Improving Mobile Video Streaming with Mobility Prediction and Prefetching in Integrated Cellular-WiFi Networks

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Abstract—We present and evaluate a procedure that utilizes mobility and throughput prediction to prefetch video streaming data in integrated cellular and WiFi networks. The effective integration of such heterogeneous wireless technologies will be significant for supporting high performance and energy efficient video streaming in ubiquitous networking environments. Our evaluation is based on trace-driven simulation considering empirical measurements and shows how various system parameters influence the performance, in terms of the number of paused video frames and the energy consumption; these parameters include the number of video streams, the mobile, WiFi, and ADSL backhaul throughput, and the number of WiFi hotspots. Also, we assess the procedure’s robustness to time and throughput variability. Finally, we present our initial prototype that implements the proposed approach.

I. INTRODUCTION

A major trend in mobile networks over the last few years is the exponential increase of powerful mobile devices, such as smartphones and tablets, with multiple heterogeneous wireless interfaces that include 3G/4G/LTE and WiFi. The proliferation of such devices has resulted in a skyrocketing growth of mobile traffic, which in 2012 grew 70%, becoming nearly 12-times the global Internet traffic in 2000, and is expected to grow 13-fold from 2012 until 2017. Moreover, mobile video traffic was 51% of the total traffic by the end of 2012 and is expected to become two-thirds of the world’s mobile data traffic by 2017. The increase of video traffic will further intensify the strain on cellular networks, hence reliable and efficient support for video in future networks will be paramount.

The efficient, in terms of both network resource utilization and energy consumption, support for video streaming in future mobile environments with ubiquitous access will require integration of heterogeneous wireless technologies with complementary characteristics; this includes cellular networks with wide-area coverage and WiFi hotspots with high throughput and energy efficient data transfer. Moreover, the industry has already verified the significance of mobile data offloading: globally, 33% of total mobile data traffic was offloaded onto WiFi networks or femtocells in 2012.

The goal of this paper is to evaluate the improvements for mobile video streaming that can be achieved by exploiting mobility and throughput prediction to prefetch video data in local storage of WiFi hotspots, efficiently utilizing the resources of integrated cellular and WiFi networks. Mobility prediction can provide information on the route that a vehicle will follow and when the vehicle will reach different locations along its route. Throughput prediction allows the mobile to determine whether to use WiFi hotspots that it will encounter along its route, and whether to perform prefetching. Although we consider mobile video data offloading to WiFi hotspots, our results and conclusions are potentially applicable to mobile video offloading to femto or small cell networks, where the backhaul throughput is smaller than the radio interface throughput. In summary, our contributions are the following:

- We propose a procedure that exploits mobility and throughput prediction for video data prefetching, i.e., proactive caching of video data in WiFi hotspot caches that the vehicle will encounter along its route, during video streaming.
- We evaluate the proposed procedure, in terms of the improved mobile video streaming Quality of Experience (QoE) and energy consumption, considering empirical measurements and a wide range of system parameter values, and show the procedure’s robustness to time and throughput variability.
- We present the high-level design of our initial prototype, whose main component is a video player client for Android devices that can stream video data from different servers during video playout.

The work in this paper is different from our previous work in [17], [16] that considers mobile data offloading for delay tolerant traffic, which requires transferring a file until some time threshold, and delay sensitive traffic, which requires minimizing the file transfer time; unlike these traffic types, video streaming requires a continuous transfer of video data to avoid impact on a user’s QoE, which thus requires a totally different prefetching procedure and evaluation. Moreover, in this paper we present the architecture of our Android client prototype for mobile video streaming from multiple servers.

The rest of this paper is structured as follows: Section II

1 Source: Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2012-2017, Feb. 6, 2013
presents related work, identifying how the work in this paper differs and advances the state-of-the-art. Section III presents the procedure to use mobility and throughput prediction to prefetch video data in order to improve mobile video streaming. Section IV uses trace-driven simulation and empirical measurements to assess the performance and energy efficiency achieved with prefetching, and investigate its robustness to time and throughput variability. Section V presents our initial prototype. Finally, Section V concludes the paper identifying future research directions.

II. RELATED WORK

Prior work has demonstrated bandwidth predictability for cellular networks [20] and WiFi [11, 12]. Bandwidth prediction for improving video streaming is investigated in [5], and for client-side pre-buffering in [15]. Both [5, 15] focus on cellular networks, while we consider integrated cellular-WiFi networks and prefetching video data in WiFi hotspots. Moreover, our goal is not to develop a new system for mobility and bandwidth prediction, but to evaluate mobility and throughput prediction to prefetch data in order to improve mobile video streaming and investigate how time and throughput variability influence the performance gains.

Exploiting delay tolerance to increase mobile data offloading to WiFi is investigated in [2]. The work of [9] showed that delay tolerance up to 100 seconds provides minimal offloading gains; however, this applies to human daily mobility, rather than vehicles. The work in [17] applies a user utility model for offloading traffic to WiFi. Our work differs in that we focus on video streaming and exploit prefetching video data in WiFi hotspots along a vehicle’s route.

Work on video streaming in heterogeneous networks that exploits cooperation between devices that communicate in an ad hoc or peer-to-peer manner is investigated in [13, 11, 4, 8]. Work on exploiting multiple heterogeneous wireless interfaces is investigated in [14, 19]. Unlike the above, our work focuses on how a single mobile device can exploit cellular and WiFi hotspot networks along its route, by using mobile and throughput prediction to prefetch video stream data in local caches of hotspots that the mobile will encounter.

The feasibility of using prediction together with prefetching is investigated in [3], which develops a prefetching protocol (based on HTTP range requests), but does not propose or evaluate specific prefetching algorithms. In this paper we propose a procedure for video stream prefetching, and evaluate its performance and robustness against time and throughput variations. Prefetching to improve the performance of video file delivery in cellular femtocell networks is investigated in [6], and to reduce the peak load of mobile networks by offloading traffic to WiFi hotspots [10]. Our work differs in that we consider prefetching in WiFi hotspots along a vehicle’s route to improve video streaming.

III. MOBILITY & THROUGHPUT PREDICTION FOR PREFETCHING

In this section we present a procedure that uses mobility and throughput prediction for prefetching data in order to improve mobile video streaming in integrated cellular-WiFi networks. Mobility prediction provides knowledge of how many WiFi hotspots a node (vehicle) will encounter, when they will be encountered, and for how long the node will be in each hotspot’s range. In addition to this mobility information, we assume that information on the estimated throughput in the WiFi hotspots and the cellular network, at different positions along the vehicle’s route, is also available; for the former, the information includes both the throughput for transferring data from a remote location, e.g., through an ADSL backhaul, and the throughput for transferring data from a local cache.

Prefetching can provide gains when the throughput of transferring data from a local cache in the WiFi hotspot is higher than the throughput for transferring data from its original remote server location. This occurs when the backhaul link connecting the hotspot to the Internet has low capacity (e.g., in the case of an ADSL backhaul) or when it is congested; this is likely to become more common as the use of the IEEE 802.11n standard increases.

The procedure to exploit mobility and throughput prediction for prefetching is shown in Algorithm 1. The procedure defines the mobile’s actions when it exits a WiFi hotspot, hence has only mobile access (Line 6), and when it enters a WiFi hotspot (Line 2). Mobility and throughput prediction allows the mobile to determine when it will encounter the next WiFi hotspot that has higher throughput than the cellular network’s throughput. From the time to reach the next hotspot and the average video buffer playout rate, the mobile can estimate the position that the video stream is expected to reach (offset) when it arrives at the next WiFi hotspot (Line 7). In our evaluation, the average video playout rate is computing based on an EWMA (Exponential Weighted Moving Average). The mobile instructs a local cache in the WiFi hotspot to start caching the video stream starting from the estimated offset (Line 8).

Algorithm 1 Using mobility and throughput prediction to prefetch video data

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1: Variables:
2: $R$: average video buffer playout rate
3: $T_{next-WiFi}$; average time until node enters range of next WiFi hotspot
4: $Offset$: estimated position in video stream when node enters next WiFi hotspot
5: Algorithm:
6: if node exits WiFi hotspot then
7:   $Offset$ ← $R$ · $T_{next-WiFi}$
8: else if node enters WiFi hotspot then
9:   Transfer video data that has not been received up to $Offset$ from original location
10: Transfer video data from local cache
11: Use remaining time in WiFi hotspot to transfer video data from original location
12: end if
13: end if
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When the node enters a WiFi hotspot, it might be missing some portion of the video stream up to the offset from which data was cached in the hotspot; this can occur if, due to time variations, the node reaches the WiFi hotspot later than the time it had initially estimated. In this case, the missing
IV. TRACING-DRIVEN EVALUATION

Our evaluation considers empirical measurements for the throughput of the cellular network and the SNR (Signal-to-Noise Ratio) of WiFi networks along a route between two locations in the center of Athens, Greece, Figure 1. Along the route we embed 2, 4, and 8 WiFi hotspots for different scenarios investigated. Based on the number of hotspots we can separate the full route into segments where the moving node has either mobile or WiFi connectivity, as shown in Table I for 4 hotspots (due to space limitations, we omit the corresponding tables for 2 and 8 hotspots).

The mobile throughput in Table I is the average of multiple measurements within each mobile segment. Unlike the mobile throughput, and because the WiFi APs along the route were not open, we estimated the WiFi throughput and the throughput for downloading data over an ADSL link that would have been achieved if WiFi APs were open as follows: We initially measured the SNR value for the various APs encountered along the route. Based on the SNR values, we estimate the throughput for downloading data stored locally at the WiFi hotspot and the throughput for downloading data over the hotspot’s ADSL backhaul link using Table II, the measurements in this table were obtained empirically from public open WiFi hotspots, at various outdoor locations. Note that we are not suggesting that the mapping shown in Table III is universal. Rather, the above approach is used to obtain realistic throughput values that can be experienced in actual systems, for the specific route that we consider. Moreover, our evaluation is not limited to the values shown Table I but considers different mobile, WiFi, and ADSL throughput values, as shown in Table III, to investigate their impact on the performance of the proposed video prefetching scheme.

The time variability determines how much the times at which the node changes access technology can differ from the empirical values shown in Table I, for example, a 10% time error means that the time the first segment (where the node has mobile access) ends and the second segment (where it has WiFi access) begins is in the interval [0.9 · 11.1 · 18] = [16.2, 19.8] seconds. Note that our empirical mobility measurements indicate that under typical road traffic conditions, the timing for the various route segments can differ 10-20%.

The throughput variability determines the throughput’s deviation from its average in Table III, for example, a 40% variability means that the mobile throughput is in the interval [0.6 · M, 1.4 · M] Mbps, where M is the average mobile throughput in Table I, measured empirically. We only consider the downlink direction, hence the backhaul throughput in Table III refers to the downstream.

The evaluation results are obtained from trace-driven simulation using the parameter values in Tables I and III for both HD-High Definition (Big Buck Bunny, 24 fps, avg: 1.6 Mbps, peak: 42 Mbps, peak/avg=26) and SD-Standard Definition (Football clip, 25 fps, avg: 0.6 Mbps, peak: 6.9 Mbps, peak/avg=11) video stream traces. The simulation models the video playout buffer, whose video frame data are removed when the frame is played, and is filled when data is obtained either from the original video stream location or from a local hotspot cache; in the former case the downloading rate is determined either from the mobile network or the ADSL throughput, whereas in the latter case the rate is determined by the WiFi throughput. When a frame needs to be played but the buffer does not contain the necessary data, the frame is assumed to be paused; the number of paused frames characterizes the

TABLE I

| Segment | Access | Time (sec) | Throughput (Mbps) |
|---------|--------|-----------|-------------------|
| 1       | mobile | 0         | 4.83              |
| 2       | WiFi   | 18        | 16.16 (WiFi) - 6.81 (ADSL) |
| 3       | mobile | 36        | 4.22              |
| 4       | mobile | 54        | 4.58              |
| 5       | mobile | 72        | 4.58              |
| 6       | WiFi   | 90        | 16.74 (WiFi) - 8.37 (ADSL) |
| 7       | mobile | 118       | 6.48              |
| 8       | mobile | 126       | 6.72              |
| 9       | mobile | 144       | 6.72              |
| 10      | WiFi   | 162       | 16.74 (WiFi) - 8.37 (ADSL) |
| 11      | mobile | 180       | 4.72              |
| 12      | mobile | 198       | 4.72              |
| 13      | mobile | 216       | 6.51              |
| 14      | WiFi   | 234       | 17.23 (WiFi) - 9.46 (ADSL) |
| 15      | mobile | 252       | 5.82              |
| 16      | mobile | 270       | 5.82              |
QoE (Quality of Experience) of the video stream playout. The video playout starts after 200 frames (approximately 8 seconds) have been downloaded. We also assume that the WiFi interface is activated 20 seconds prior to connecting to the WiFi hotspot. The graphs presented show the average and the 95% confidence interval from 120 runs of each scenario, with the same parameter values. Also, the values in Table II depicted as default are those that do not change in the specific evaluation scenario (graph).

### A. Number of paused frames

In this section we evaluate the performance of prefetching in terms of the number of paused frames, which expresses the QoE of video streaming, and investigate how this metric is influenced by the various parameters shown in Table II.

**Number of video streams:** Figures 2(a) and 2(b) show the number of paused frames as a function of the number of video streams, for the HD and SD video streams respectively. The results show that the gains with prefetching are high for both HD and SD video streams: For 4 HD streams, prefetching achieves 48% and 76% fewer paused frames compared to when prefetching is not used (i.e., the WiFi network is used opportunistically), and when only the mobile (cellular) network is used. Moreover, note that prefetching can support 3 HD streams without paused frames, whereas WiFi without prefetching has 15 paused frames and using only the mobile network results in 60 paused frames. For 11 SD streams, Figure 2(b) shows that prefetching achieves 68% and 98% fewer paused frames compared to when prefetching is not used and when only the mobile network is used, respectively. As expected, for a small number of streams, i.e., for a small network load, the gains with prefetching are smaller.

**Number of WiFi hotspots:** Figures 3(a) and 3(b) show that the performance for the two mobile & WiFi schemes improves with more hotspots. For the HD stream, Figure 3(a), prefetching achieves more than 36% fewer paused frames compared to when prefetching is not used. For the SD stream, Figure 3(b), prefetching achieves a significantly fewer paused frames (more than 67% fewer) for 2 and 4 hotspots. On the other hand, for 8 hotspots, prefetching does not provide gains; this happens because the remaining frame pauses occur during the initial mobile segment, which cannot be avoided with prefetching.

**Mobile, WiFi, and ADSL backhaul throughput:** Figure 4(a) shows the number of paused frames for different values of the mobile throughput. Observe that the performance for all schemes improves as the mobile throughput increases. Moreover, the performance of prefetching is significantly better compared to the other two schemes: the number of paused frames is more than 48% lower compared to the case where prefetching is not used and more than 75% lower compared to the case where only the mobile network is used; indeed, for mobile throughput 1.2 · M, where M is the mobile throughput shown in Table I the number of paused frames are less than 20, which are more than 70% smaller than the number when WiFi is used without prefetching, and more than 84% smaller than when only the mobile network is used.

Figure 4(b) shows the number of paused frames for different values of the WiFi throughput. As expected, the performance with prefetching improves when the WiFi throughput increases, while the performance for mobile & WiFi when prefetching is not affected by changes of the WiFi throughput, since the ADSL backhaul is smaller than the WiFi throughput hence limits the downloading rate.

Figure 4(c) shows the number of paused frames for different values of the ADSL backhaul throughput. Observe that the performance for both mobile & WiFi schemes improves as the ADSL throughput increases; however, the performance when prefetching is not used is influenced most. Indeed, when

### Table II

| Parameter       | Values                                                      |
|-----------------|-------------------------------------------------------------|
| SNR (dB)        | WiFi (Mbps)       | ADSL (Mbps)       |
| >-90            | 19.90            | 15.87            |
| -60 to -50      | 18.30            | 11.86            |
| -70 to -60      | 17.76            | 10.13            |
| -90 to -70      | 17.23            | 9.46             |
| < -90           | 16.74            | 8.37             |
|                 | 16.16            | 6.81             |

With more hotspots. For the HD stream, Figure 5(a), prefetching achieves more than 36% fewer paused frames compared to when prefetching is not used. For the SD stream, Figure 5(b), prefetching achieves a significantly fewer paused frames (more than 67% fewer) for 2 and 4 hotspots. On the other hand, for 8 hotspots, prefetching does not provide gains; this happens because the remaining frame pauses occur during the initial mobile segment, which cannot be avoided with prefetching.

**Table III**

| Parameter               | Values                                      |
|-------------------------|---------------------------------------------|
| Number of streams       | 2, 3, 4 (default), 5 (for HD stream)        |
| Mobile throughput       | 8, 9, 10, 11 (default) for SD stream        |
| WiFi throughput         | 0.6 · M, 0.8 · M, M (default), 1.2 · M     |
| Backhaul throughput     | 0.6 · W, 0.8 · W, W (default), 1.2 · W     |
| Throughput variability  | 0.6 · A, 0.8 · A, A (default), 1.2 · A    |
| Number of WiFi hotspots | 10% (default), 20%, 30%, 40%               |

(a) HD stream

(b) SD stream

Fig. 3. Paused frames for a different number of hotspots.
the ADSL throughput is lower than the mobile throughput, the performance when WiFi is used can be worst than when only the mobile network is used. Moreover, the performance gains of prefetching are reduced when the ADSL backhaul throughput increases, which is expected since prefetching has gains when the difference between the WiFi and the ADSL backhaul throughput is higher.

Time variability: Figure 5(a) shows that the number of paused frames for prefetching is not noticeably influenced by the time variability. This can be explained by the following: If a WiFi hotspot is reached later than estimated, some video data that was downloaded to a local hotspot cache would have already been received by the mobile, hence are not useful, but the longer time to reach the hotspot would allow more video data to be prefetched at a local cache, and subsequently downloaded to the mobile node at the higher WiFi throughput. On the other hand, if a WiFi hotspot is reached earlier than estimated, then the video data downloaded to a local hotspot cache would be for a later point in the video stream, but reaching the WiFi hotspot earlier would allow downloading data at the available ADSL throughput, which if higher than the mobile throughput would improve the video streaming performance.

Throughput variability: Figure 5(b) shows the influence of the variability of the mobile, WiFi, and ADSL backhaul throughput. A higher throughput variability increases the number of paused frames for all three schemes. Nevertheless, prefetching can achieve more than 45% fewer paused frames compared to the mobile & WiFi scheme without prefetching, and more than 75% fewer paused frames than when only the mobile network is used.

B. Energy efficiency

In this section we investigate the energy efficiency achieved with prefetching. The energy consumption is estimating using Table IV obtained from [13].

Figures 6(a) and 6(b) show the energy consumption of the investigated schemes for a different number of video streams, for HD and SD streams respectively. Figures 7(a) and 7(b) show the energy consumption of the investigated schemes for a different number WiFi hotspots, for HD and SD streams respectively. Observe that prefetching achieves lower energy consumption compared to the case where WiFi is used without prefetching, which in turn achieves lower energy consumption compared to the case where only the mobile network is used. Nevertheless, the gains in terms of energy efficiency are comparatively lower than the gains of increased performance, in terms of a fewer number of paused frames, Figures 2 and 3. This is due to the significantly higher power consumption per transferred data of the mobile network compared to WiFi, Table IV.

| Technology | Transfer (Joule/MB) | Idle (Watt) |
|------------|--------------------|------------|
| 3G         | 100                | 0          |
| WiFi       | 5                  | 0.77       |

Fig. 4. Paused frames for different mobile, WiFi, and ADSL throughput. HD stream.

Fig. 5. Paused frames for different time/throughput variability. HD video stream.

Fig. 6. Energy consumption as a function of the number of video streams.

Fig. 7. Energy consumption for a different number of WiFi hotspots.
been tested on a Android 4.0.3 (API 15) smartphone.

and the server uses a proprietary protocol. The prototype has a client and the server/local cache and between the local cache of the video file to the client, when it enters the corresponding cache, which receives requests from the client to prefetch the server. The other component of the implementation is the local addresses of the local hotspot caches and the original video using TCP. Note that the client needs to know a priori the IP Player.

by the downloaders. The video player module reads and plays the video stream that are stored in the smartphone’s memory interfaces to operate simultaneously. The video file reassembly Android system currently do not allow both the WiFi and 3G different parts of the video stream. However, restrictions of the downloader threads to operate in parallel, each downloading the local cache. Note that our implementation allows multiple actually downloading video data, from the original server or of a WiFi hotspot. The downloader module is responsible for WiFi interface to obtain video data from the local cache -ager, utilizing mobility information, decides when to turn on the estimated video offset, Algorithm

In addition to the above functionality, the downloader manager, utilizing mobility information, decides when to turn on the WiFi interface to obtain video data from the local cache of a WiFi hotspot. The downloader module is responsible for actually downloading video data, from the original server or the local cache. Note that our implementation allows multiple downloader threads to operate in parallel, each downloading different parts of the video stream. However, restrictions of the Android system currently do not allow both the WiFi and 3G interfaces to operate simultaneously. The video file reassembly module moves to the SD card, in the correct order, the parts of the video stream that are stored in the smartphone’s memory by the downloaders. The video player module reads and plays the video stream from the SD card, using Android’s Media Player.

The downloader modules obtain video stream data, either from the original video stream server or from a local cache, using TCP. Note that the client needs to know a priori the IP addresses of the local hotspot caches and the original video server. The other component of the implementation is the local cache, which receives requests from the client to prefetch the part of the video file starting from some offset and sends parts of the video file to the client, when it enters the corresponding hotspot. Currently, the communication between the mobile client and the server/local cache and between the local cache and the server uses a proprietary protocol. The prototype has been tested on a Android 4.0.3 (API 15) smartphone.

VI. CONCLUSIONS AND FUTURE WORK

We have presented and evaluated a procedure that exploits mobility and throughput prediction to prefetch video data in integrated mobile and WiFi networks, in order to improve mobile video streaming. The procedure can significantly reduce the number of paused frames (QoE), while being robust to time and throughput variability and achieve reduced energy consumption.

Our evaluation considered scenarios where the cellular network is overloaded, i.e. its throughput is smaller that the minimum throughput required to avoid frame pauses. In situations where the cellular network is underloaded, prefetching can still provide gains in terms of reduced energy consumption. Indeed, these gains are expected to be higher than the overloaded case, since a higher percentage of the video stream can be offloaded to WiFi. In the underloaded case the prefetching algorithm would be different than the one presented in this paper; future work will investigate the gains achieved with prediction and prefetching in underloaded cellular-WiFi networks. Other ongoing work includes evaluating the performance of our prototype implementation in a realistic setting. Also, future work includes adopting a standard protocol, based on MPEG-DASH (Dynamic Adaptive Streaming for HTTP), for communication between the mobile client and the video servers or caches.

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