Characterizing WiFi Connection and Its Impact on Mobile Users: Practical Insights

Suranga Seneviratne
School of EET, University of New South Wales & NICTA, Australia
s.seneviratne@student.unsw.edu.au

Aruna Seneviratne
School of EET, University of New South Wales & NICTA, Australia
aruna.seneviratne@nicta.com.au

Prasant Mohapatra
Department of Computer Science, University of California, Davis
CA, 95616
prasant@cs.ucdavis.edu

Pierre-Ugo Tournoux
NICTA, Australia
tournoux@gmail.com

ABSTRACT

Smartphones and WiFi networks are becoming pervasive. As a result, new applications and services are being offered to smartphone users through WiFi networks. Some of the more novel applications provide data services to pedestrians as they move through WiFi coverage areas in public locations such as railway stations. One significant factor that will influence the data transfers for users when they are on the move, is the connection set-up time. In this paper we characterize the WiFi connection set-up process. Using data from voluntary Android smartphone users, we show that WiFi connection setup have significant delays, sometimes as high as 10s. Then through a detailed analysis of the connection set-up process we show that, contrary to previous findings, this is due to losses of DHCP messages at the WiFi access point. We also show that some of the methods that have been adopted by device manufactures are suboptimal and this can be addressed at the WiFi access point. Finally using this insight we extend a known mathematical model, which will help in the dimensioning of WiFi networks for pedestrian smartphone users.

Categories and Subject Descriptors

C.4 [**Computer-Communication Networks**]: Network Architecture and Design—*Wireless communication*

Keywords

WiFi; WiFi Performance; Smartphones

1. INTRODUCTION

The proliferation of mobile devices is enabling a new class of applications and services that disseminate information to pedestrians. Examples of such applications and services are providing free metro newspapers in a digital form and scheduling the distribution of content to be downloaded by users when they move through areas covered by WiFi networks at public locations such as railway stations, shopping malls, and airports [16, 12]. To make these applications and services viable, it is necessary for a mobile device to be able to establish a connection with a WiFi access point, and download a minimum quantity of data during the time the user is within the coverage area of a given access point, namely through a short lived connection.

During a short connection period, the amount of the data that can be downloaded will depend on the connection establishment delay and data throughput that can be achieved once the connection is established. The latter will depend on a number of factors such as the signal strength at the receiving mobile device, mobility characteristics of the user, and interference. It will also be influenced by various system characteristics such as the use of caching and the way network has been dimensioned [13].

The former will depend on the connection establishment process of WiFi networks. Although this has been studied extensively from a handoff performance and vehicular networking point of view, it has not been investigated in the new environments where smartphones are the end devices and the users are pedestrians. This is important, as it has recently been reported that operational characteristics of smartphones when connected to WiFi networks differ significantly from other systems [8, 11]. This paper provides analysis of the factors that influence the data transfers when WiFi networks are used for data dissemination through short lived connections, by characterizing the WiFi connection set-up time and its impact when using commercial off-the-shelf smartphones. To the best of our knowledge, this is the first time such a study has been carried out.

We make the following contributions:

- Characterize the connection establishment time for smartphones of different manufacturers and show that WiFi connection set-up time significantly affect the data transfer capability of short lived connections.

- Show that set-up delay is significant and limits the possibility of data download. Furthermore, contrary to what has been suggested previously, we show that

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the high connection set-up delay is due to the message losses at the WiFi access points. Because of this, we show that previously proposed solutions for addressing connection set-up delays are sub optimal.

The remainder of this paper is organized as follows. Section 2 details the various phases of the WiFi connection process while Section 3 describes our experimental setup and the characteristics of the used devices. Section 4 provides details of our experimental results and provides a clear understanding on impact of various components of the connection phase. In Section 5, an extended model of the connection set-up time and the transferrable volume of data during a connection is presented. Section 6 discusses the possible solutions and enhancements while Section 7 describes the related work. In Section 8, we conclude the study.

2. BACKGROUND

Data transfer in a WiFi network involves a connection set-up and the transfer of data. The connection set-up process consists of three main phases: network discovery (scanning), network association and IP address acquisition, as schematically shown in Figure 1. Therefore the performance of these three phases will affect the overall network connection set-up time. In contrast, the transfer of data will be dependent on the mobility of the user, the interference due to the radio channel characteristics and the number of users in the WiFi coverage area. In this paper we evaluate the connection set-up time experimentally and the data transfer by modeling it analytically.

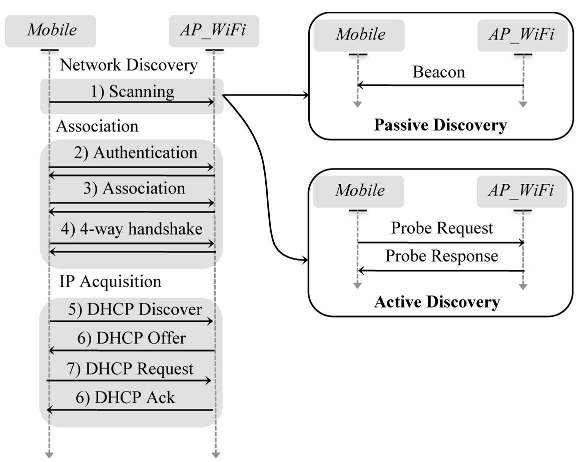

Figure 1: Connection set-up phases

2.1 Network discovery

A mobile device can discover available access points either passively or actively. Passive discovery uses beacon frames broadcasted by the wireless access point (AP) at intervals of 100ms or some multiple of 100ms [10]. It has been widely reported in studies which were focusing on handoff performance, that network discovery or scanning phase can be significant [15, 9]. However, in the application scenarios that are being considered in this paper, the users would have had an association with the network in the past. Therefore the devices will be using active discovery, where the mobile device transmits a probe request for each AP it has connected previously on each WiFi channel. The frequency of the active probe request depends on the WiFi card of the mobile device. When active probing is used, the network discovery phase becomes a relatively small component of the connection set-up time except when:

- In either active or passive modes in the region at the perimeter of the coverage area of an AP, where the beacons from the AP could been seen but the signal strength is insufficient to associate with the AP.
- The WiFi subsystem of a smartphone sleeps and wakes up periodically to save energy. Therefore, when the devices are mobile, inter-wakeup time might be longer than the time which the device is in the coverage area of an AP. This can lead to increases in network discovery times [7].

For the scenarios considered in this paper, both these can be ignored for the following two reasons. Firstly, as the APs in public WiFi networks will transmit a beacon at regular intervals and the users are mobile, the effect at the boundaries will not be significant. Secondly, the smartphones can be assumed to automatically connect to previously known APs, if they are found to be in range.

2.2 Association to the Access Point

Once a suitable network is identified, device enters an Authentication-Association (AA) phase where the mobile device transmits an Authentication frame to authenticate itself with the AP. Once authenticated, it sends an Association Request to the AP to associate itself with the AP. This process is straight forward and is again a relatively small component of the overall connection set-up time. In some WiFi networks, depending on the security mechanisms being used, an Association Response is followed by a four-way handshake. As the focus is on data dissemination over WiFi networks in public places, this can be ignored.

2.3 IP address acquisition

The IP address acquisition begins with the smartphone broadcasting a DHCP Discover message. This informs the DHCP servers in the network, the presence of a new mobile device. In response, the DHCP servers send DHCP Offer messages. When a DHCP Offer message is received, the smartphone broadcasts a DHCP Request message requesting the offered IP Address. The DHCP server confirms the reception of a DCHP request by returning a DHCP Acknowledgement. If no response is received for the DHCP Request or DHCP Discover messages, the sender waits for a period of time determined using an exponential back-off algorithm with an initial values of $4(\pm 1)$ sec.

Once an IP address is acquired, the connection set-up is complete and the data transfer can commence.

3. EVALUATION METHODOLOGY

Analyzing the smartphones' WiFi connection establishment requires distinguishing between the three phases of connection set-up, namely network discovery (scanning), network association and IP address acquisition, as well as the reason for any retransmissions that might take place.

However, this information cannot be obtained through the APIs provided for off-the-shelf smartphones, and requires access to the smartphone's MAC layer events. Furthermore it

Table 1: Composition of the field dataset by device manufacturer

Device manufacturer	% from observed connections
Samsung	37.09%
LG	22.56%
Motorola	17.72%
HTC	14.18%
Other	8.45%

Table 2: Composition of the field dataset by Android version

Android version	% from observed connections
2.2	3.78%
2.3.4	22.56%
2.3.5	4.78%
4.0.3	27.76%
4.0.4	26.82%
4.1.2	14.29%

is necessary to instrument the access points and the DHCP servers. This severely limits the environments in which experimentation could be done. To overcome this limitation, we collected two different datasets.

3.1 Field Dataset

Field Dataset was obtained by installing an application we developed, *Wifi Event Monitor*[1] on volunteers' smartphones. *Wifi Event Monitor* runs in the background and logs the WiFi connectivity events explained in Section 2, with timestamps during devices' everyday use[2]. Therefore this dataset provides general statistics of real life environment.

The app was distributed among 22 volunteers and data was collected for a period of two weeks at different locations in four different countries. Collected data was used to measure the connection set-up time for a variety of WiFi networks

The dataset contains devices from most of the major Android smartphone manufactures and includes 6 different Android OS versions as can be seen in Table 1 and Table 2.

3.2 Experimental Dataset

The *field data set* provides general statistics on the real life environment. However without special hardware or Android devices with custom ROMs it is not possible to observe the various phases of the connection set-up process in sufficient detail. To overcome this limitation, a second data set was collected using the *Airpcap Nx*[3]. A number of commodity Android phones with *Wifi Event Monitor* were used to periodically connect to a number of different APs with different configurations. During the connection establishment process we monitored the wireless link using the *Airpcap Nx* and collected messages passed between the smartphones and the APs.

Devices used to obtain experimental data set are presented in Table 3 and the details of the two datasets are summarized in Table 4.

[1]https://play.google.com/store/apps/details?id=com.wim.wifieventmonitor

[2]The app was written using the Android developer API, so that in can be used in any commodity Android phone without modification.

[3]http://www.riverbed.com/us/products/cascade/wireshark_enhancements/airpcap.php

Table 3: Devices used in experimental dataset

Smartphones	Access points
HTC Desire HD	LinkSys WRT54GS
LG Optimus Spirit	Cisco Aironet
Google Nexus One	Netgear DGN2000

Table 4: Summary of the datasets

	Field Dataset	Experimental Dataset
Collection Period	14 days	N/A
No. of users	22	N/A
Phone models	13	3
Platforms	Android	Android
Wireless SSIDs	54	3
Observed connections	1693	2451

4. MEASUREMENT RESULTS

4.1 Field Dataset

4.1.1 Characterization of total connection setup time

Figure 2 shows the CDF of the total connection set-up time, namely the sum of the Authetication-Association time and IP Address Acquisition times, for the field dataset. As explained in Section 2.1, it is possible to ignore the network discovery time. Figure 2 shows that 10% of the total connection attempts took more than 10s to complete the connection set-up.

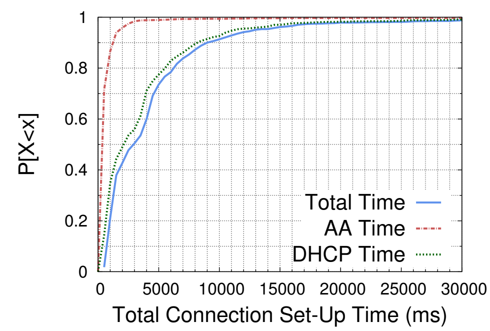

Figure 2: CDF of total connection set-up time

4.1.2 Authentication Association and IP Address Acquisition Times

For this data set, the Authentication-Association time has a mean of 633ms and the 95^{th} percentile is 1782ms. IP Acquisition time has a mean of 3752ms and a 95^{th} percentile of 11244ms. It is clear that the IP Acquisition time is the dominant component of the connection set-up time. This is also visible in Figure 2. The total time and the IP Acquisition time curves have similar shapes. The slight plateaus observed in the IP address acquisition time plots at 3-4, 6-7 and 9-10s are due to the timeouts of DHCP messages as explained in Section 2.3.

4.1.3 Device specific characteristics

The Association and IP Acquisition time characteristics of the different phone models are shown in Figure 3, and Figure 4.

As Figure 3 shows, only 2 phone models out of the 13, namely HTC Desire HD and the Samsung Nexus S, have a

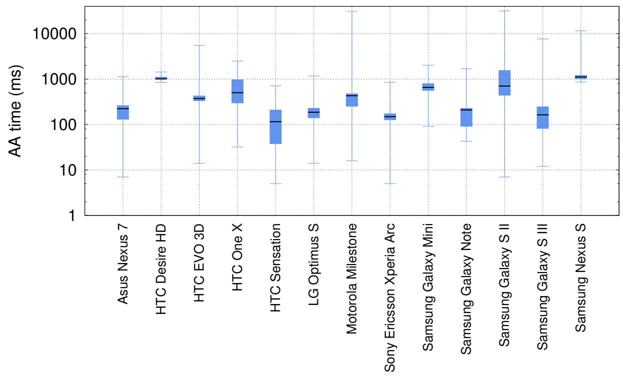

Figure 3: Minimum, 25^{th}, 50^{th}, 75^{th} percentiles and maximum of AA time

median association times of greater than 1s. 8 phone models have a 75^{th} percentile of less than 500ms and it is less than 1550ms for all the phone models.

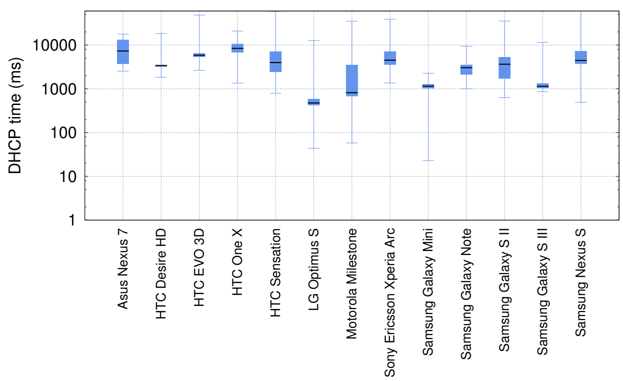

Figure 4: Minimum, 25^{th}, 50^{th}, 75^{th} percentiles and maximum of DHCP time

Figure 4 shows that 7 phone models have a 75^{th} percentile of IP Acquisition time of greater than 5s and for 4 phone models, it is greater than 7s. For two models the 75^{th} percentile was greater than 10 seconds.

The combined association and IP Acquisition times are thus significant and this impedes the content distribution to pedestrian users. This is discussed further in Section 5.

4.2 Experimental dataset

From the field dataset, it is clear that IP Acquisition time is the dominant competent, amounting to as much as 80% of the total connection set-up time. To gain a better insight, we therefore observed the *elapsed seconds* parameter in DHCP messages exchanged between the smartphone and the DHCP server. According to the DHCP specification [4] *elapsed seconds* indicates the number of seconds elapsed since the client began address acquisition process.

When *elapsed seconds* parameter is non-zero, we examined the message exchanges shown in Figure 5, where, first the smartphone sends the DHCP Discover message as a broadcast message. Then the AP acknowledges the reception using a L2 acknowledgment. Once that message is relayed back on the wireless link and the wired network, the rest of the messages also follow a similar pattern.

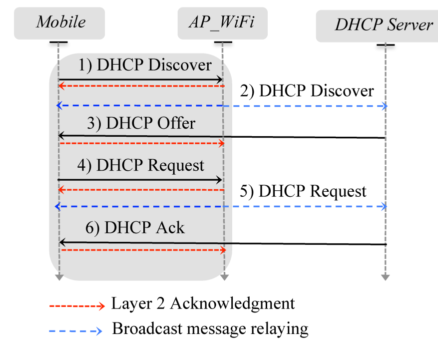

Figure 5: Detailed DHCP message flow

This analysis reveals that there are three primary reasons for the long IP Acquisition times:

- The AP acknowledges the receipt of a DHCP Discover message. However, it does not relay it back. As a result the smartphone has to wait until its timer expires to resend another DHCP Discover message (*DHCP Discover discard*).

- The AP receives a DHCP Request message and acknowledges the receipt. However, it's not relayed back on the wired and wireless network. As a result again the smartphone has to wait until its timer expires to resend the DHCP Request message (*DHCP Request discard*)

- There is a delay at the access point when replying to a DHCP offer message (*DHCP Offer delay*)

These results show, contrary to previous work that implied the long DHCP times in WiFi networks were due to the loss of DHCP Discover and DHCP Request messages in the wireless link [5], the delay is caused by certain APs discarding these messages as shown in Figure 6. In all the cases we observed, smartphone retransmits the frames until an acknowledgement is received. Table 5 shows the percentage of L2 retransmissions observed for each DHCP message type.

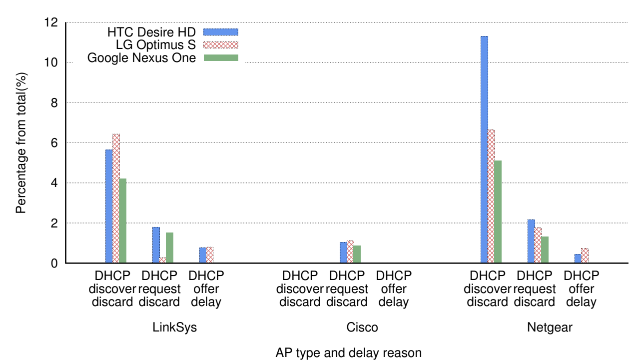

Figure 6: DHCP delay reasons

[4]http://www.ietf.org/rfc/rfc2131.txt

Table 5: Percentage of L2 retransmissions observed for each message type

Message Type	% of retransmissions from total
DHCP Discover	14.2%
DHCP Offer	6.1%
DHCP Request	11.45%
DHCP Ack	6.6%

4.2.1 *Device specific characteristics*

Authentication-Association time appears to be dependent only on the type of smartphone. The processes within the AP has a minimum impact. This is illustrated in Figure 7, where irrespective of the AP a smartphone is connected to, the CDF of AA times are similar.

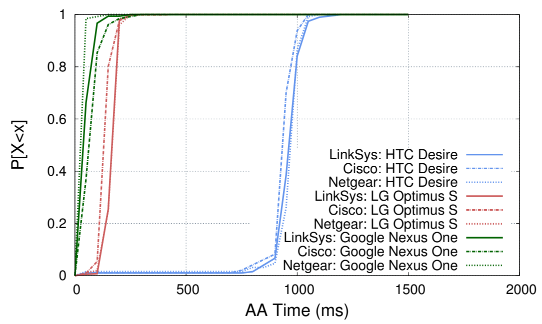

Figure 7: CDF's AA time

On the other hand Figure 8 indicates that the IP Acquisition time is dependent on both the AP and smartphone as the CDFs are not clustered based on either AP type or the smartphone type.

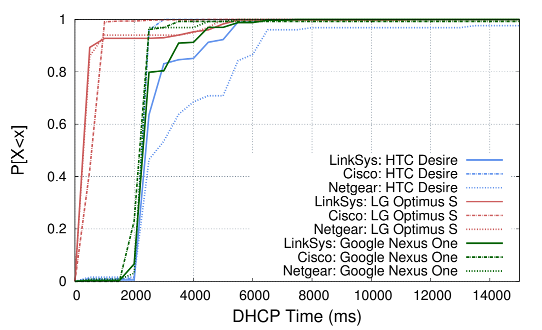

Figure 8: CDF's DHCP time

5. IMPACT OF SET-UP TIME

To evaluate the effect of connection set-up time on data download, we extended the mathematical framework proposed in [4] by introducing the connection set-up time as a parameter.

5.1 Pedestrian data download model

When a user walks from point A to D as shown in the Figure 9, the time spent in the coverage area of an AP, depends on the walking speed of the user and the distance between A and D. It is assumed that an AP has a circular coverage area and hence the distance AD has a direct relationship with the angle at the AP, θ, referred to as *angle of entry.*

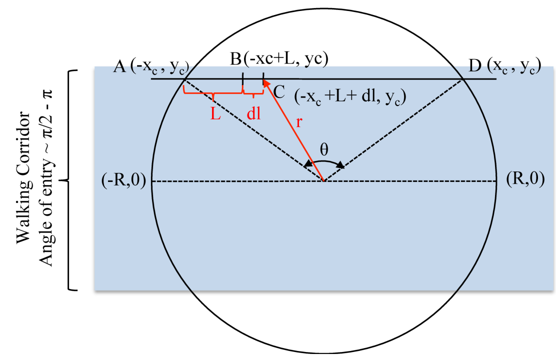

Figure 9: Parameter definition

Now we define a *walking corridor* by restricting the angle of entry from $\frac{\pi}{2}$ to π. The *walking corridor* resembles the walking paths followed by pedestrians when walking across WiFi network coverage areas in public places. Assume that the walking speed of users is $v = 1.4ms^{-1}$, the connection set-up time is t_i, and the angle of entry θ is given by $\sim U(\frac{\pi}{2}, \pi)$. Then the distance travelled during the connection set-up time is given by $L = v.t_i$

We use the following distance throughput model obtained from [4] for 802.11n WiFi networks.

$$S(r_n) = \begin{cases} (ar^2 + br + c) & \text{if } 0 < r < R_{max} \\ 0 & \text{otherwise} \end{cases}$$

Where $a = -0.009n$, $b = -0.8n$ and $c = 40n$ and $n = 1, 2$, the number of antennas and $R_{max} = 35.18m$.

Transport layer overheads are considered in the model and hence it directly give the application level throughput.

Then the average throughput of the mobile user crossing the coverage area of an AP is given by

$S_{av} = \frac{1}{(2x_c - L)} \int_B^D S(x, y)\, \mathrm{dl}$ .... (1)

As a result downloadable data volume, I is given by

$I = S_{av}.t_{dwell} = S_{av} \frac{(2x_c - L)}{v}$

where t_{dwell} is the time spent under the access point coverage. By substituting from (1), we get

$I = \frac{1}{v} \int_B^D S(x, y)\, \mathrm{dl}$ .... (2)

Where $S(x, y)$ is the throughput distance relationship of the access point at point (x,y).

The path in Figure 9, can be parameterized by the substitution $x(t) = (-x_c + L) + (2x_c - L)t$ and $y(t) = y_c$ where $0 \le t \le 1$.

The instantaneous distance from the center is given by $r = \sqrt{[(-x_c + L) + (2x_c - L)t]^2 + {y_c}^2}$

Substituting r in (2) we get

$I = \frac{(2x_c - L)}{v} \int_0^1 S(\sqrt{[(-x_c + L) + (2x_c - L)t]^2 + y_c{}^2})\, \mathrm{d}t$

where $x_c = Rsin(\frac{\theta}{2}), y_c = Rcos(\frac{\theta}{2})$ and $L = vt_i$.

We define *percentage loss of data download*, P_{loss} for a given angle of entry as follows.

$$P_{loss} = \frac{I_{ideal} - I_{nonideal}}{I_{nonideal}} * 100$$

Where I_{ideal} is the downloadable data volume when there are no losses in DHCP messages and $I_{nonideal}$ is the downloadable data volume when there are DHCP message losses. P_{loss} quantifies the percentage increment in downloadable data volume that can be achieved for a given angle of entry if DHCP message losses are fixed.

In Figure 10, we plot P_{loss} for two non-ideal scenarios: average connection set-up time when there are DHCP losses, and 90^{th} percentile of the connection set-up time when there are DHCP losses. According to the figure it can be seen that, on average the downloadable data volume can be increased by 1.7-3.9% and 10% of time, it can be increased by 7.1-15.5% if the DHCP losses can be avoided.

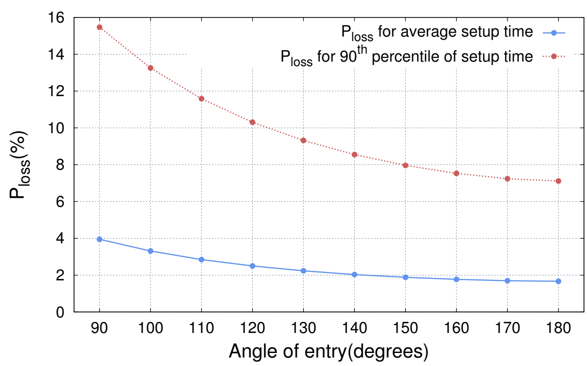

Figure 10: Percentage loss of data download in 802.11n WiFi networks

In terms of data volumes these percentages map to 1.6-2.3MB and 6.3-10.0MBs for the average and 90^{th} percentiles of the connection set-up times when DHCP losses are present, respectively. According to [6] an average SD resolution YouTube video clip is around 10MB. Hence due to the overheads of connection set-up time, 10% of the time a pedestrian loses the opportunity of downloading a complete video clip.

6. POSSIBLE SOLUTIONS

6.1 IP caching

Caching of the IP addresses [2], enables the smartphone to initially request the IP address that is in cache whenever it reconnects to a network it has connected previously. This eliminates the DHCP discover phase. We observed this is used by some phone models such as the Samsung Galaxy Mini and iPhone 4.

However, the Samsung and iPhone 4 implementations appear to be different. If the IP address is cached, Samsung devices request the previous IP address even if the lease has expired, whereas the iPhone 4 requests the IP address only if the DHCP lease is valid. Both the approaches will work when the networks are servicing a small user population. However in public WiFi networks where the networks have to serve large user populations, most of the previous IP addresses are most likely not going to be available for lease again.

Figure 11 illustrates the CDFs of IP address acquisition times of iPhone 4, for scenarios “no IP caching”, “cache hit” and “cache miss”. As can be seen a “cache hit” yields a significant improvement in the IP address acquisition time. The difference of around 100 ms between “cache miss” and “no cache” can be attributed to the additional messages passed in “cache miss” scenario i.e requesting the previous IP address and the DHCP server rejecting it.

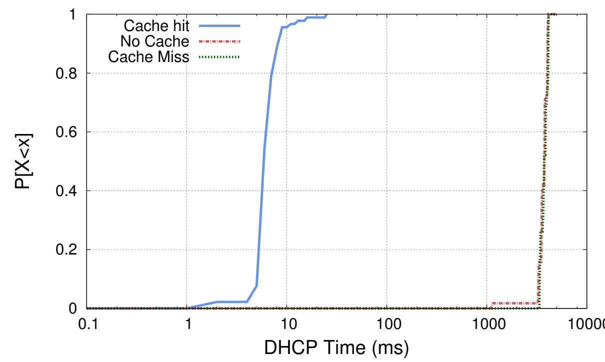

Figure 11: CDF of DHCP time in iPhone4

6.2 Optimization at the access point

AP software can be modified to provide higher priority to DHCP messages and ensure that they are not discarded. As shown in Figure 6, this is being effectively done in at least one of the commercial grade access points we experimented with. Therefore, we have opened a bug report with one of the widely used open firmware offerings to draw the attention of the community. In addition, a further optimization can be done by making DHCP Discover unicast when the IP address of the DHCP server is known from a previous connection. This will avoid unnecessary message relaying by the AP as DHCP servers are usually connected via a wired connection to the AP.

6.3 DHCP timeout change

Eriksson et al.[5] proposed to reduce the DHCP Discover and DHCP Request timeouts to 100ms. As the messages are lost at the AP rather than the link, this approach is not desirable since it will increase the number of broadcast messages on the network. This will cause the smartphones in sleep mode to wake up and thus increasing their energy consumption [11].

7. RELATED WORK

Prior work has studied similar aspects of the connection set-up times under the context of vehicular networks. Bychkovsky et al. [2] measured the connection set-up times to available WiFi access points while driving around Boston and Seattle and reported that delay could be improved to be less than 350ms by caching the IP address while honoring the lease time. The effectiveness of this type of solution will be dependent on the cache hit rate and lease validity. For the reasons given in Section 6.1, we believe , especially the lease validity will be low in public WiFi networks.

Eriksson et al. [5] and Soroush et al. [14] proposed to reduce DHCP timeouts, which are usually in the range of seconds to 100ms in order to achieve faster connections setups under the context of vehicular networks. Using this method, the authors were able to bring down the setup time to 400ms and 1.3s respectively compared to the value of 10 seconds when standard wireless software is used.

The primary differentiators of our work from the above are the use of commercially available smartphones without any software or hardware modification and the focus on how the connection set-up time affect the walk through scenarios.

Teng et al. [15] and Murray et al. [9] measured the scanning delays associated with the hand over process between two wireless APs. As described in Section 2.1 we expect the public WiFi networks to transmit a beacon at regular intervals and the smartphones will automatically connect to previously known APs if they are found to be in range.

It might be argued that WiFi proposals such as WiFi Direct [1] might address this issue. However, WiFi Direct is still in its early ages of development and its full impact and adoption is unclear due to possible mobile OS restrictions. Finally, ZeroConf [3] has been in existence since 2005, and has only had little impact. Therefore it is still necessary to have a clear understanding of the impact of the technology used on the currently available devices, especially for short lived connections.

8. CONCLUSION

This paper highlights the significance of connection setup time, when pedestrian users download data on to their smartphones while walking through areas where public WiFi is available. Using empirical measurements from real smartphone users and through experiments with off-the-shelf smartphones and wireless access points, we showed that one of the three components of the WiFi connection set-up process, namely the IP address acquisition time, on average contributes to 80% of the total connection set-up time. Furthermore, we showed that the IP address acquisition delay is dependent on both the smartphone and the wireless access point.

We then presented a more detailed analysis of the IP address acquisition delay and showed that, contrary to what has been suggested previously, the major cause of the IP address acquisition delay is the discard of DHCP messages at the WiFi access point than these messages being lost on the wireless link. Then two methods of addressing this problem that has been adopted by some of the device manufacturers were evaluated. The analysis showed that these solutions are not optimal for the use in public WiFi hotspots to distribute content to pedestrians. Finally, through experimentation, we showed that the loss of DHCP messages is an implementation issue, as the losses do not occur on high-end access points.

Finally, we provided an extension to an existing mathematical model to calculate the downloadable data volume for pedestrian users while walking across WiFi coverage areas. The analysis of the connection set-up time and the mathematical model provides useful insights for dimensioning public WiFi networks for pedestrian users.

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