

Utilizing Crowd Sourced Analytics for Building Smarter Mobile Infrastructure and
Achieving Better Quality of Experience

by

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BEng, University of Victoria, 2009

A Thesis Submitted in Partial Fulfillment of the
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ABSTRACT

There is great power in knowledge. Having insight into and predicting network events can be both informative and profitable. This thesis aims to assess how crowd-sourced network data collected on smartphones can be used to improve the quality of experience for users of the network and give network operators insight into how the networks infrastructure can also be improved.

Over the course of a year, data has been collected and processed to show where networks have been performing well and where they are under-performing. The results of this collection aim to show that there is value in the collection of this data, and that this data cannot be adequately obtained without a device side presence. The various graphs and histograms demonstrate that the quantities of measurements and speeds recorded vary by both the location and time of day. It is these variations that cannot be determined via traditional network-side measurements. During the course of this experiment, it was observed that certain times of day have much greater numbers of people using the network and it is likely that the quantities of users on the network

are correlated with the speeds observed at those times. Places of gathering such as malls and public areas had a higher user density, especially around noon which could be a normal time when people would take a break from the work day. Knowing exactly where and when an Access Point (AP) is utilized is important information when trying to identify how users are utilizing the network.

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And my wife and family for providing me the love and support needed throughout the writing process.

Do. Or do not. There is no try.

Yoda

Chapter 1

Introduction

This thesis explores how modern mobile devices utilize mobile and Wi-Fi networks. It will show how current methods assess the Quality of Service(QoS) experienced by users and how crowd sourced analytics can be used to provide an inexpensive and effective approach of assessing Quality of Experience (QoE)

Network topology and traffic patterns are heavily studied fields. This includes how to design and build a network and to studying how a network is used. There is such a large volume of research in this field, due to the fact that many different industries are heavily reliant on a secure and stable network. From small businesses to large industries, network connectivity is essential for operations. Problems with a network could result in massive losses for these organizations. Therefore, there is significant value for them to have a reliable connection that meets a minimum level of service.

Another challenge for networks is that subscriber growth is increasing along with bandwidth demands. This makes the need for a smarter network an important time sensitive issue. The research in this paper could have a significant impact on the mobile industry making networks more prepared to handle increasingly heavy loads.

Using mobile devices as data collecting probes, a perspective of the network that was impossible to previously see can be observed. Data is collected and sent to a server, where it is aggregated and analyzed. The data is then formatted and displayed on a web-page in a way that makes the user of the system able to easily extract relevant information. Using information collected this way, network operators can make vast improvements to their networks with very little cost. This data can also provide an operator knowledge about networks owned by competing providers.

This thesis will dig deeper into how device side data can be crowd-sourced to help prepare cellular and cable network operators for the large increases in subscriber growth by saving on cost while maintaining a good quality of experience. The methods presented herein suggest a solution that could help reduce costs and enhance reliability of new technologies that rely on network information such as Self Organizing Networks (SON). An application was designed to collect network data, and open the door to interesting analytic possibilities. From this data, trends can be seen that provide insight into how networks are being used and where they are performing at a satisfactory level.

Chapter 2

Prior Art

Monitoring network quality has been an active area of network research. However a fairly recent movement is occurring in which monitoring quality of service is being augmented by monitoring quality of experience. This section will detail some of the prior studies done to help measure how a network is performing, and how those studies have evolved to measuring the users perceptions of how the network is performing.

2.1 Crowd Sourced QoE

2.1.1 Real-time Scalable Visualization of Network Data on Smartphones [1]

Pattath and Ebert presented a paper titled Real-time Scalable Visualization of Network Data on Smartphones. This paper aims to prove how smartphones are capable of providing network and location data to an accuracy level that can be used to plot useful real-time visualizations. The data for the visualizations is based on network, video and text information such as video request patterns and perceived video quality requested from the user to get personalized QoE information.

The main experiment discussed in that paper is called eStadium. eStadium is a long-term, and collaborative project that aims to improve spectator network experience while at Purdues Ross-Ade Stadium during football games.

The experiment and data collection in that paper was done in 2006 using devices such as the Dell Axim X51v PDA, which are far less capable than modern smartphones. The experiment consists of collecting wireless network access information from the Access Points (APs), and combine them with related video and text data to display various visualizations that are time synchronized. This paper postulates that through the combined visualization and analysis of video and text data, we can gain insight into network performance and congestion, crowd analysis, and emergent social behaviour. The intent was to provide a proof of concept that the data smartphones are capable of providing and the resulting analytics can be used to help improve network performance.

Within this work it was determined that some of the APs were completely non-utilized while other APs exhibited episodes of marked activity between APs. The authors claim that smartphone data has network engineering value to determine, for example, usage patterns and parameter settings for APs. The authors also state that more data would enable richer analysis.

That paper represents an early work in the field which this thesis seeks to modernize and expand upon. Clearly the usefulness of the approach can be extended well past football stadium scenarios, given the near ubiquitous distribution and use of modern mobile wireless devices. There is a limited set of published papers that explore experiments utilizing crowd source data. This makes for some interesting similarities with the research presented in this thesis.

2.2 Data Analysis + Big Data

2.2.1 Applications of Big Data Analytics to Identify New Revenue Streams & Improve Customer Experience [2]

Device wide deployment of QoE mobile measurements translate directly to data analysis and big data problems. Lakhina et al postulate that by combining multiple data sources, Communication Service Providers (CSPs) can open up new sources of revenue, improve customer experience and reduce churn. Churn is of particular concern as it denotes when a customer moves from one service provider to another, potentially due to QoE issues. Churn can be a significant source of revenue loss for network and cable providers and hence reducing churn is one of their core business focusses.

Very large datasets, usually from a combination of multiple data sources are generally referred to as Big Data [10]. This paper highlights the challenge faced by operators with the growing volumes of data due to the rise of IP content, smart devices, sensory and Machine to Machine (M2M) technologies. It also expands into why this Big Data needs to be harnessed to allow operators to identify QoE opportunities that improve revenue and operations without adversely impacting day-to-day operations.

Lakhina et al identify 3 main Big Data application areas of significant CSP value: IP Video/CDN operations, High Speed Data operations and Customer & Network operations. Even more value could be achieved through applying QoE assessment in combination across these areas.

Lakhina et al states that the market outlook for CSPs is undergoing a period of extreme change. Leveraging data analytics should provide a significant competitive advantage, minimize churn, and improve customer experience. The paper also believes that CSPs will need to adapt to the trend of Over-the-Top (OTT) services to supply competitive services by identifying changes in the network.

That paper presents an analysis of how various Big Data sources might be used, particularly data constructable from smartphones. This reinforces the hypothesis that the smartphone collection of network and device data can improve customer experience and give CSPs the information required to make targeted and effective infrastructure decisions.

2.3 Tailoring a Network For Its Users

2.3.1 From Social Sensor Data to Collective Human Behaviour Patterns Analysing and Visualising Spatio-Temporal Dynamics in Urban Environments [3]

The following paper was chosen, because it provides insight into how psychological studies into network traffic patterns and how a device is used can also be applied to building smarter networks. This can help identify targeted users than may be more appropriate for offloading to specific APs which will be described later. For example, identifying a user that only uses their device for streaming high definition video may be transitioned to APs catered to servicing high bandwidth requirements, while a user who occasionally checks their emails may be more effectively served by an AP that can provide a lower latency. The paper also shows how the type of information collected has uses even outside of the mobile carrier industry.

The primary focus of the authors was to analyze digital network traces left behind by users to study temporal patterns of collective human dynamics. This was done through a combination of mobile phones and social media platforms. The results show collective human activity and mobility hotspots, in the select European urban environments used for their research.

The authors conclude from the results shown in that paper that spatio-temporal analysis of social sensor data in combination with geo-visualisation methods can contribute to a better understanding of urban systems in general and related inherent social dynamics regarding activity and mobility in particular. They identify more work in the field that could improve their analytics due to limitations in distribution between the various network providers.

This prior work provides a different perspective of how the data collected from smartphones can be analyzed. Analyzing human behaviour is another means of helping network operators acquire the information that could help them optimize settings for APs dynamically based on the surrounding environment. This complements the hypothesis outlined in this thesis in that there are a large variety of potential methods to analyze mobile data collected from smartphones to have a better understanding of the network.

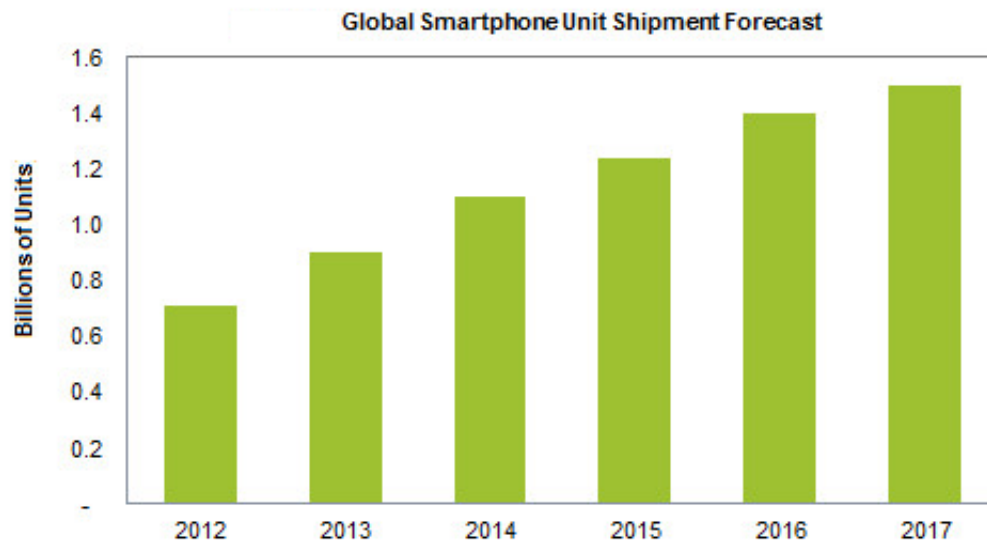
Chapter 3

The Problem

Mobile devices have become the standard communication device for consumers. Historically, mobile devices were very simple and provided basic telephony features limited to voice calls through a cellular infrastructure. Modern mobile devices are generally referred to as smartphones and are multi-network devices that can use technologies such as Cellular, Wi-Fi, and Bluetooth. These smartphones are data hungry devices that provide users with the ability to surf the web, watch streaming media content, send emails and a variety of other useful functions. This trend is expected to continue as is shown in Figure 3.1 [7].

Cellular data technology has been constantly evolving to meet the requirements of a demanding market. Initially launched as 2G in 1991, the speed and technology has improved dramatically as the technologies have greatly improved. Table 3.1 shows how the technology has improved throughout each generation. Ultimately connection speeds are getting faster and have evolved to the point where they can deliver high definition video content in real time.

Due to the recent high adoption rate of smartphones on the market, cellular networks are having challenges managing the ever increasing data loads on their network,



Source: IHS, July 2013

Figure 3.1: Global Growth of Shipments of Smartphones[7]

even despite the advances in cellular technology. The previous cellular networks were designed to service voice calls[11]. These follow well known Markovian traffic models which are not bursty in nature [12]. Whereas packet switched networks, specifically web and other services, have been shown to exhibit more complex traffic characteristics including self-similarity, heavy-tailed and long range dependent behaviours[13] leading to observed bursty behaviours. The original cellular infrastructure in Canada was built without the expectation that the amount of web traffic would increase at the rate it was. Figure 3.2 [8] shows statistics collected from Cisco that shows just how quickly data consumption has climbed from 2012 to 2015, with this exponential growth rate expected to continue through 2017.

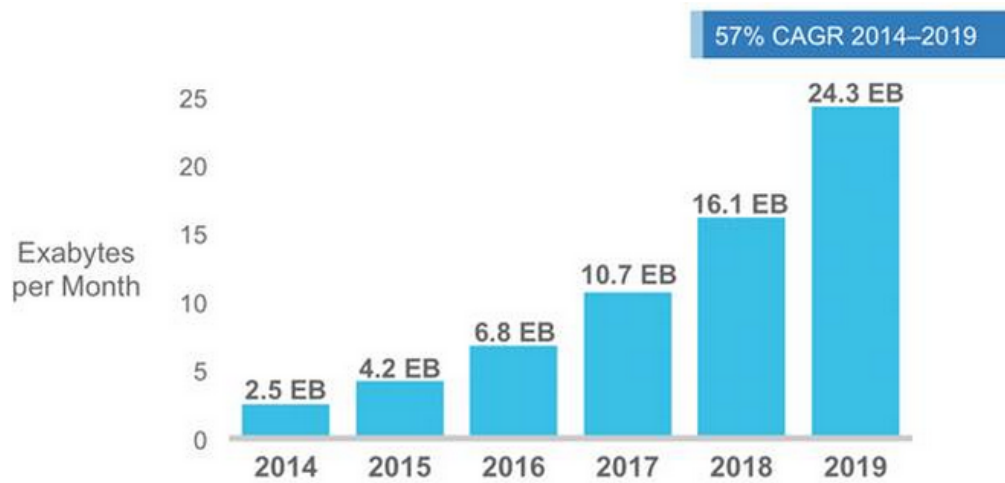
This trend is also not only a result of existing users using more data, but also the growing rates of smartphone use as shown in Figure 3.3 [9]. Under Markovian traffic models larger aggregation should reduce the statistical variation, whereas this does not occur under self-similar network loads[14].

Cellular	Generation	Technology	Speed(Theoretical Maximum)
	2G	TDMA/CDMA	9.5/14.4kbps
	2.5G	GPRS	56-115kbps
	3G	CDMA, UMTS, EDGE	14.4Mbps
	3.5G	HPSA	8-20Mbps
	4G	WiMAX, LTE	100Mbps-1Gbps
Wifi		Technology	Speed(Theoretical Maximum)
		802.11	2Mbps
		802.11.b	11Mbps
		802.11.a	54Mbps
		802.11.g	54Mbps
		802.11.n	600Mbps
		802.11.ac	1,300Mbps

Table 3.1: Evolution of cellular and Wifi technology in terms of speed[4][5][6]

Massive data growth is the issue currently faced by operators. Data usage causes much higher loads on existing networks and can lead to congestion issues[15]. Excessive congestion can result in a poor quality of experience for users of the network. An example of this could be a user requiring a certain connection speed to stream a high definition movie. If congestion occurs, the bandwidth the user requires may not be available. If a technology such as adaptive bitrate streaming is used, then the video will switch to a lower quality, otherwise the video will lag and will appear choppy for the user.

Access points have a maximum throughput they are capable of handling and they try to achieve fairness across their connected users. If there are too many users, users experience slower connection speeds as they compete for the services of the Access Point(AP). To address demand increases, providers have several possible choices. One option is perform expensive infrastructure upgrades costing many millions of dollars. This requires that they first identify where gaps in connectivity are. Historically, public opposition to cellular sites can restrict new deployments. Hence this is not a viable option in many cases. Cellular providers must seek more viable options.



Source: Cisco VNI Mobile, 2015

Figure 3.2: Growth of Mobile Data Consumption[8]

3.1 Network Offload

Network offload to Wi-Fi networks provides one attractive alternative as increasing Wi-Fi density is generally low in cost and more practical than adding new cell towers. This solution approach though does however require pre-determining proper locations for Wi-Fi offload access points.

3.1.1 Pico and Femto Cellular Networks

There are also movements to create pico and femto cellular networks, which are small cellular base stations that typically covers a small area, such as indoor buildings (offices, shopping malls, etc.), in planes or other vehicles[16][17]. In cellular networks, picocells are typically used to extend coverage to indoor areas where outdoor signals do not reach well, or to add network capacity in areas with very dense phone usage, such as a train station[16][18]. By comparison, a femtocell network is a small, low-power cellular base station, typically designed for use in a home or small business[19]. A broader term which is more widespread in the industry is small cell, with femtocell

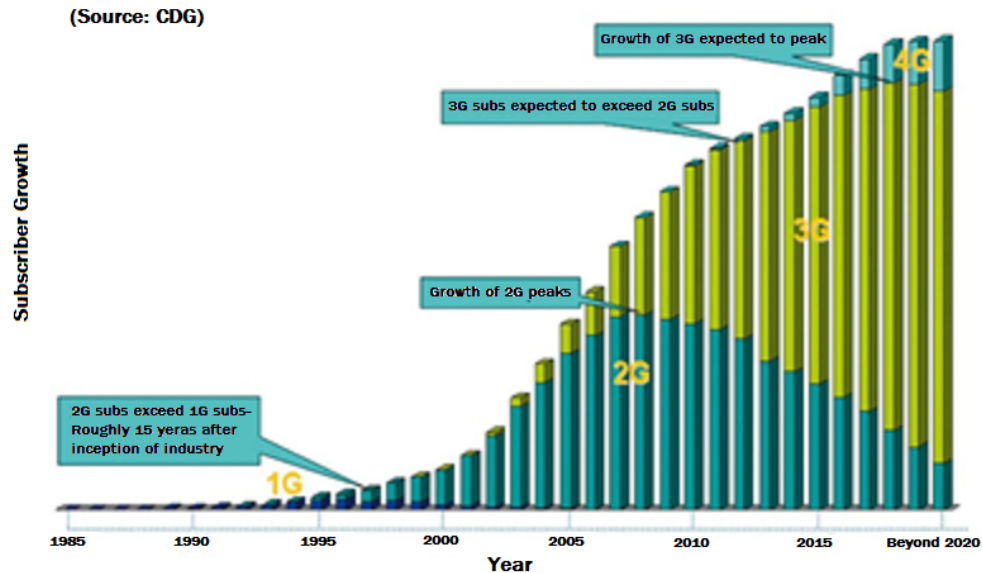


Figure 3.3: Estimation of 3G/4G Subscriber Growth from 1985 to 2020 [9]

and picocell as a subset[20]. Both network types connect to service provider networks via broadband (such as DSL or cable).

Picocells are normally installed and maintained directly by the network operator, who would pay for site rental, power and fixed network connections.

Femtocells differ from picocells because they are intended to be much more autonomous. They are self-installed by the end user in their home or office, primarily for their own benefit. Femtocells automatically determine at which frequency and power levels to operate, rather than being managed centrally. This allows the network to adapt automatically as new femtocells are added or moved without the need for a completely new frequency plan.

The disadvantage is that femtocells would not normally hand-off to neighbouring cells. Mobile phones would thus maintain the connection on the femtocell as much as possible, but risk dropping the call or having an short outage if the call needs to be switched across to an external macro or microcell[21].

3.2 Quality of Service(QoS) vs Quality of Experience(QoE)

With current technologies, a mobile device would never consider moving the user onto a separate network with a signal strength only moderately higher. This can result in some APs being overloaded and other APs being underutilized. This may result in a poor quality of experience for a consumer even though there are already an adequate number of access points available in the area. A basic analysis of the available throughput and latency that a device can detect may not derive the smartest decision that could be made to improve which access point a mobile device would truly have a better experience on. However switching people to new access points, based off on these metrics is not the complete solution since some applications have different requirements for a network.

A simple game may need only a low latency network to which it can periodically make requests, while another application that is streaming video would have a much higher bandwidth requirement. On the other hand, some access point may be better at handling low latency applications as opposed to applications with high throughput requirements. The difference between how the AP should be performing and the performance experienced by the user is the difference between quality of service and quality of experience. Even though there could be an adequate number of access points that have high signal strength, the user may still having a poor experience using the network. Therefore an alternate approach could be to profile the performance of APs as well as smartphone applications so that users can be offloaded onto APs that are the most appropriate for the types of activities they are doing at the time. APs that have historically provided good throughput can service applications that require

high bandwidth. Similarly, applications that require low-latency can also be directed to the appropriate APs.

Current standards focus on the quality of service aspect which is primarily concerned with the mechanisms that are needed to be able to achieve good service, but not how to actually achieve a good experience. This paper attempts to demonstrate how some basic analysis could potentially improve decisions on how a user should be connected to a network. The information obtained through the analysis of applications and access points would be augmented with crowd-sourced data to make a better determination of how the users are connecting to APs in an area. It would also improve connection decisions to provide coordinated control across the set of users. This would help prevent congestion issues that could occur as a result of these offload decisions.

3.3 Emerging Standards

Currently the hand-off problem is something that is being addressed through emerging standards. These standards were designed to let mobile devices automatically and seamlessly transition between networks. Done correctly this can provide consumers with better bandwidth and services while also alleviating infrastructure congestion. The two main standards that lead the way in this field are Hotspot 2.0 [22], which is also known as Wi-Fi Certified Passpoint, and Access Network Discovery and Selection Function (ANDSF)[23]. Hotspot 2.0 was developed by the Wi-Fi Alliance while ANDSF was first conceived by the 3GPP in Release 8 of the standard. Therefore, regarding offloading data from cell towers to Wi-Fi APs, ANDSF is preferred by the cellular networks and Hotspot 2.0 is the preferred standard for cable operators.

These are two emerging standards that were written from the opposite perspectives of the cable operators and cellular providers. Since both standards could utilize signal strength measurements taken from devices and APs relating, a network ping-pong effect could be created as a device hops between APs due to the variations in their observed signal strengths. Some APs with the strongest signal strengths may also have restricted access, only allowing certain devices to connect to it. Both standards achieve the same results. However they are very simplistic and generally refer to connecting smartphones to APs based on received signal strength.

3.3.1 Hotspot 2.0

Hotspot 2.0 is based on the IEEE 802.11u standard and was intended to support 802.11u Wi-Fi APs. Under Hotspot 2.0 supported mobile devices will automatically connect to 802.11u APs and roam to supported APs. This would be a seamless to a user without a break in connectivity during this transition.

3.3.2 ANDSF

ANDSF is a part of the evolved packet core (EPC) of the system architecture evolution (SAE) for 3GPP compliant mobile networks. The purpose of the ANDSF is to assist devices to discover non-3GPP networks (Wi-Fi, WIMAX, etc.) that can be used to communicate data in addition to 3GPP access networks (HSPA, LTE, etc.) and to provide rules to the devices on how to police these network connections[23]. This would also be a seamless transition between APs that the user would not be aware of.

3.3.3 Limitations of These Standards

Both of these standards use only measured signal strengths to determine which connection to establish. Transition between non-ideal APs can possibly shift a user from an overloaded network to an ever worse performing AP, effectively giving the user an ever poorer quality of experience. An example of this could be a cell phone user playing a game in a crowded shopping mall. This shopping mall has a Wi-Fi access point in the food court, and in the surrounding area. Since this user has just gone to the food court for lunch, the highest signal strength access point is the one directly in the food court. However since everyone else at the food court is also using this access point, the user keeps having service issues even though they see full reception bars on their phone. However all of the surrounding access points are barely used and even though their signal strength isnt quite as good as the one in the food court, it is non-congested, and would not cause the same service issues. A network operator, with the appropriate data, could predict these trends and be able to automatically balance how devices are connecting to APs to utilize the available network most efficiently. This approach allows the network operator to utilize the existing service structure to provide users with an improved QoE.

3.4 Current Methods of Obtaining Network Data

Collecting data from smartphones is not the only way service providers have collected information that can be used to improve their infrastructure as well as customer experience. Traditionally this type of information was provided via Deep Packet Inspection and Truck Rolls.

3.4.1 Deep Packet Inspection

Deep Packet Inspection (DPI) is a form of filtering used to inspect data packets sent from one computer to another over a network. Also known as a complete packet inspection and information extraction system, DPI is a complex method of packet filtering that operates at the from the data link layer(Layer 2) to the application layer(Layer 7) of the Open System Interconnect (OSI) model[24]. One of the effective uses of DPI is to allow the packet analyzer to track down, identify, categorize, reroute or stop packets with undesirable code or data.

As opposed to other forms of packet filtering, which typically only inspect packet headers, DPI inspects the packet payloads. DPI contains techniques that allow organizations to have greater visibility of their networks to reduce and augment data invested from the addition of core network technologies.

DPI systems typically are inserted into the network at inspection points set up in the network and packets are routed through them for analysis[25]. This can slow down the transmission of network requests due to the extra routing. DPI have the limitation of only being able to analyze packets that are routed through the DPI systems. Packets that fail to hit the DPI system would never be seen.

3.4.2 Truck Rolls

Another common practice to measure network quality is to use specialized equipment in trucks that periodically drive through areas in a city measuring signal strength and other network information. The data is then reported as a general perception of the quality of service in that area. This type of collection is generally regarded as an expensive, but necessary step to acquire real-time traffic patterns and network capabilities for the areas that the trucks pass through. This practice, although expensive,

is the only way that service providers are able to analyze a network without having sensors tied directly into the network.

Another issue that many truck rolls cannot overcome is that they are carrying out their measurements from the street. This limits them to only be able to accurately measure network capabilities from outdoor APs. Any measurement of an indoor AP would be a poor test, since it could not account for any unpredictable interference between the truck and the AP or the propagation through structures.

Truck rolls provide a relatively poor proxy for real users since they do not measure locations, and real user device interactions, etc. They only mimic user on-device behaviours.

3.5 Limitations of QoS in Evaluating QoE

Measuring network-side QoS is a well-established method in cellular and cable provider networks to assess how users perceive their network. Crowd sourced data provides a unique perspective of actual user experience. DPI can attempt to infer user experience, however this strategy relies on the users being able to properly connect to a network. The information provided is more appropriately described as quality of service information rather than quality of experience. Also, DPI has a limitation when it comes to encrypted information as well as identifying issues where a user is completely unable to connect to a network. Encrypted data such as video is next to impossible for DPI techniques to gather enough useful information about to determine whether or not a user is having a good quality of experience. Truck rolls can overcome some of the shortcomings of DPI techniques, however it can be an expensive process as trucks with drivers have to physically travel to places which are desired to analyze network connectivity. It is difficult to identify where exactly a truck roll would be required as

well as to have a truck nearby to analyse the network connectivity of area when it is needed.

3.6 Implications For Self Organizing Networks

Self Organizing Networks (SON) is an emerging idea to allow carrier-grade networks to dynamically adjust their own configuration parameters to better service the surrounding environment[26]. The goal is to better utilize the existing infrastructure. However, the information that these networks have on which to base these decisions come primarily from traditional sources of network QoS measurements, DPI and truck rolls.

In order to reduce human caused errors when building and expanding a network, clear requirements have been stated by the Next Generation Mobile Networks (NGMN) Alliance to enable a set of functionalities for automated Self-Organization of LTE networks, so that human intervention is minimized in the planning, deployment, optimization and maintenance activities of these new networks[26].

The ability to dynamically and in near real-time provide accurate information is something that would further enhance the success of SON networks. An example of this could be a SON AP changing its channel frequency if there are frequency conflicts occurring with other surrounding APs. The AP could also increase its gain because the signal strength is too low for devices to utilize effectively, or to change the direction of the AP to provide the best coverage to maximize their effectiveness.

The limitations of DPI and truck rolls make crowd-sourced collection methods an attractive source of obtaining the information required that would improve connection decisions for SON networks. Knowledge of the variations in network behaviours in

regards to latency, throughput and user location could assist SON networks in better suiting the needs of the users.

Chapter 4

The New Approach

The experiments presented herein were conducted using an application designed to periodically test the latency and throughput of a network while the application is in use as well as provide information about the device itself and its current state. This application was built on both the Android and iPhone platforms.

4.1 Network Measurement

The application tested the impact of data usage on the network by providing a consistent periodic network load, as well as random load samples based around location and connection changes. Although there are applications currently available that perform network tests, this new approach crowd sources all that information on a larger scale to be able to identify outliers and assess the health of the network.

Two types of tests are performed to get a better idea of how access points can handle applications with low latency requirements and applications that have high bandwidth requirements. Tests to measure request speeds, latency, jitter and packet-loss were performed every 30 seconds while tests to measure bandwidth availability (upload and download throughput) were performed every 2 minutes. The data col-

lected contains information gathered from around Victoria and focus on a potentially highly congested target. A large number of the test were performed at the Bay Center in downtown Victoria during times where one would expect congestion to be at a high point.

4.2 Device Side Measuring

QoE reported from the device may not always be caused by the performance of the AP. The current operations of the user as well as other processes running on the device could also impact performance. Collecting device performance measurements is critical to identifying the QoE a user has while on a network. For example, if a user has many applications running in the background and the CPU load of the device is high, the device could go into a low memory state. In this state the device will be slow and a device side issue may be perceived as network caused. Also, if there are multiple background services using the network, the user may think that their network is always slow whereas the reality is that it is the other applications on their device that are consuming all of the available bandwidth. CPU, Memory usage, battery levels, and other metrics are all collected to aid in understanding exactly what is really causing reduced QoE. Device application awareness also allows a view into the network impact of certain applications have. Knowledge of how a user is utilizing the network could indicate which APs are better suited to handle that type of network load. Knowing the network traffic patterns of other applications could also indicate a rogue application on a device that likes to hog bandwidth.

Device-side measurements are normally unavailable to operators and can help differentiate between QoE issues that occur because of issues with the network or issues with the device itself.

4.3 Advances in Network Awareness

There are usually many APs on a network and sometimes a network is underutilized because of the behaviours of a single AP. Utilizing the existing infrastructure network providers are capable of improving this experience without expensive upgrades. By embedding network analytic software inside of phones, it is possible to crowd-source network information to give operators an improved view of how their network is constantly changing as the usage patterns in the network change. This collection application was designed for both iOS and Android devices to record latency and throughput information and well as the state of the device at the time these measurements were recorded.

Chapter 5

Experiments

To test the proceeding hypothesis an application was developed for both the Android and iOS platforms. This is a smart application that is capable of collecting a multitude of types of devices and network related information. The data is recorded in an SQLite database that is usable on both device types. The majority of the data collected comes from the application placed on the Android Play Store and the Apple App Store. This data collection preserves privacy so that the information cannot be traced back to any individual person.

A unique identifier is collected from the device and then put through a SHA-512 Hash algorithm. During the analysis process, each device reporting data is analyzed according to this hashed identifier. This type of information could be useful for technicians servicing customer calls. Only if a customer supplied this identifier, could information be retrieved, using the same hashing algorithm, that relates to the individual.

The data is then exported, from the various devices used in the testing process, to a server that aggregates the data into a single Mongo database. The data is then sent to a set of servers that are used for the analysis process.

This data collection ran for a year and a half from Feb 20, 2014 to Aug 27, 2015. This resulted in a dataset consisting of 259,691 records. There were two types of tests performed during this time. The first test measures both upload and download throughput of an AP, while the second test measures the network latency, jitter and packet-loss. These tests are triggered by connection changes experienced by the device, user location changes, periodic timers, and by manually requesting a network test. This was designed in a way to gather as much information as possible about the users currently perceived network experience.

5.1 Devices Used For Collection

Table 5.1 shows the devices personally used for collection. However since the application that is recording this information was also placed on the Google Play Store and the Apple Store. These measurements were combined with the measurements from in house devices. In addition to the devices listed in table 5.1, there were 38 additional devices that reported data as shown in table 5.2.

Android	iOS
Samsung S5	iPhone 3G
Samsung Mega	iPhone 3Gs
HTC One	iPhone 4Gs
LG	iPhone 4G
Sony Xperia	iPhone 5G

Table 5.1: List of internal devices collecting measurements

5.2 Collection Methodology

One aspect of collecting information is knowing what data is useful. To properly assess a network, it is important to have an understanding of how the network is used.

Manufacturer	Number of Devices
Sony	11
Asus	8
HTC	5
LGE	4
Motorola	3
ZTE	1
iPhone 4Gs	4
iPhone 5G	2

Table 5.2: List of external devices collecting measurements

For applications such as streaming video or Voice over IP (VoIP), large quantities of bandwidth are required to ensure that the quality of video and voice streams stays appropriate. Both video and VoIP applications are also sensitive to jitter and packet-loss since these can result in a choppy video or a stuttering voice calls. While other applications including online games and texting applications can require that the server respond extremely quickly to network requests. High latency networks tend to make such applications appear to be slow due to network lag.

To save on battery most smartphone devices have different power modes for their network radios. If the network hasn't been used in a while, the device enters a low power state to preserve battery life. However it is then not operating at its peak transfer speeds. After moderate usage the device then re-enters its higher power consumption state enabling the full capability of the device to be used.

Collecting various network measurements allows carriers to understand networks from the device perspective through collating with measurements taken from the AP itself. Sometimes constraints on network speeds may not be caused by an AP, but from limitations of the device attempting to use the network.

An end point is a server somewhere in the internet that a device communicates with over a network. The location of an end point of the test is another factor that

can affect the measurements taken. Downloading a file for a throughput test would be much slower if the file was located on a distant internet server. Therefore Amazons Cloud Edge was used for the devices to communicate with, which uses nearby servers to increase localization.

5.2.1 Measuring Bandwidth with Throughput Testing

Measuring throughput capabilities of an AP provides useful information for high bandwidth requirement smartphone applications. Throughput test can be performed to measure the bandwidth capabilities of both devices and APs. A throughput test is performed by uploading and downloading a file to and from a closely located server and measuring the time it takes to for the file to complete the transfer. The tests performed used a 10MB file for the download test and a 1MB file for the upload test. There are many reasons for wanting to vary the sizes of the files used for testing. Testing throughput with smaller file sizes, while never entering the radios high power state, can still give information regarding how an application should expect the network to behave when transferring smaller files. Testing throughput using larger file sizes is more useful to measure how an AP would service a higher bandwidth application with requirements for activities such as streaming video or to stress test the AP.

5.2.2 Testing Latency, Jitter and Packet-Loss

The other network test measures latency, jitter and packet-loss. This test will be further referred to as a server response test. This test is performed by precisely measuring the time it takes to send out a series of packets to a nearby server using UDP and when the servers echoed response packets are received. This test shows how quickly an AP can respond to network requests. UDP transmission was used

because, unlike TCP, UDP is connectionless. By eliminating the delays caused by network handshaking in TCP start up a more accurate measurement is possible. Each packet used in this test has a 1 byte payload that contains an integer that corresponds to the order that the packets were sent out. Because of this, duplicate, missing and out of sequence packets can all be identified. Then by implementing the MEF 10 Jitter algorithm[27] accurate measurements of latency, jitter and packet-loss can be calculated.

5.2.3 Test Triggers

There are two types of tests that are supported: active tests and passive tests. An active test measures the network at a specific point in time with set payloads. A passive test attempts to measure network performance by tracking how the network changes during user normal user operations. The software used for the data collected herein used only active tests. These tests are triggered at set time intervals, location and connection changes. All of these triggers were implemented to acquire the data used for analysis. Each of these triggers prompted both the throughput and the server response tests to be performed.

1. **Periodic Testing:** Tests occur every 3 minutes, regardless of other conditions.
2. **Testing on Location Change:** After the user has moved 10 meters and 30 seconds has elapsed a test will occur. User location is obtained from either the GPS on the device or from its IP on the network.
3. **Testing on Connection Change:** When the device undergoes a change in its connection a network test is performed. This occurs when the connection changes regardless of whether it connected using a different technology. For example a user seamlessly transitioning between Wi-Fi APs would still trigger

a network change once it transitioned to the new AP. This also works the same when transitioning between cell towers or between Wi-Fi and cellular APs.

4. **Manual Testing:** The user has an option to manually perform a network test with the press of a button inside the application.

5.3 Key Performance Indicators

The main goal of designing this application is to collect various types of device and network related data. There were however some limitations with the iOS platform when compared to the Android platform for the type of data that could be collected. One of these limitations is access to information about all of the surrounding access points. Android can collect and record signal strength, authentication information, SSIDs, BSSIDs, and the frequency channel of the surrounding access points along with the one it is connected to, while iOS devices cannot.

Below is a list of a few of the network and device related key performance indicators (KPIs) that were collected during this experiment.

- **Location:** The approximate location of the user when a test was performed. The device reports location either from the network or by utilizing the devices build in GPS if available.
- **Latency:** The average latency measured during a server response test.
- **Throughput:** The upload and download throughput of test files sent and received during communication between the device and a nearby server in a throughput test.
- **Jitter:** The variation in the delay across a sequence of sent and received packets during a server response test.

- **Packet-Loss:** The number of packets that were lost, duplicate and out of sequence during a server response test.
- **RSSI:** The received signal strength indicator is the relative strength of the AP to device signal.
- **Channel Frequency:** The frequency on which the currently connected Wi-Fi AP is broadcasting on.
- **BSSID:** The unique identifier for each broadcasting Access Point.
- **CPU:** The available CPU load of the device.
- **Memory:** The amount of available memory on the device.
- **Battery Level:** The current battery level of the device. This is useful to help indicate whether or not the device is in a state where it will try to conserve as much battery as possible.

5.4 Experiment details

The analysis is summarized within graphs that show a year and a half of trial data. These graphs are then followed by heat maps which shows the overall experience of a user as defined in section 5.5. The results of this data were compiled from 259,691 total tests uploaded from devices. When comparing results by location, there were 31080 tests for the downtown Greater Victoria region and 2213 measurements taken for the second location chosen just outside of the downtown Victoria area. The exact location bounds used are shown in table 6.1.

5.5 Defining Visualization Parameters

To show meaningful results in the various heat maps in section 6.3, certain bounds on good and poor measurements required defining. The heat maps in this section focus on measurements taken over Wi-Fi connections.

It is expected that mobile devices will not upload and download as quickly as a Mac or a PC would due to higher constraints on battery drain, which would account for devices exhibiting slower throughput capabilities than a personal computer would. Battery consumption is considerably higher when the radios of the device is in a high power state. Therefore, the constraints for visualizing the results of these measurements for Wi-Fi connections were chosen as approximately 20% of the speed advertised by local cable companies for the lowest-cost public offering. Over time the constraints were modified after aggregating large quantities of the collected data and determining an average performance. These values help define which areas should be represented in green on a heat map to indicate good connectivity, and which areas should be in red to indicate poor connectivity. Values between the good and poor thresholds are indicated in yellow. Table 5.3 shows the values chosen as good and poor for this experiment. These visualizing constraints can be easily modified to represent the needs of whomever is viewing the data.

Settings			
	(Kbps)		(ms)
Download Throughput Good	3000	Latency Good	95
Download Throughput Poor	2500	Latency Poor	100
Upload Throughput Good	350	Jitter Good	20
Upload Throughput Poor	300	Jitter Poor	45
	(%)		(dBm)
Packet-Loss Good	4	RSSI Good	-50
Packet-Loss Poor	5	RSSI Poor	-70

Table 5.3: QoE Level Visualization Settings

Chapter 6

Evaluation, Analysis and Comparisons

The most important measures in evaluating the performance of a network are the upload and download throughput and latency. It is the results of these measurements that will be the focus of this section. One of the key points to evaluate is how these results vary by the locations where they are collected. To show how results vary by location two different locations were chosen in Victoria BC. Table 6.1 how the location bounds that were chosen to represent different areas.

All of the following throughput measurements were recorded in the units Kilobits per second (Kbps) and latency measurements are in milliseconds (ms). The timestamps associated with the data were originally unix timestamps, but were modified to group the data into bins organized by the day. This shows that there were 31 unique days worth of network measurements obtained during the year long collection period for the locations chosen.

City Ranges			
Location 1		Location 2	
Latitude 1	Longitude 1	Latitude 1	Longitude 1
48.419	-123.379	48.427	-123.369
Latitude 2	Longitude 2	Latitude 2	Longitude 2
48.426	-123.350	48.433	-123.340

Table 6.1: Location Bounds For Experimental Data

6.1 Throughput Observations

6.1.1 Upload Throughput Observations

Figure 6.1 shows the complete data set results for the upload throughput. An interesting observation is that throughput results spike in the early stages of collection. This could be caused by a high adoption rate of users taking tests initially, but then slowing down over the course of the data collection period.

Figure 6.2 shows a histogram of all the collected data and shows how it varies over time. The histogram shows how the frequency of results of the measurements have changed over time. Figure 6.3 does a further breakdown of the results obtained through the course of the experiment. Both of these histograms compare results obtained between the first and the second half of the collection period. The goal of representing the data this way is to show how the frequency of upload throughput values has changed over time.

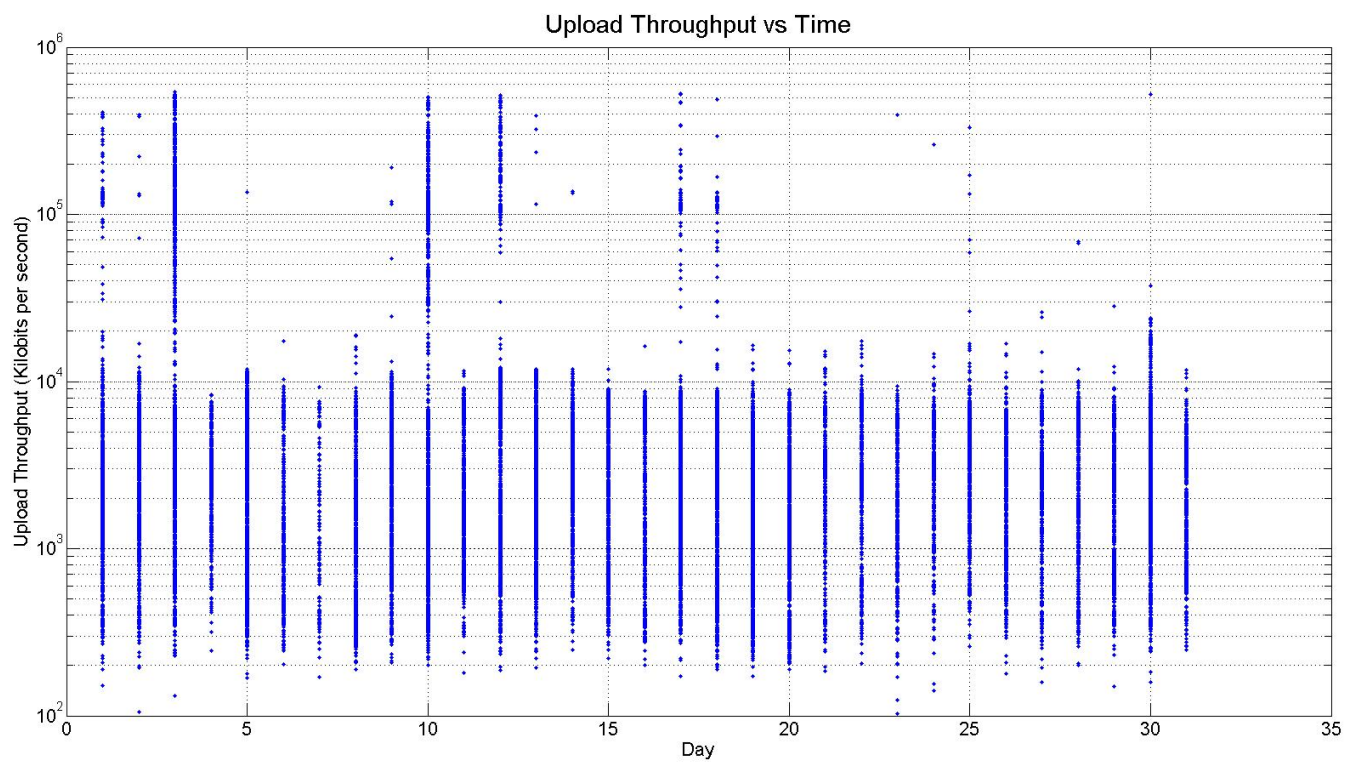


Figure 6.1: Upload Throughput in Log Scale

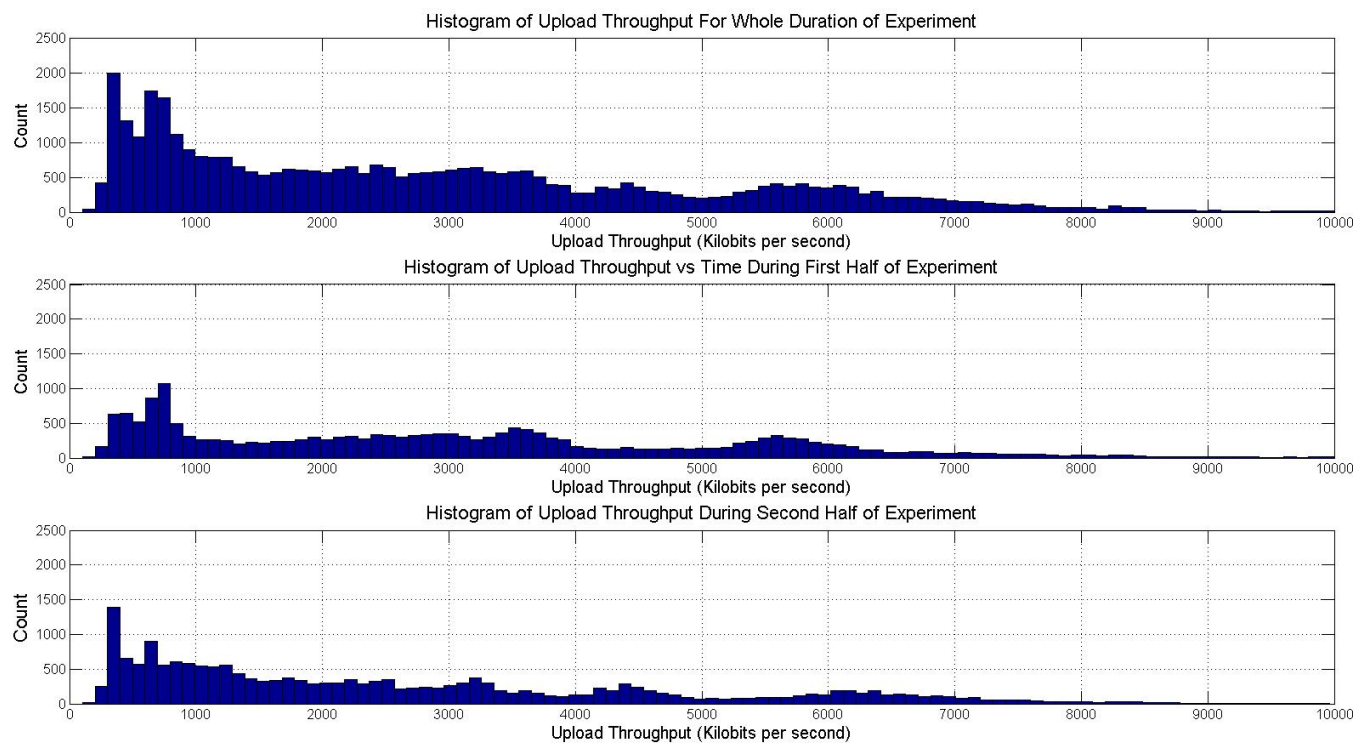


Figure 6.2: Histogram of Upload Throughput

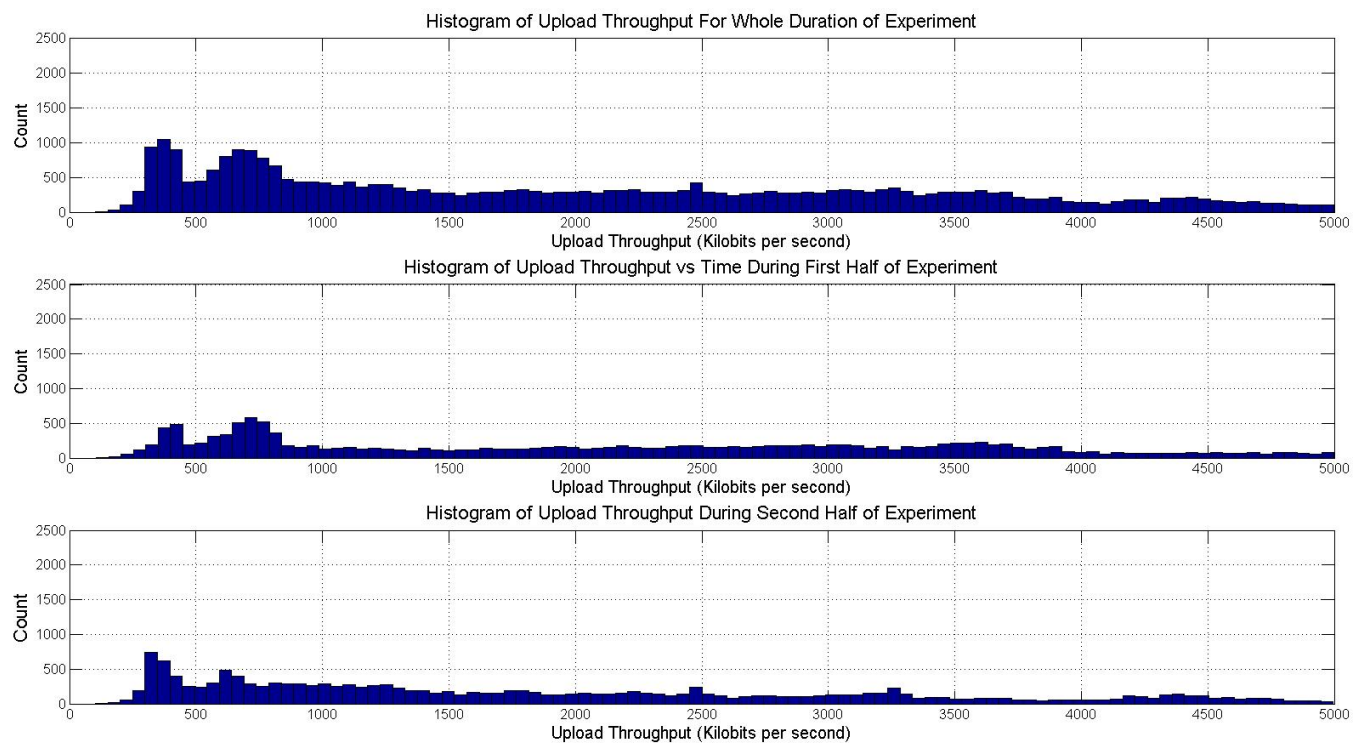


Figure 6.3: Histogram of Upload Throughput of Lower Values

6.1.2 Download Throughput Observations

The total download data shows a similar trend as upload throughput in that during certain times, more results and faster throughput speeds are recorded. Figure 6.4 show the results of these measurements.

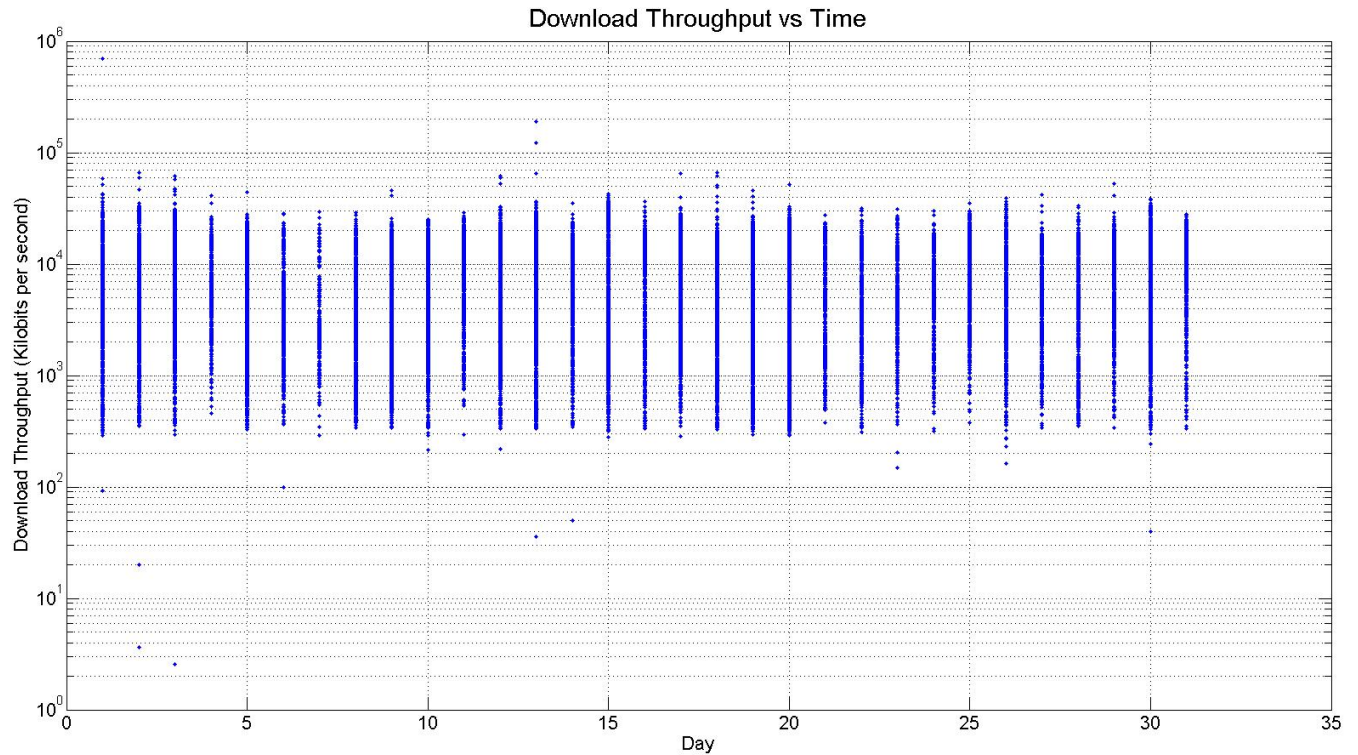


Figure 6.4: Download Throughput in Log Scale

Figure 6.5 shows a histogram of the collected download throughput test data. Similar to the histograms for upload throughput, the download throughput histogram also breaks down the data into a comparison of how result frequency has varied for certain throughput ranges between the first and the second half of the experimental period.

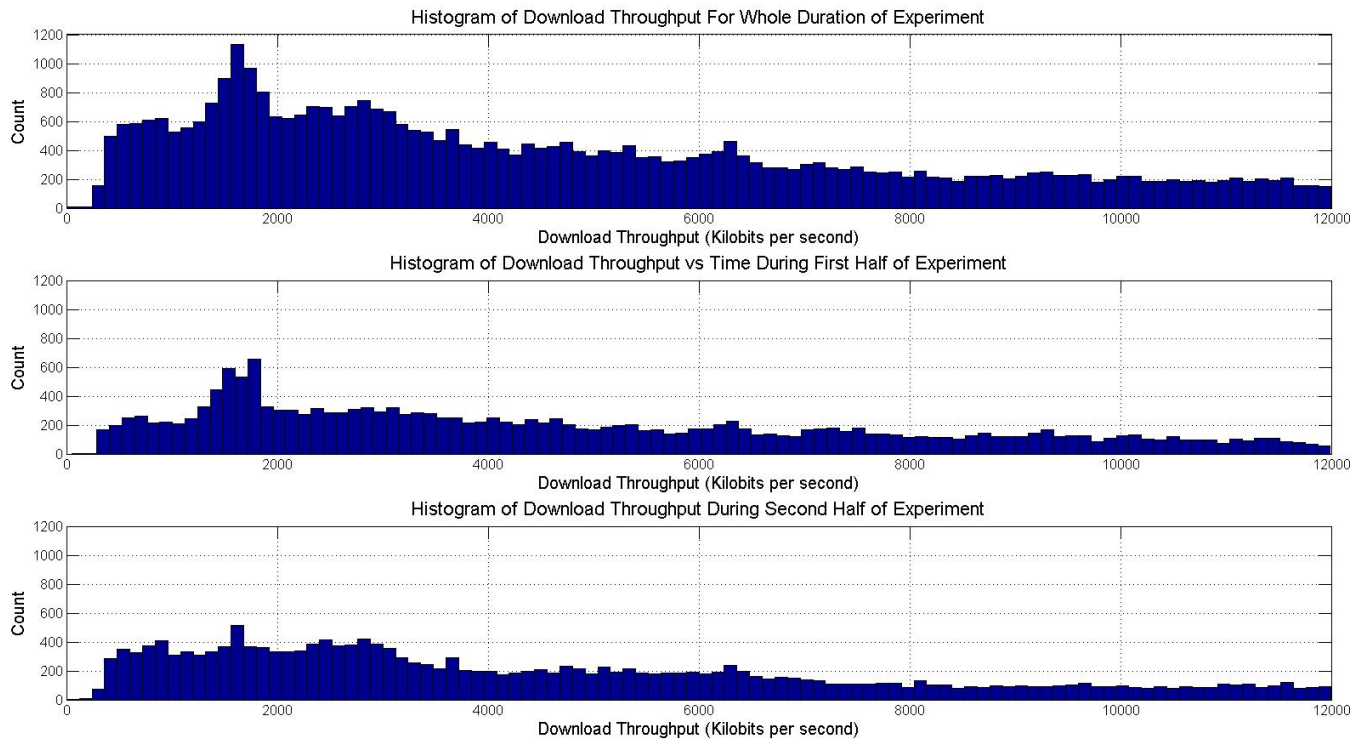


Figure 6.5: Histogram of Download Throughput

6.1.3 Upload and Download Observations Varied by Location

To demonstrate how these values change depending on the location of the recorded measurements, the differences are shown in Figure 6.6 and Figure 6.7. The first column in these figures shows location 1 data, which has a much larger quantity of data than in the location shown by the second column of these figures. This is an indication that there are many more devices located in the first area that are utilizing the data collection application. This is likely caused by the first location being closer to the Victoria downtown core, which contains a greater number of readily available APs to connect to.

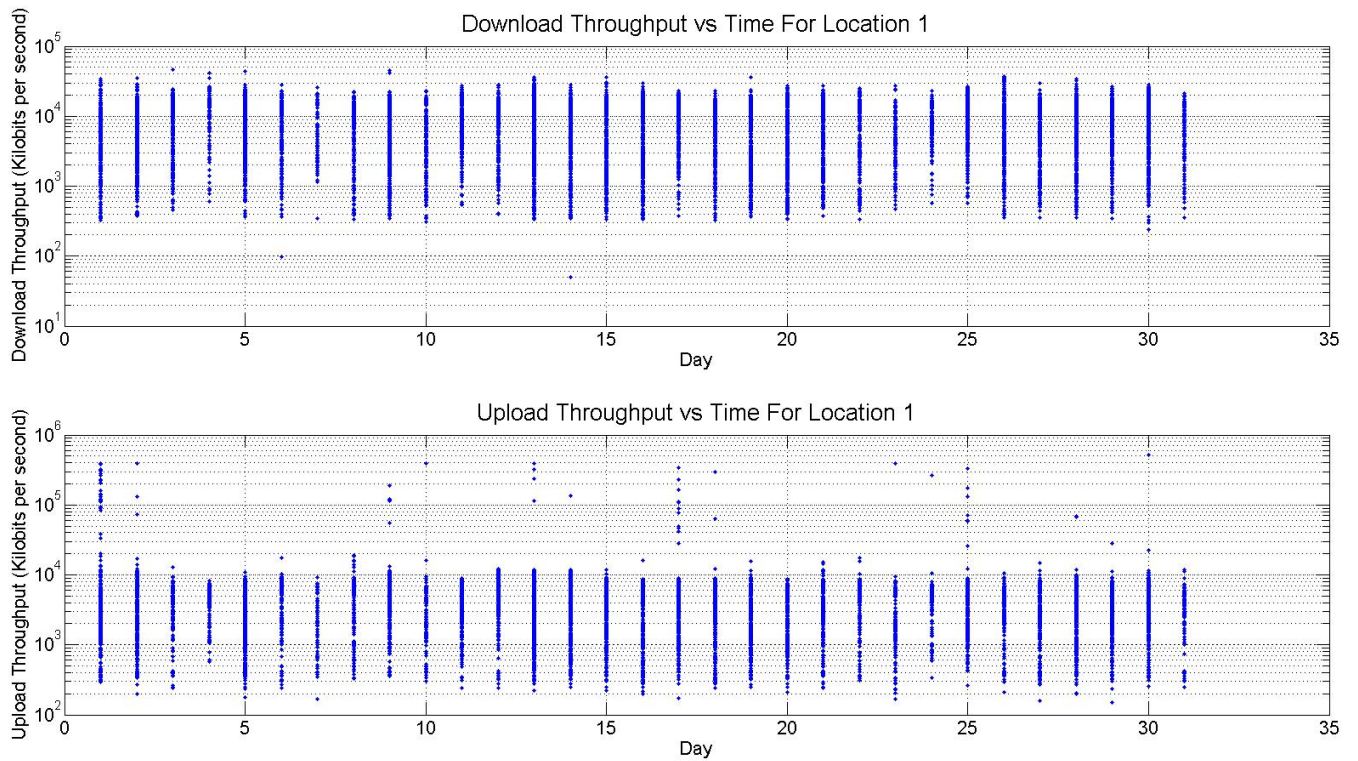


Figure 6.6: First Locations Upload and Download Throughput in Log Scale

Figure 6.8 shows a histogram of both the upload and the download speeds as they vary by location. Figures 6.9 and 6.10 go even deeper and show how the throughput speeds have varied not only by time, but by their locations as well.

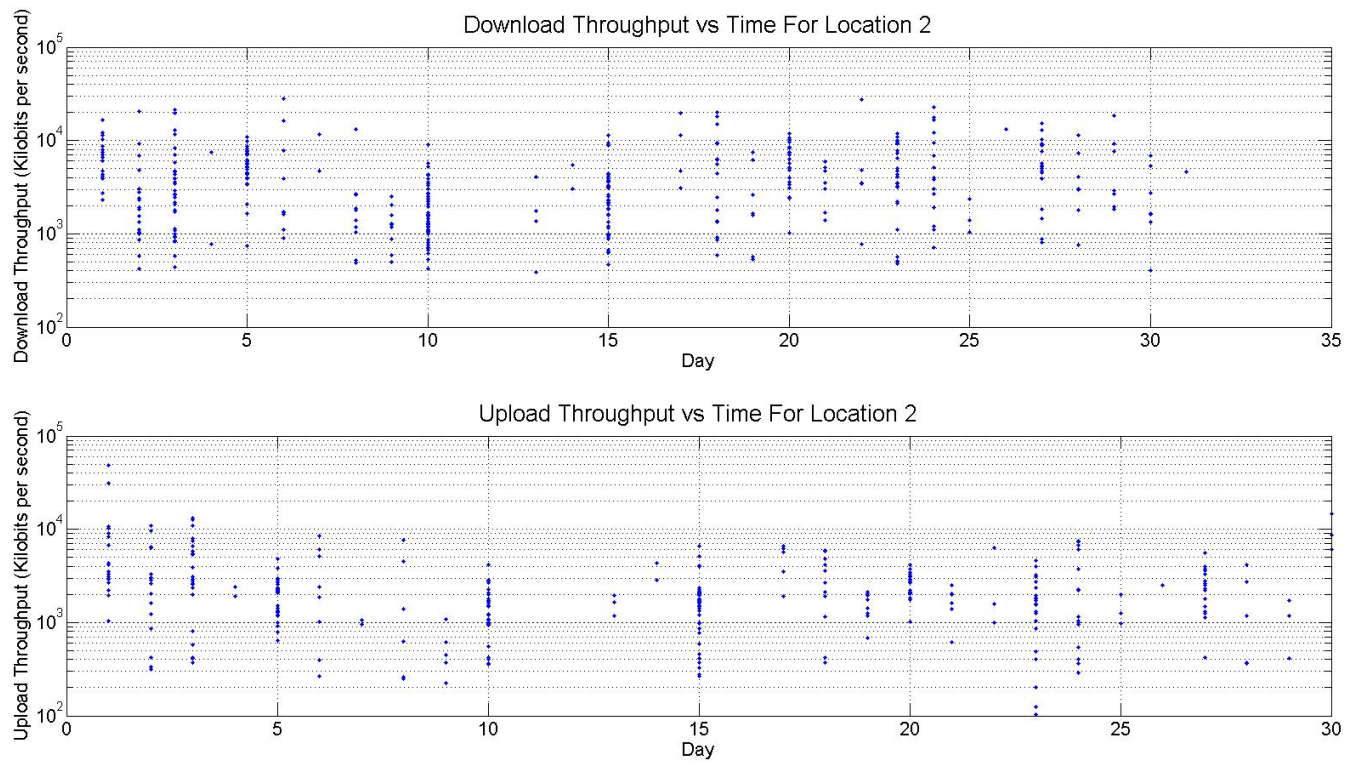
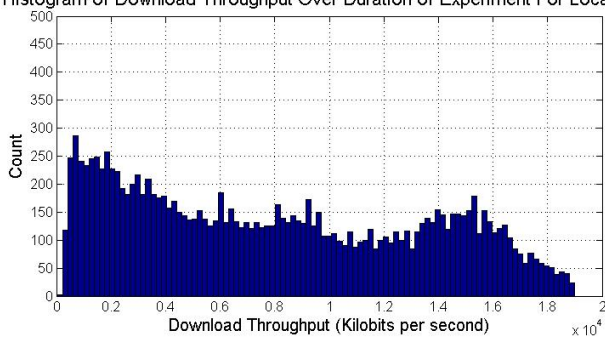
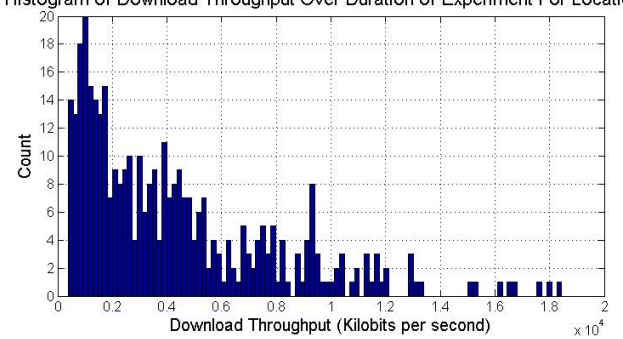


Figure 6.7: Second Locations Upload and Download Throughput Log Scale

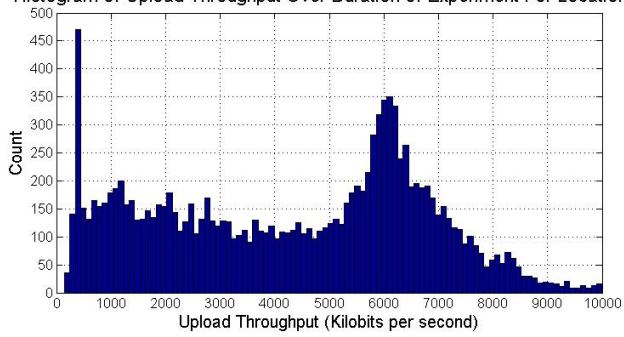
Histogram of Download Throughput Over Duration of Experiment For Location 1



Histogram of Download Throughput Over Duration of Experiment For Location 2



Histogram of Upload Throughput Over Duration of Experiment For Location 1



Histogram of Upload Throughput Over Duration of Experiment For Location 2

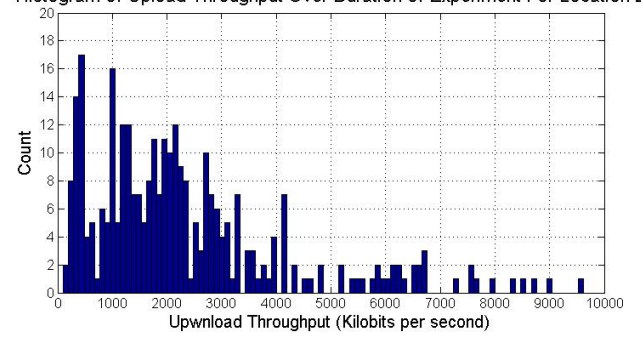


Figure 6.8: Histogram of Upload and Download Throughput By Location

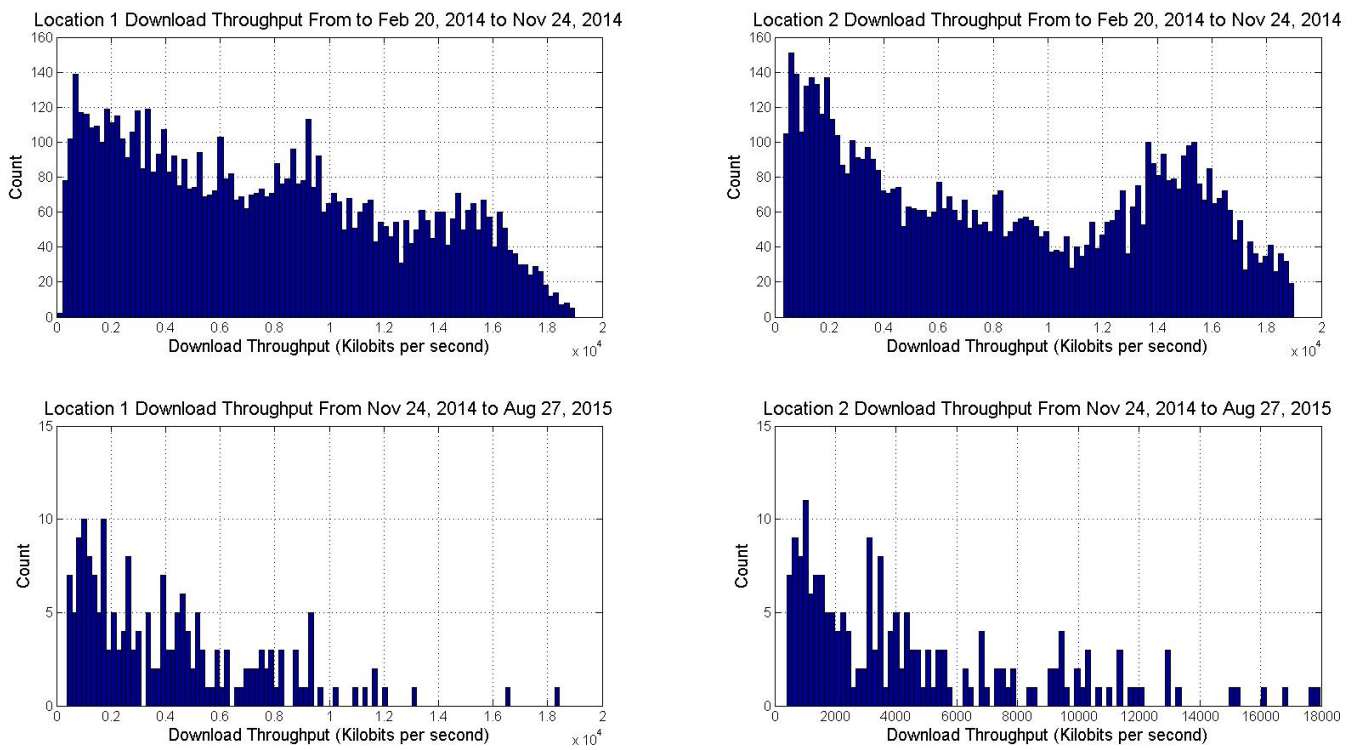


Figure 6.9: Histogram of Download Throughput By Location and Time

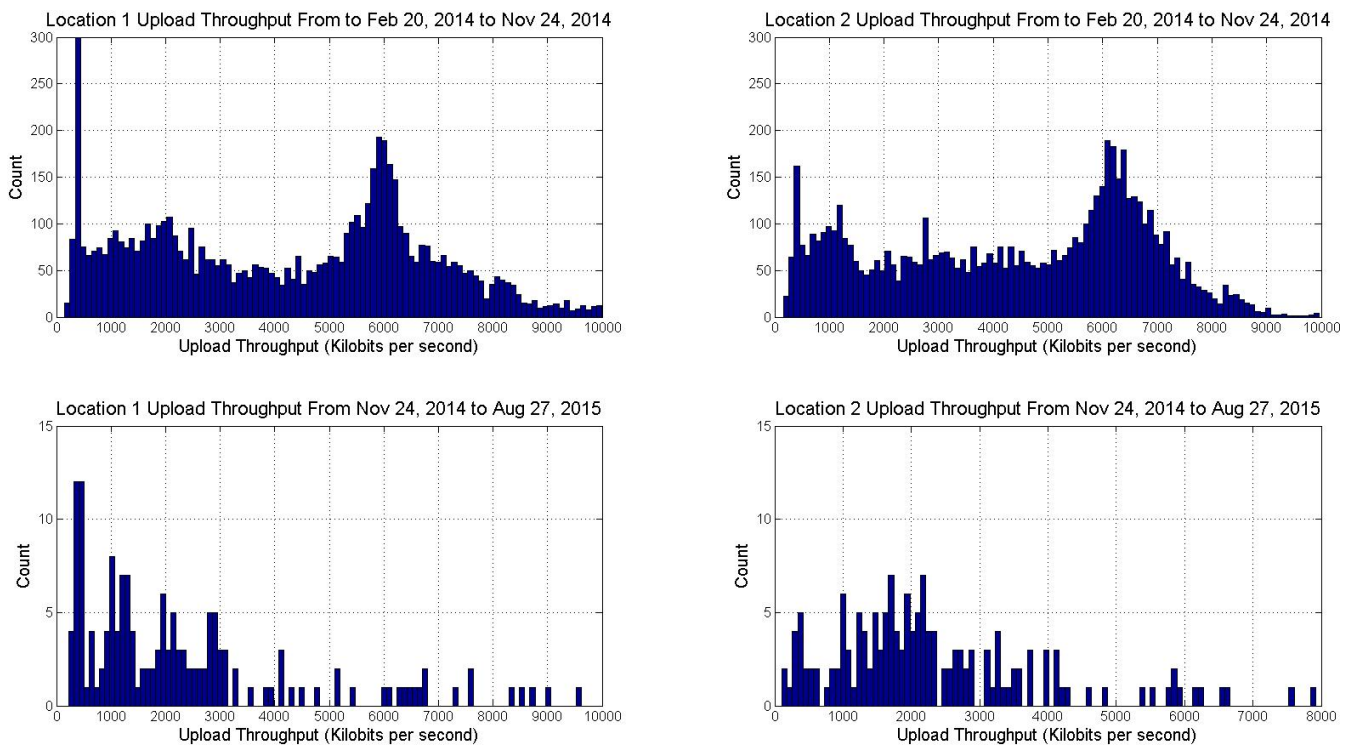


Figure 6.10: Histogram of Upload Throughput By Location and Time

6.2 Latency Observations Varied by Location

The latency measurements are also a key indicator of the health of a network. Figure 6.11 shows the latency collected for the 2 different locations chosen for comparison. Similar to the throughput observations, the first area is showing much higher quantities of data. However, there are observed periods of much higher latency than in the second area. High latency is an indicator possible network network congestion. The first area chosen was in the downtown Victoria area. This area has a greater population density than location 2 and therefore it could be expected to have greater numbers of people utilizing APs in those areas.

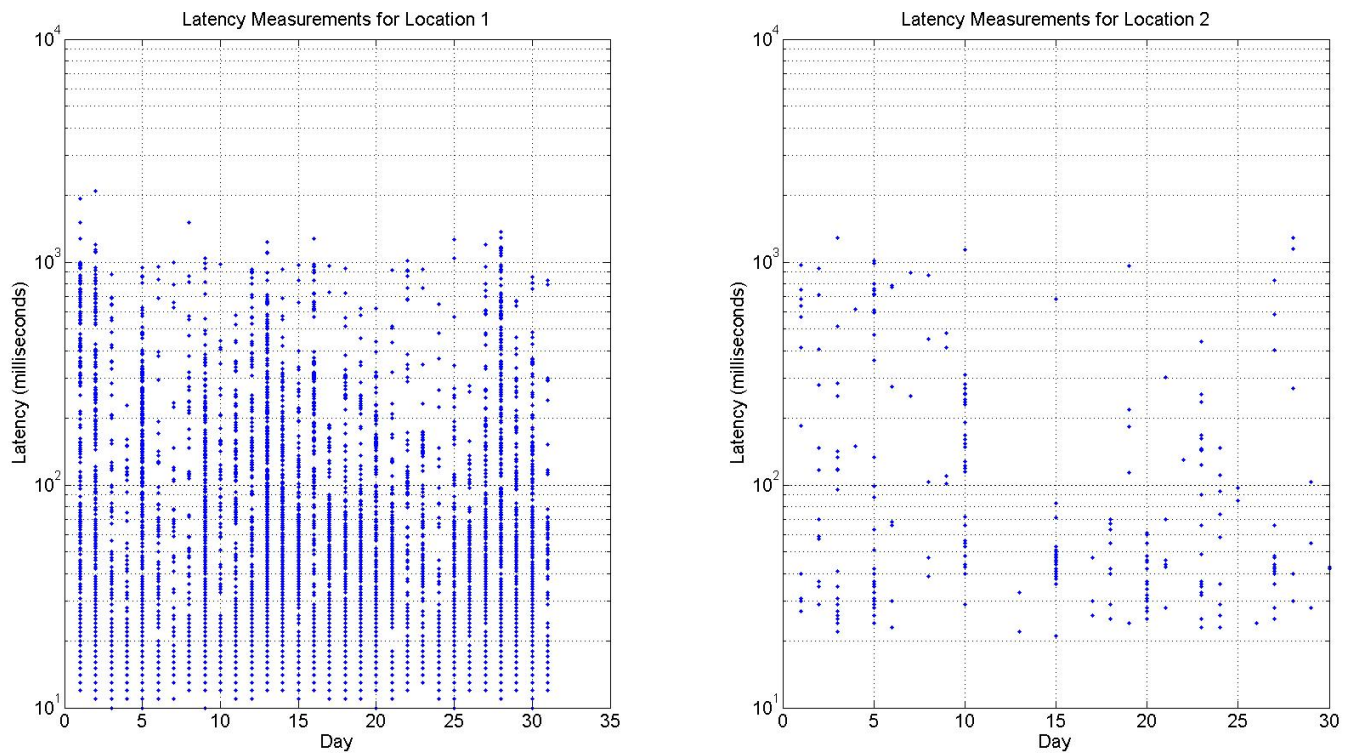


Figure 6.11: Latency Variances by Location in Log Scale

Figures 6.12 and 6.13 show a histogram of the latencies observed for the first half of the experiment as compared to the second half. Figures 6.14 and 6.15 show how

the latencies observed vary by both time and location. Figure 6.15 goes deeper into the bulk of collected data to give a better distribution of likely to be observed results.

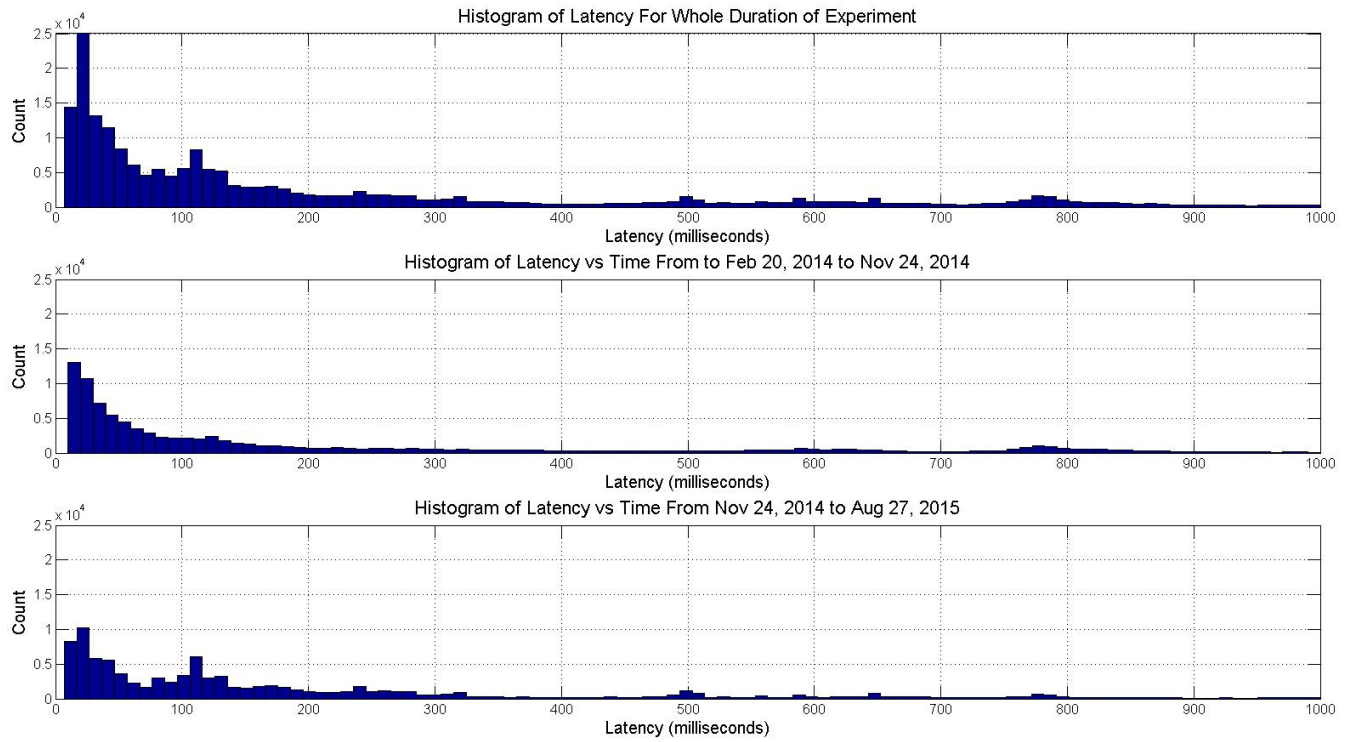


Figure 6.12: Latency Histogram of Full Dataset

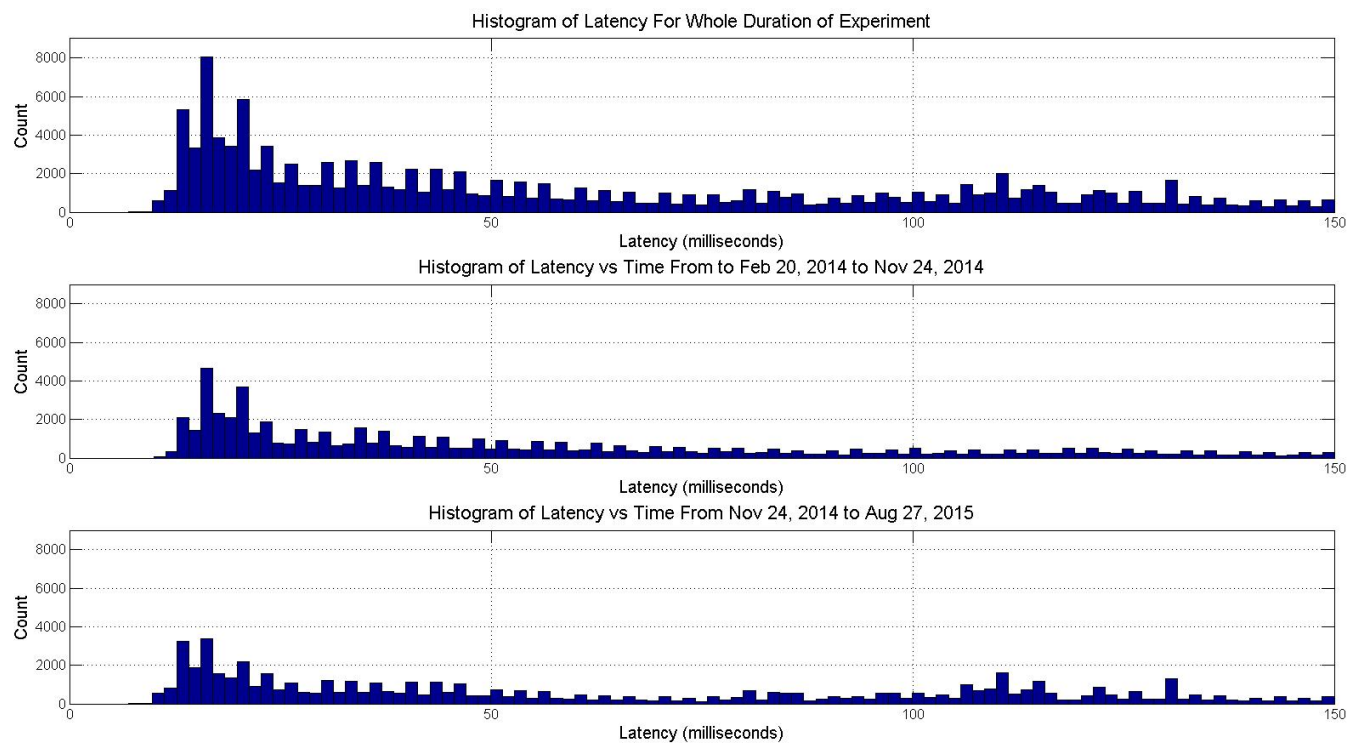


Figure 6.13: Latency Histogram of Lower Values

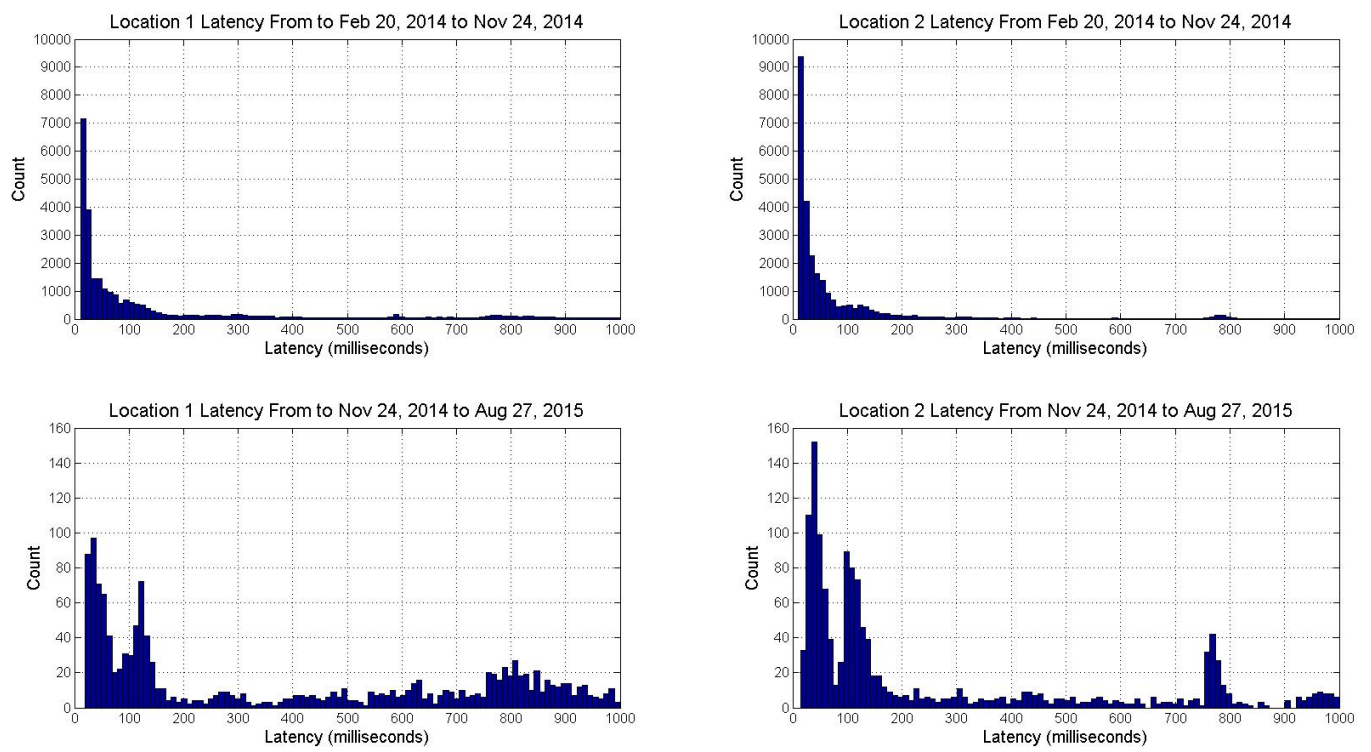


Figure 6.14: Latency Histogram by Time and Location

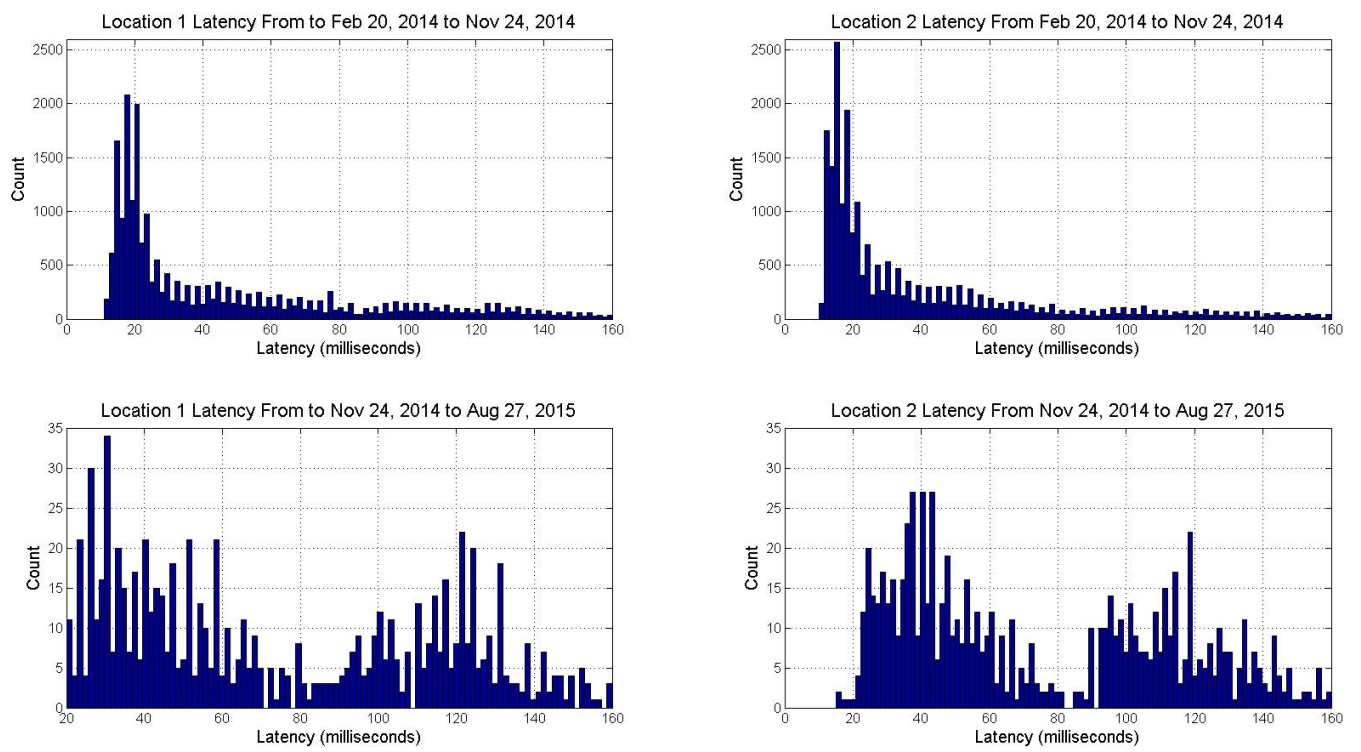


Figure 6.15: Latency Histogram by Time and Location Lower Values

6.3 Heat Maps

A heat map is a two-dimensional representation of data in which values are represented by colors. This creates an immediate visual summary of information. By understanding user behaviour on a network, service providers can optimize it for them.

The heat maps and graphs in this section show the relative network performance for the observed area. They show the culmination of the entire collection period. The data is aggregated together and the results displayed on the locations on the map of where the measurement was taken. The average value for that precise location is displayed according the parameters in Table 5.3. Greater quantities of data could produce more accurate assessments of the quality of a network.

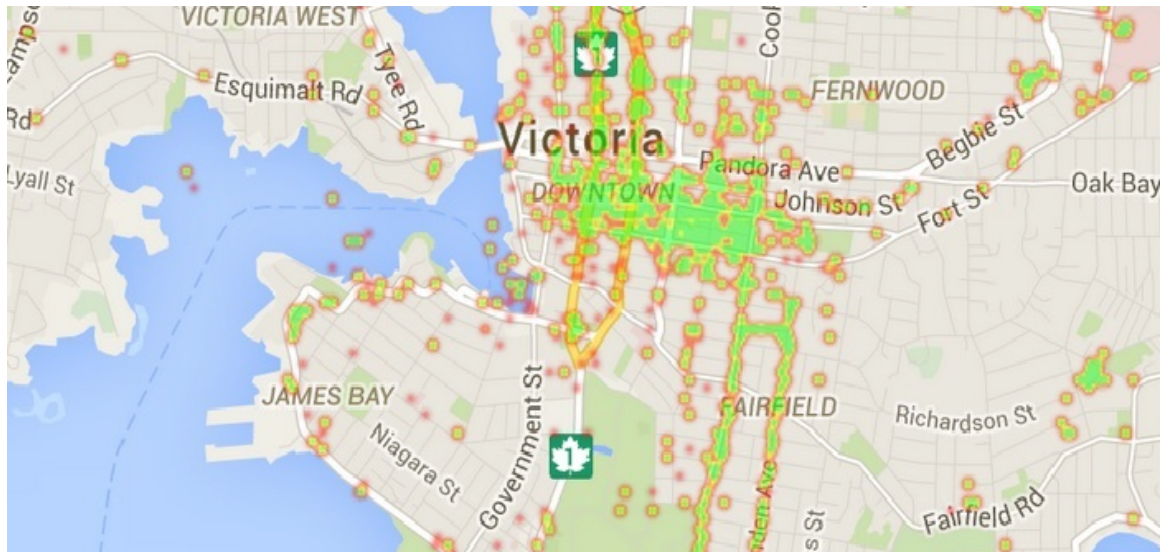


Figure 6.16: Download Throughput Heat Map

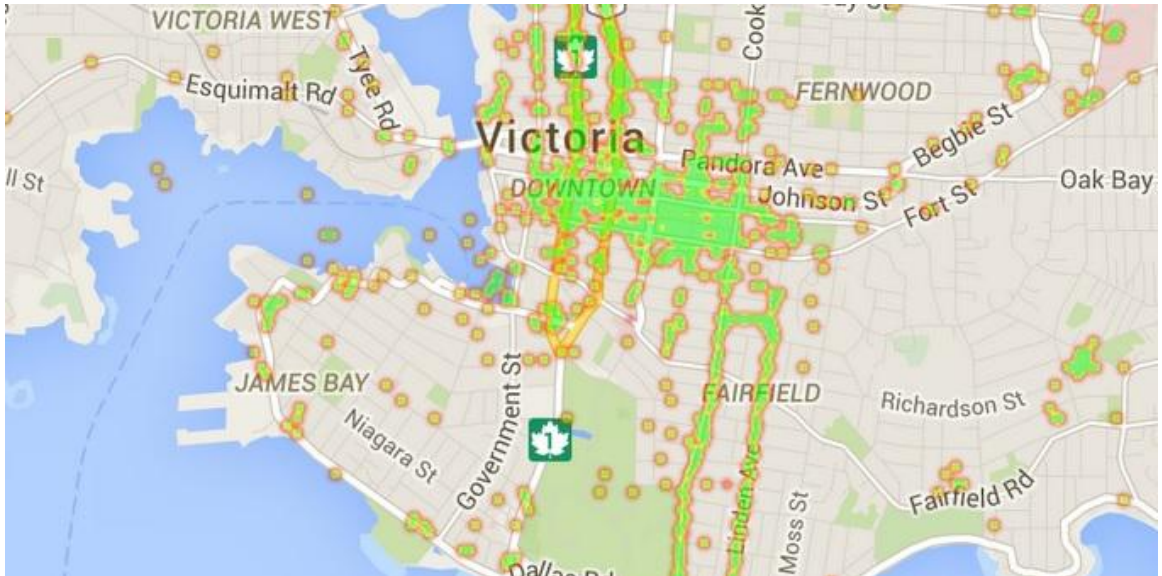


Figure 6.17: Upload Throughput Heat Map

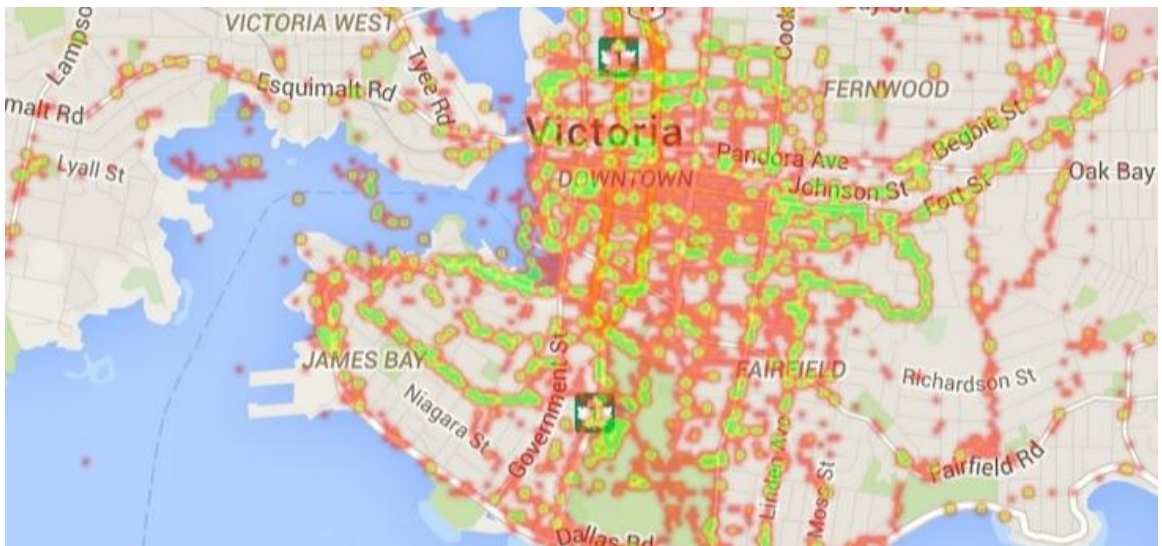


Figure 6.18: Latency Heat Map

6.4 Further Observations

There are many ways to visualize the data that was measured. Figures 6.20, 6.20, and 6.20 show some of the different ways that the data could be visualized. These measurements were aggregated to show how latency is affected by time of day. The entire data set was used for the aggregation, for results in the same Victoria region as the heat maps in section 6.3. Figure 6.20 shows how the latency measurements for Wi-Fi and cellular networks varied by time of day. Figure 6.20 shows how the observed signal strengths varied by time of day. These graphs could be displayed in many different ways, including increasing the localization by breaking the data down further.

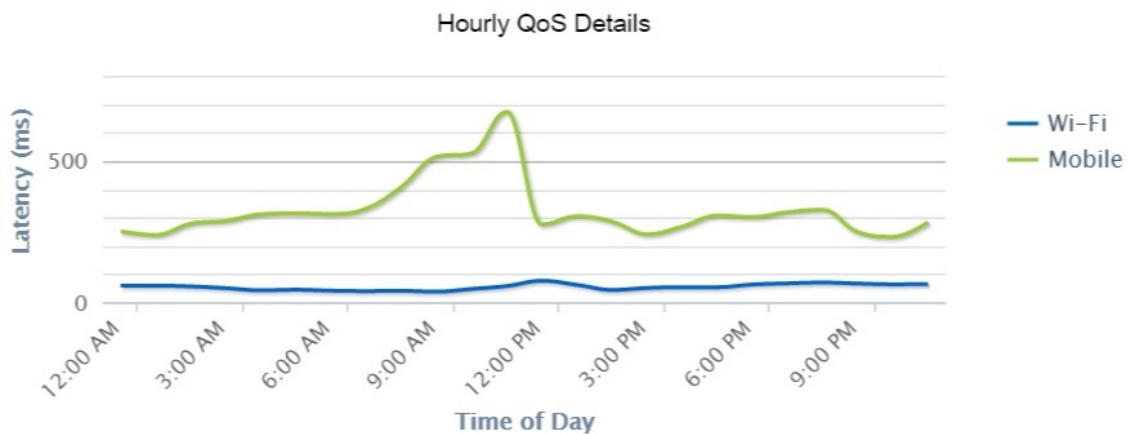


Figure 6.19: Observed Latency by Network Technology

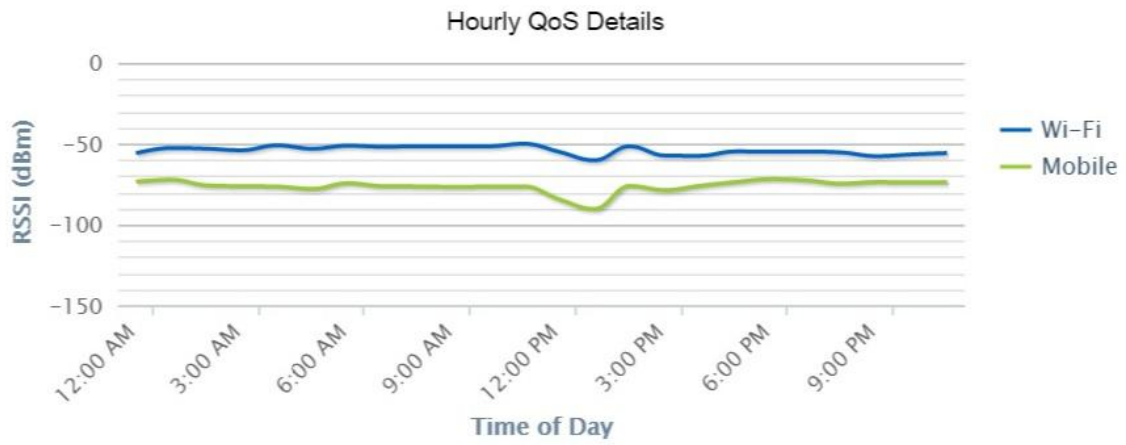


Figure 6.20: RSSI per Network Technology

Chapter 7

Conclusions

From the measured results, it can be seen that this information could be useful to a service provider that was interested in improving their service quality and overall customer experience. The data shows when users are on their phones most often, and the connection quality they are experiencing. QoE could be ascertained from the continuous collection of this data, especially if the data is in near real-time. It is worth noting that this data was collected and aggregated over the duration of a year and a half. Trends could also be ascertained that relate to how the data is changing over other periods of time, comparing results weekly or even daily. These wide variations preclude simple analytic models and other traditional performance measures including truck rolls and DPI and make a compelling case for crowd-sourced techniques.

There is a growing need to obtain the type of network information obtained during the collection period to help manage and expand upon the existing network infrastructure. There is a strong link between cellular and Wi-Fi connections since they are the two main sources of connectivity for all the users of mobile devices. Having information about both these connections as seen from the device provides a more

complete view of the network landscape as a whole and how it can be enhanced in the future.

7.0.1 Future Work

This is a powerful tool for understanding system behaviour from the user perspective. It was shown how the data varies across multiple dimensions such as time and space. These dimensions could also extend to devices and applications. Collations between network results obtained and device information could yield some interesting analytics regarding whether or not carriers would prefer certain devices on their networks over others. Historical trends over longer periods of time could produce insights into how people use networks as a whole, as well as analyze the growing app market. This information could be important for marketers to advertise which carrier a customer should subscribe to based on their location and usage habits.

The collected measurements could help make estimates about AP locations. This could be achieved by collating known signal strength information and BSSID for each AP with the location and signal strength information from the user. The measurement results could also provide information regarding frequency conflicts occurring between neighbouring APs.

Ultimately by being able to collate the data collected by devices and the data collected through methods such as DPI and truck rolls, an enriched picture of the network could be seen. This could result in more analytic discoveries. We have merely touched upon the analytic potential of the data that was collected.

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