Performance and Energy Efficiency of Mobile Data Offloading with Mobility Prediction and Prefetching

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Abstract—We present a detailed evaluation of procedures that exploit mobility prediction and prefetching to enhance offloading of traffic from mobile networks to WiFi hotspots, for both delay tolerant and delay sensitive traffic. We consider empirical measurements and evaluate the percentage of offloaded traffic, data transfer delay, and energy consumption of the proposed procedures. Our results illustrate how various factors such as mobile, WiFi and hotspot backhaul throughput, data size, number of hotspots, along with time and throughput estimation errors, influence the performance and energy efficiency of mobile data offloading enhanced with mobility prediction and prefetching.

I. INTRODUCTION

A major trend in mobile networks in the last few years is the exponential increase of powerful yet affordable personal mobile devices, such as smartphones and tablets, with multiple 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 2011 grew 2.3-fold, more than doubling for the fourth year in a row, and is expected to grow 18 times from 2011 until 2016\(^1\). On the flipside, despite its increase, the mobile data revenue significantly lags behind the exponential growth of data traffic. One solution to address the strain from the mobile data traffic is to move a portion of it to WiFi networks, exploiting the significantly lower cost of WiFi technology and existing backhaul infrastructure.

The goal of this paper is to evaluate procedures that exploit mobility prediction combined with WiFi and mobile throughput prediction, along with data prefetching to enhance mobile data offloading to WiFi [14]. Mobility prediction can provide information on a vehicle’s route and the time that the vehicle will reach different locations along its route. Such mobility information can be combined with geo-location information regarding WiFi hotspot access and WiFi and mobile throughput, to predict the number of WiFi hotspots the vehicle will encounter, the duration of access and estimated throughput for each hotspot, and the estimated mobile throughput along the route where it will have only mobile access. The current paper’s contribution is to provide a detailed evaluation of the procedures initially proposed in [14], considering empirical measurements and investigating the impact of various factors on the overall performance. In particular,

- we evaluate the percentage of offloaded traffic, the data transfer delay, and the energy consumption of the proposed mobile data offloading schemes, and
- we investigate the influence of the data object size, the mobile, WiFi, and ADSL backhaul throughput, number of WiFi hotspots, and errors in throughput and time estimation on the performance and energy efficiency.

Prior work has shown the predictability of bandwidth for cellular networks [15] and for WiFi [10], [11]. The work of [16] investigates how bandwidth prediction can improve scheduling in vehicular multi-homed networks and [17] investigates improvements for mobile video rate adaptation. Bandwidth prediction, together with transparent roaming and handover, for improving video streaming is investigated in [3]. Bandwidth prediction for client-side pre-buffering to improve video streaming is investigated in [13]. The works [17], [3], [13] focus on mobile networks, whereas our work investigates mobile data offloading to WiFi. Moreover, unlike [13] which considers pre-buffering at the client device, we investigate prefetching data to local caches in WiFi hotspots.

Exploiting delay tolerance to increase mobile data offloading to WiFi is investigated in [1], [12]. The work of [7] showed that delay tolerance of up to 100 seconds provides minimal offloading gains; however, this applies to human daily mobility, rather than vehicles. The work in [6] applies a user utility model to reduce the mobile throughput by offloading traffic to WiFi, focusing on a transport layer protocol design to integrate cellular and WiFi networks, and utilizing throughput prediction over a 1-second interval. Our work differs in that we consider both delay tolerant and delay sensitive traffic, and exploit data prefetching and prediction involving multiple WiFi hotspots along a vehicle’s route.

The feasibility of using prediction together with prefetching is investigated in [2], which develops a prefetching protocol (based on HTTP range requests), but does not propose or evaluate specific prefetching algorithms. In this paper we propose algorithms for delay tolerant and delay sensitive traffic, and evaluate their performance and robustness against time and throughput estimation errors. Prefetching to improve the performance of video delivery is investigated in [4], which proposes a centralized model to prefetch data in cellular femtocell networks. Prefetching algorithms to reduce the peak load of mobile networks by offloading traffic to WiFi hotspots are investigated in [9]. Our work differs in that we consider prefetching for multiple WiFi hotspots along a vehicle’s route, and investigate client-side algorithms for prefetching in

the case of both delay tolerant and delay sensitive traffic. In this respect, our work also differs from \cite{8, 5} which focus on identifying the subset of nodes, along with their storage, for disseminating information using opportunistic communication.

As mentioned above, prior work has shown the predictability of bandwidth for cellular networks \cite{15} and for WiFi \cite{10, 11}. Hence, our goal is not to develop a new system for mobility and bandwidth prediction, but to evaluate procedures that exploit prediction information that is available by systems such as the ones mentioned above, in order to utilize prefetching and enhance mobile data offloading to WiFi.

The rest of this paper is structured as follows: Section II discusses the mobile data offloading procedures to exploit prediction and prefetching for delay tolerant and delay sensitive traffic. Section III evaluates the procedures considering empirical measurements and investigating how various factors impact the performance and energy efficiency. Finally, Section IV concludes the paper identifying future research directions.

II. ENHANCING MOBILE DATA OFFLOADING WITH MOBILITY PREDICTION AND PREFETCHING

Next we present the procedures that exploit mobility prediction and prefetching to enhance mobile data offloading, which were originally proposed in \cite{14}. 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 the aforementioned mobility information, we assume that there is information on the estimated throughput of the WiFi hotspots and the mobile network, at different positions along the vehicle’s route; for the former, the information includes both the throughput for transferring data from a remote location, e.g., through an ADSL backhaul link, and the throughput for transferring data from a local cache over a WiFi link (this estimate is used only in the case of prefetching).

Prefetching can be advantageous when the throughput of transferring data from a local cache in the WiFi hotspot is higher than the throughput from the data’s original server location. This occurs when the backhaul link connecting the hotspot to the Internet has low capacity (e.g., an ADSL link) or when it is congested; this is likely to become more common as the IEEE 802.11n standard becomes more widespread.

A. Delay tolerant traffic

For delay tolerant traffic our objective is to maximize the amount of data offloaded to WiFi, while ensuring that the whole data object is transferred within a given delay threshold. The pseudocode for the procedure to exploit mobility prediction and prefetching is shown in Algorithm 1. The procedure defines the computations and actions that a mobile node takes when it exits a WiFi hotspot, hence it has only mobile access (Line 15), and when it enters a WiFi hotspot (Line 24). Initially, the procedure estimates the amount of data that can be transferred over WiFi (Line 16), and from this the amount of data that needs to be transferred over the mobile network (Line 18). Additionally, the procedure estimates the total time the node has WiFi access (Line 17) and, from this value and the delay threshold, it estimates the duration the node has only mobile access (Line 18). From the amount of data that needs to be transferred over the mobile network and the duration of mobile-only access, the minimum throughput for transferring data over the mobile network can be estimated (Line 19). To perform prefetching, whenever the node exits a WiFi hotspot the procedure estimates the amount of data to be prefetched (cached) in the next WiFi hotspot (Line 20) and the corresponding offset (Line 21); this offset depends on the amount of data that will be transferred over the mobile network until the node reaches the next WiFi hotspot.

When the node enters a WiFi hotspot, it might be missing some portion of the data object up to the offset from which data has been cached in the hotspot; this can occur if, due to a time estimation error, the node reaches the WiFi hotspot earlier than the time it had initially estimated. In this case, the missing data needs to be transferred from the data object’s original remote location (Line 25). Also, again due to a time estimation error, the amount of data cached in the WiFi hotspot can be smaller than the amount the node could have transferred while it is in the hotspot’s range. In this case, the node uses its remaining time in the hotspot to transfer data from the data object’s original location (Line 27).

Algorithm 1 Procedure to exploit mobility prediction and prefetching for delay tolerant traffic

1:  Variables:
2:  1: \( D \): size of data object to be transferred
3:  2: \( T_{\text{thres}} \): maximum delay threshold for transferring data object
4:  3: \( N_{\text{WiFi}} \): remaining WiFi hotspots to be encountered until \( T_{\text{thres}} \)
5:  4: \( D_{\text{cache}} \): estimated minimum amount of data to be transferred in all WiFi hotspots
6:  that will be encountered
7:  5: \( D_{\text{mobile}} \): amount of data to be transferred over mobile network
8:  6: \( T_{\text{nextWiFi},i} \): average time until node enters range of next WiFi
9:  7: \( T_{\text{nextWiFi},i} \): min, max throughput of WiFi
10:  8: \( T_{\text{nextWiFi},i} \): min, max duration node is connected to WiFi \( i \)
11:  9: \( R_{\text{mobile}} \): throughput to download data over the mobile network
12:  10: \( D_{\text{nextWiFi},i} \): amount of data cached in next WiFi hotspot
13:  11: \( \rho_{\text{min},i} \): estimated position in data object of data transferred until node enters next WiFi hotspot
14:  12: \( \rho_{\text{nextWiFi},i} \): amount of data offloaded in next WiFi hotspot
15:  Algorithm:
16:  15: if node exits WiFi hotspot then
17:  16: \( D_{\text{nextWiFi},i} \leftarrow \sum_{i \in N_{\text{WiFi}}} \left( R_{\text{nextWiFi},i} \cdot T_{\text{nextWiFi},i} \right) \)
18:  17: \( D_{\text{mobile}} \leftarrow D - D_{\text{nextWiFi},i} \).
19:  18: \( R_{\text{mobile}} \leftarrow D_{\text{mobile}} / T_{\text{mobile}} \)
20:  19: \( \rho_{\text{mobile}} \leftarrow \rho_{\text{nextWiFi},i} / T_{\text{nextWiFi},i} \)
21:  20: \( \rho_{\text{mobile}} \leftarrow \rho_{\text{mobile}} / T_{\text{mobile}} \)
22:  21: \( \rho_{\text{mobile}} \leftarrow \rho_{\text{mobile}} / T_{\text{mobile}} \)
23:  22: \( \rho_{\text{mobile}} \leftarrow \rho_{\text{mobile}} / T_{\text{mobile}} \)
24:  23: \( \rho_{\text{mobile}} \leftarrow \rho_{\text{mobile}} / T_{\text{mobile}} \)
25:  24: else if node enters WiFi hotspot then
26:  25: \( D_{\text{nextWiFi},i} \) stored until \( \rho_{\text{mobile}} \) from original object location
27:  26: \( \rho_{\text{mobile}} \leftarrow \rho_{\text{mobile}} / T_{\text{mobile}} \)
28:  27: \( \rho_{\text{mobile}} \leftarrow \rho_{\text{mobile}} / T_{\text{mobile}} \)
29:  28: end if

The procedure for exploiting mobility prediction without prefetching estimates the traffic expected to be transferred over WiFi, and subsequently the amount of traffic that needs to be transferred over the mobile network and the necessary mobile throughput. The algorithm is presented in \cite{14}.
B. Delay sensitive traffic

Similar to delay tolerant traffic, when the mobile node exits a WiFi hotspot it estimates the offset and the amount of data that needs to be prefetched in the next WiFi hotspot that the node will encounter. However, unlike delay tolerant traffic, in order to minimize the transfer delay for delay sensitive traffic, the node always uses the maximum throughput that is available in the mobile network. Moreover, note that there is no procedure for exploiting only mobility prediction (without prefetching) for delay sensitive traffic, since the maximum mobile throughput is always used. The prefetching algorithm for delay sensitive traffic is presented in [14].

III. EVALUATION

We consider empirical measurements for the mobile throughput and the SNR of WiFi networks along a route between two locations in the center of Athens, Greece, Figure 1, along which we we embed 2, 4, and 8 WiFi hotspots for the various 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 the values measured for each mobile segment. However, 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 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 ADSL backhaul link using Table II, whose measurements were obtained empirically from open WiFi hotspots. It is important to note that we are not suggesting that the mapping shown in Table II is universal. Rather, the above approach is used to obtain realistic throughput values that can be experienced in actual systems. Moreover, our evaluation considers different mobile, WiFi, and ADSL throughput values, as shown in Table III, to investigate their impact on the overall performance of the mobile data offloading schemes considered.

The time error determines how much the times at which the node changes access technology can differ from the empirical values in Table I; for example, a 10% time error means that the time at which 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 · 18; 1.1 · 18] = [16.2; 19.8] seconds. Note that our empirical measurements show that under typical road traffic conditions, the timing for the various route segments can differ 10-20%.

The throughput error determines the throughput’s deviation from its average in Table III; for example, a 40% throughput error 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 which is measured empirically. In this paper we only consider the downlink direction, hence the backhaul throughput in Table III refers to the downstream.

Estimation of the energy consumption uses Table IV, which was obtained from [12]. We assume that the WiFi interface is activated 20 seconds prior to connecting to the WiFi hotspot.

The evaluation results presented in this section are based on numerically computing the data transferred over the mobile and WiFi networks for the parameters in Table I and III. The graphs presented show averages and 95% confidence intervals.
from 120 runs of each scenario. Also, the values in Table III depicted as default are the values of the parameters that do not change in the specific evaluation scenario (graph).

A. Delay tolerant traffic

In this subsection we discuss results for delay tolerant traffic, where a data object needs to be transferred until the end of the vehicle’s route in Figure 1. We compare the following three cases: the procedure that exploits mobility prediction and prefetching (Algorithm 1), the procedure that exploits only mobility prediction without prefetching, and the case when prediction is not utilized and the maximum available mobile throughput is always used. The metrics we consider are the percentage of traffic that is offloaded to the mobile network and the energy consumption.

Data object size: Figure 2(a) shows the percentage of offloaded traffic for different data object sizes. For all data sizes the percentage of offloaded traffic with the prediction + prefetching scheme is more than 65% higher compared to the case where prediction and prefetching is not used. Moreover, the gains are higher for smaller data sizes. For large data sizes, the performance of the prediction scheme is close to the performance when prediction is not used; this occurs because for large object sizes the mobile network is used close to its maximum throughput, hence prediction is not beneficial.

Figure 2(b) shows that the energy efficiency gains reflect the gains in terms of offloaded traffic. Specifically, the energy efficiency gains with the prediction + prefetching scheme is approximately 85% for a 40 MB data object size and 35% for a 70 MB object size. For large data sizes, the energy consumption of the prediction scheme is close to the energy consumption when prediction is not used.

Mobile, WiFi, ADSL backhaul throughput: Figure 3(a) shows the percentage of offloaded traffic for different mobile throughputs. As expected, the percentage of offloaded traffic for the prediction + prefetching and the prediction schemes does not depend on the mobile throughput, since these schemes use less than the maximum available mobile throughput. On the other hand, when prediction and prefetching is not used, the percentage of offloaded traffic decreases when the mobile throughput increases.

Figure 3(b) shows the percentage of offloaded traffic for different WiFi throughputs. For the prediction + prefetching scheme the amount of offloaded traffic increases significantly when the WiFi throughput increases. On the other hand, it does not affect the prediction scheme and the case when prediction and prefetching is not used, since in these cases the amount of offloaded traffic is constrained by the ADSL throughput.

Figure 3(c) shows the offloaded traffic for different ADSL backhaul throughputs. When the throughput is low, the performance when only prediction is used is close to the performance when prediction is not used; this happens because when the backhaul throughput is low, the mobile network needs to be used more, hence the mobile throughput is close to its maximum. On the other hand, when the backhaul throughput is high, then the performance of prediction and prefetching is close to the performance when only prediction is used; this occurs because when the backhaul throughput is high and close to the WiFi throughput, there are smaller gains from prefetching and downloading data from a local cache.

Number of WiFi hotspots: Figure 3(d) shows that for two hotspots, the prediction scheme has similar performance when no prediction is used; this occurs because for few hotspots, the prediction scheme uses mobile throughput close to the maximum. On the other hand, the prediction + prefetching scheme achieves performance which is more than 30% higher than the prediction scheme and more than 60% higher than when prediction and prefetching is not used.

Time error: Figure 4(a) shows how the percentage of offloaded traffic is affected by the time error. Observe that the performance when prediction and prefetching are used and when only prediction is used decreases as the time error increases; this occurs because the time error reduces the effectiveness of prediction and prefetching. Nevertheless, the offloading percentage when prediction and prefetching are used is more than 60% higher than the offloading percentage when prediction and prefetching are not used, and more than 50% higher than the offloading percentage when only prediction...
is used. Figure 5(a) shows that the gains in terms of reduced energy consumption follow the gains of the increased amount of offloaded traffic, Figure 4(a).

**Throughput error:** Figure 4(b) shows that the throughput error affects the performance of the prediction and prefetching scheme most. Nevertheless, its performance remains more than 40% higher than the prediction-only scheme and more than 70% higher than the case where prediction and prefetching are not used, even when the throughput error is as high as 80%. Figure 5(b) shows that the gains in terms of reduced energy consumption follow the gains of the increased amount of offloaded traffic, Figure 4(b).

### B. Delay sensitive traffic

A key difference compared to delay tolerant traffic is that now the maximum mobile throughput is always used. We compare three cases: the procedure that exploits both mobility prediction and prefetching, the case where prediction and prefetching are not used, and the case where only the mobile network is used. The performance metric is the delay for transferring a data object and the energy consumption.

**Data object size:** Figure 6(a) shows the transfer delay as a function of data object size. Prediction and prefetching achieve a delay that is lower by 25-35% compared to the case where only the mobile network is used, and 15-25% compared to WiFi offloading without prediction and prefetching.

The energy efficiency gains with prediction and prefetching are approximately 20-25% compared to the case of WiFi offloading without prediction and prefetching. The energy gains with prediction and prefetching are even higher compared to when only the mobile network is used: 40-50%.

**Mobile, WiFi, ADSL backhaul throughput:** Figure 7(a) shows that the transfer delay gains with prediction and prefetching are higher for a smaller mobile throughput. Moreover, for a high mobile throughput, the transfer delay with offloading can be worse than when only the mobile network is used, when the mobile throughput is higher than the ADSL throughput.

Figure 7(b) shows the transfer delay as a function of the WiFi throughput. As in the case of delay tolerant traffic, the performance of prediction and prefetching in terms of reduced transfer delay increases as the WiFi throughput increases. On the other hand, the transfer delay in the case of WiFi offloading without prediction and prefetching and when only the mobile network are used is not influenced by the WiFi throughput.

Figure 7(c) shows the influence of the ADSL throughput on the transfer delay. Observe that for a low ADSL throughput, the performance of WiFi offloading without prediction and prefetching is close to the performance when only the mobile network is used. On the other hand, for high values of the ADSL throughput the performance in the case of prediction and prefetching is close to the performance in the case of WiFi offloading without prediction and prefetching; this occurs because the gains of prefetching are reduced when the ADSL throughput approaches the WiFi throughput.

**Number of WiFi hotspots:** Figure 7(d) shows the transfer delay for a different number of hotspots. As expected, the transfer delay improves with prediction and prefetching when the number of hotspots increases: The transfer delay with prediction and prefetching with two hotspots is approximately 13% and 17% lower than offloading without prediction and when only the mobile network is used, respectively, while it is approximately 24% and 43% lower when there are 8 hotspots.

**Time error:** Figure 8(a) shows that as the time error increases, the variability of the transfer delay increases slightly (the 95% confidence interval is larger), but the average transfer delay for all schemes remains the same. Figure 9(a) shows the energy consumption as a function of time errors. Observe that the average energy efficiency gains are independent of the time errors and are relatively higher compared to the transfer delay gains: When prediction and prefetching are used the energy consumption is more than 40% lower than when only the mobile network is used, whereas the transfer delay reduction is approximately 27%.

**Throughput error:** Figure 8(b) shows the influence of the throughput error on the transfer delay. As expected, the transfer delay gains are higher for lower throughput errors;
implementing a prototype to demonstrate the gains of the proposed offloading procedures. Moreover, we are extending the procedures to allow different tradeoffs between the delay, the amount of offloaded traffic, and the energy efficiency, and to exploit prediction and prefetching for streaming video.

### References