each second of all 4 trials across the three mobility conditions. The office condition performs the best, receiving the video clip with the maximum encoded bitrate 100% of the time. The highway case also performs well, seldom receiving streams with encoded bandwidths of less than 225 Kbps. The encoded rates of the streams received by the city client are more uniformly distributed across all possible encoding rates. This indicates that while high quality streaming might be possible in the city scenario, the streaming quality is highly variable depending on network conditions.

Our tests of the effects of mobility on streaming bandwidth suggest that interference impacts the level of bandwidth a client achieves more than velocity does. Even though in the city the client moved at a speed that was at least 20 km/h slower than on the highway, it did not perform better than the higher mobility client. This is likely as a result of sources of interference present in a city environment, that were not present in the highway experiments.

4.2. Jitter and Frame Rate

Jitter was measured using RealTracker[17] which calculates jitter as the standard deviation of the inter-frame playout time. We observed that jitter experienced by a streaming client is relatively consistent across different

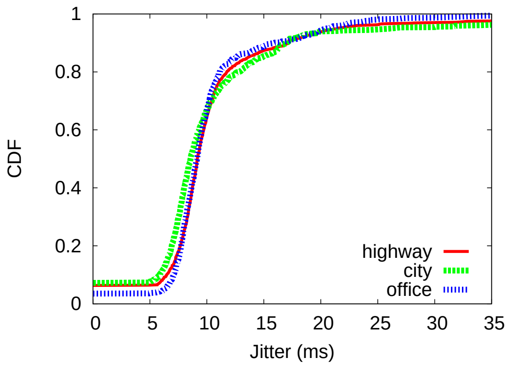


Figure 4. CDF of observed jitter (HelixServer using UDP transport)

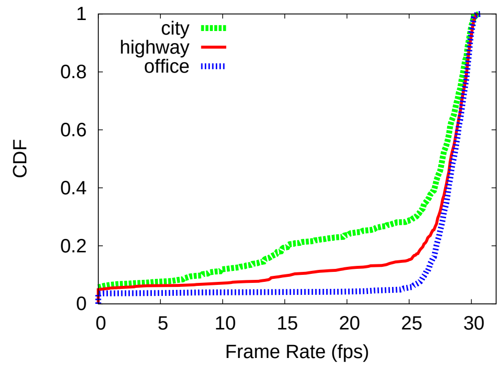


Figure 5. CDF of observed frame rate (HelixServer using UDP transport)

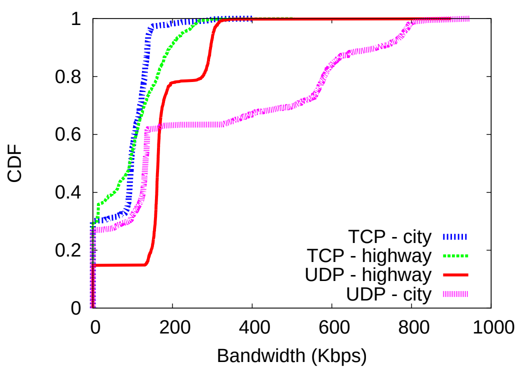


Figure 6. CDF of observed bandwidth (Windows Media Server)

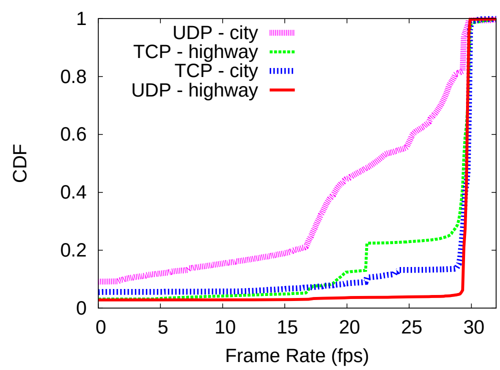


Figure 7. CDF of observed frame rate (Windows Media Server)

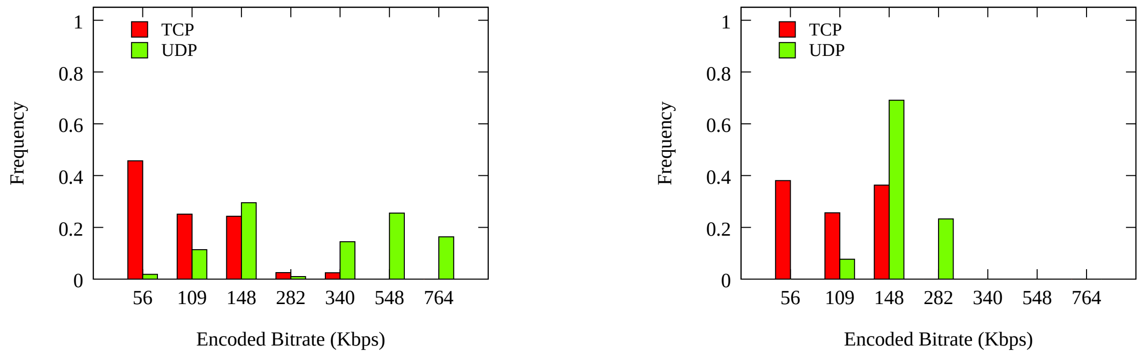
levels of mobility, as shown in Figure 4. In all mobility cases, 90% of the time, jitter experienced by the client is less than 17 ms. This suggests that mobility has little effect on the jitter experienced by streaming clients in an EV-DO network. It is likely that the jitter experienced by the streaming client primarily results from queuing in the wired Internet and variability in delivery times across the wireless channel. Our results suggest that the variability in delivery time of packets across the wired and wireless links is not greatly impacted by mobility.

Frame rate also remains relatively constant across all mobility scenarios. Figure 5 shows the CDF of frame rate observed at each second of all 4 trials for each mobility condition. Our results show that the highway condition performs better than the city scenario in terms of frame rate and the office condition gives the best results. However, even in the city scenario, the client is still able to receive 25 frames per second 70% of the time. These results indicate that even at high mobility levels a streaming client is able to achieve frame rates that are highly sufficient for fluid video playback.

5. THE EFFECTS OF TRANSPORT PROTOCOL ON MOBILE STREAMING

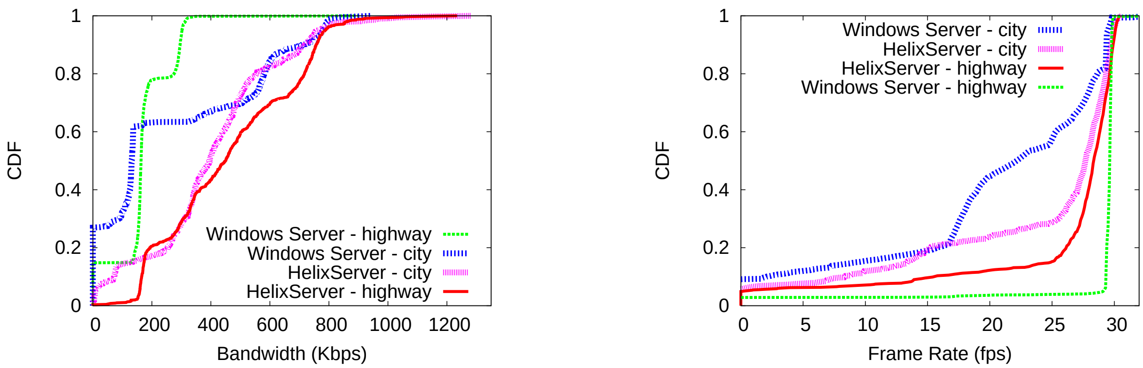
The effects of transport layer protocol on mobile streaming media were studied using the Windows Media Server application in city and highway conditions. Windows Media Server was used in these experiments as a result of problems experienced when streaming with HelixServer using TCP. In our experiments using HelixServer and TCP we observed that the server did not adjust its sending rate to the very low transmission rate of the TCP connection. As a result, playback was only sustainable for a few seconds at a time, and the connection was usually reset by the client.

Figure 6 shows the CDF of the observed bandwidth of clients using Windows Media Server and either TCP or UDP across two of the mobility conditions. In both mobility cases, the streaming client using UDP achieves



a) City b) Highway

Figure 8. Histogram of encoded bitrate using Windows Media Server



a) CDF of observed bandwidth b) CDF of observed frame rate

Figure 9. Mobile streaming performance of Windows Media Server and HelixServer

higher bandwidth than the clients using TCP. TCP flows react to lost packets by reducing their sending rate. This method of congestion avoidance can cause problems in a wireless environment, where packet loss may be caused by characteristics of the wireless channel.

Figure 7 shows the CDF of the observed frame rates. Both UDP and TCP show good performance in the highway condition with the UDP client performing slightly better than the TCP client. However, in the city condition, the frame rate of the UDP client shows high variability, with frame rates above 29 fps observed only 19% of the time. In contrast, the TCP client performs much better in the city condition, with frame rates above 29 fps observed 85% of the time. The varying frame rate experienced by the UDP streams in the city scenario is likely as a result of the UDP streams attempting to receive the video at higher bitrates, as illustrated in Figure 8 (a).

The encoded bitrates achieved when streaming using UDP and TCP streams, for both the city and highway mobility patterns, are compared in Figure 8. In both cases, the UDP streams tend to have a higher encoded bitrate than the TCP streams. The higher bitrate streams received by the UDP client are made possible by the higher bandwidth achieved by these streams. In the city, the UDP client attempts to receive very high bitrate streams, however, this results in the client experiencing a less consistent frame rate, likely as a result of interference and variable network conditions. In contrast, when network conditions are more consistent, such as in the highway condition the UDP client is still able to achieve higher bitrates and higher frame rates than the TCP client.

6. WINDOWS MEDIA SERVER VERSUS HELIXSERVER STREAMS

This section presents results that compare and contrast the mobile streaming performance of Windows Media Server and HelixServer. The results presented in Figure 9 are for streaming using UDP as the transport layer protocol.

Figure 9 (a) shows the bandwidth achieved by Windows Media Server and HelixServer clients in city and highway conditions. The HelixServer client consistently achieves higher bandwidth than the Windows Media Server client. On the highway, the Windows Media client rarely exceeds bandwidths of 300 Kbps, whereas 70% of the time the HelixServer client in both highway and city mobility experiments exceeds bandwidths of 300 Kbps. Also, the HelixServer client exceeds bandwidths of 600 Kbps 18% and 30% of the time in the city and highway scenarios, respectively.

Frame rates experienced by the Windows Media client show much higher variability between mobility conditions than the frame rates seen by the HelixServer client. This is illustrated in Figure 9 (b). On the highway, Windows Media provides high frame rates consistently, whereas in city conditions, Windows Media performs significantly worse. This suggests that the high variability of network conditions seen in the city experiments may have had an impact on the ability of the Windows Media Server to provide fluid playback of the video clip. In contrast, HelixServer provides comparable performance in both the city and highway conditions, and is able to provide fluid playback of video in both cases.

7. CONCLUSIONS AND FUTURE WORK

This study presents experimental measurements of streaming media performance over a CDMA2000 1xEV-DO network. Our study considers three mobility conditions (stationary, city, highway), two streaming servers (Windows Media Server, HelixServer), and both TCP and UDP transport. Through our experiments, insights are gained into the performance of streaming media in various mobility conditions, as well as the performance of existing protocols in the new high mobility streaming environment. We find that the impacts of interference on mobile streaming media performance can be greater than the impacts of high velocity. Also, in the city, where the user can move through a variety of network conditions, performance of existing streaming applications can be highly variable. Despite the variability of network conditions, our tests show that in all the mobility patterns examined, fluid playback of videos is possible with frame rates of over 25 fps being achieved 70% of the time using the HelixServer.

When examining the impacts of transport layer protocol on streaming media, we find that TCP streams perform significantly worse than UDP streams. The TCP streams examined achieve significantly lower bandwidth and generally receive streams encoded with lower bit rates. The poor performance of TCP streaming in the EV-DO environment can be attributed to the congestion avoidance behavior of TCP streams reacting to packet loss and corruption in the wireless channel.

Through tests of application layer protocols, it is found that HelixServer streams tend to achieve higher bandwidths than Windows Media Server streams. Also, Windows Media streams show more variability in frame rates between the city and highway conditions.

There are many additional factors that contribute to the performance of mobile streaming media that would be worth examining in future work. Examining the effects of the signal to noise ratio on streaming performance could provide insights into the results seen in the city scenario, where streaming performance varied widely. Also, our results show that there is potential to improve streaming performance for mobile clients. For example, buffering techniques that take into account the highly variable nature of the mobile link may help improve video quality for mobile clients. Finally, examining the impacts of handoffs between EV-DO networks and CDMA2000 1xRTT networks would be relevant since EV-DO has yet to be deployed widely in remote locations. In a highway setting, users travelling far from major urban centers may not have access to EV-DO networks for their entire journey and may encounter this type of handoff situation.

Our results show that streaming media over EV-DO networks is feasible and in most cases fluid playback of high quality video is possible. We find that HelixServer using UDP provides the best playback quality. Although streaming media is possible in EV-DO networks, some improvements could be made to streaming protocols to improve their ability to deal with widely varying network conditions.

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