Augmenting Wireless Quality of Service Metrics with Crowdsourced Wireless Quality of Experience Data

by

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BEng, McGill University, 2010

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ABSTRACT

Due to advances in mobile devices, service providers must support a roughly year over year doubling of data traffic on their wireless networks. Large capital expenditures are required on an ongoing basis to upgrade networks and keep up with this increasing demand. However, revenue growth is not keeping pace with these capital costs. This is placing significant capital strain on wireless service providers as they seek to increase the extent and capacity of their infrastructure deployments.

Service providers are highly motivated to increase revenues in order to improve their bottom line. Unfortunately it is difficult to increase average revenue per user (ARPU), which has remained stagnant for most service providers in North America for the last 3 years. Instead, 70% of service providers cite improved customer attraction and retention, often achieved through providing a better wireless user experience, as being their core strategy for improving revenues and affording the required network upgrades.

The understood dynamic is that customers do not have strong loyalties to their wireless service providers. They will willingly change providers to receive a better wireless experience. However the approach of attracting customers with superior quality of experience can only work for some service providers. When it comes to improving customer retention and attraction rates there must be winners and losers since not every service provider can deliver the best quality of service. This has produced a highly competitive customer acquisition and retention landscape with each service provider striving to attract a growing share of customers so that more revenue is available to support reinvestment into their networks. In many cases service providers will go so far

as to buy customers out of their existing competitor contracts in order to gain their patronage[1].

Given that the majority of wireless service providers are competing on wireless quality to attract and retain customers, the industry has reached a critical point at which being profitable relies on near perfect deployment of a limited amount of capital to improve customer experience. A wireless service provider who poorly deploys its capital will fall behind their competition in terms of wireless quality and will lose portions of their critically important customer base. This means that revenues drop further - reducing the capital available to re-invest into the network. This accelerates the process so that once a wireless service provider falls behind in quality it becomes increasingly difficult to catch up. Hence it is critical for service providers to understand what is influencing wireless user experience on their networks so that effective strategies can be put in place for cost-efficient continuous improvement. Service providers are actively seeking solutions to help them be more intelligent with how they spend their network improvement dollars.

Basic economics suggests that companies may compete on both price and quality. This is of course also true for communications networks and some smaller players have emerged which compete by offering a lightweight, low-cost feature set. However the same core dynamics exist among this group of service providers. If one of the low-cost players poorly deploys their capital, and provides a lower quality of service at a given price point, then they will lose customers to those offering better service at the same (or lower) price point. Losing those customers reduces revenue for that wireless service provider making it difficult for them to remain competitive. Hence, even among low-cost providers, it is critical that they deploy solutions that help them spend their network deployment and improvement capital as intelligently and cost effectively as possible.

Quality of Service (QoS) has traditionally been measured using network probes deployed within the service provider's core network. Hence QoS describes the network's perspective of user experience. At this time, the majority of network investment decisions are made to achieve the greatest gains to QoS. This approach does achieve some level of customer perceived success. However making decisions based on maximizing QoS does not necessarily mean that the consumers will see improvement. QoS often fails to reflect the consumer's perception of wireless quality which can, at times, be substantially different.

Using QoS as the key performance indicator for a wireless network creates problems because it only incorporates information collected with core network probes or via deep packet inspection. As an example to highlight the shortcomings of network-side monitoring, consider what happens when a mobile device fails to connect to a communications network. In this case the dropped call doesn't reach the network and network monitoring solutions in the core are blind to the error. However if monitoring was also performed directly on the mobile device that event would be recorded. It is increasingly important to make decisions to maximize the customer's perspective of received quality.

Wireless service providers can therefore improve the effectiveness of their network investments by augmenting their existing QoS information with user experience information collected directly on mobile handsets. These device-side readings reflect the consumer's perspective of quality. Additionally, by monitoring directly on mobile handsets types of failure events can be captured that are not measureable by core network probes and deep packet inspection. Quality of Experience (QoE) is a term coined to characterize these key performance indicators of a wireless user's experience built by incorporating direct mobile handset data collection. QoE requires not just on-device measurement but also and understanding of what on-device applications require what levels of network service.

Customers experience networks through the applications they use on their wireless devices. Hence for a service provider to truly understanding a customer's QoE they must monitor experience from the application layer of their customers' mobile handsets and build an understanding of how specific network conditions affect the performance of mobile applications. For example service providers must become well-versed in the customer's perspective of video and voice over IP calling (VoIP) sessions occurring over their networks, where these are distinct from, for example, the network demands of text messaging.

This report explores the differences in QoE and QoS in order to highlight the benefits of deploying solutions focused on monitoring QoE to enhance network planning and operations practices. In particular customer QoE as it relates to video and VoIP services is examined as those are the services that tend to be the most network sensitive while having a strong potential to impact a service provider's customer churn rate.

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Dr. Thomas Darcie and Dr. Stephen Neville for not giving up on me.

The University of Victoria for the exposure to industry I needed.

And my classmates David Yarish and Brennen Chow for ensuring that I never suffered alone.

Chapter 1

Introduction

Mobile devices have evolved far past the point of their original cordless phone predecessors. Mobile devices are now a primary mechanism for digital content consumption, storage, and delivery of all kinds; be it music, games, internet browsing, file sharing, productivity applications, data storage etc. Furthermore, phone manufactures and software developers push the limit of device capabilities year after year as they deliver newer device models. It is not surprising then that the data transmission demand from mobile phones roughly doubles yearly. Latest estimates indicate that data demands may increase 10x from 2014 – 2019 [2]. In particular, the proliferation of multi-player gaming, internet based voice over IP (VoIP) calling, and video streaming applications have caused unprecedented network strains [3].

For mobile operators, this is a problem. When the majority of global cellular networks were designed and installed, the modern mobile phone had not yet been conceived of. Hence, the bandwidth to support mobile device advances isn't usually available and network upgrades are required. However, these upgrades are expensive. As a result, service provider costs are growing much faster than their incremental revenue from supporting additional bandwidth. In many cases this has made it difficult or impossible for service providers to keep up with modern bandwidth demands. Hence, to remain competitive, service providers are being forced to look for more cost effective ways to increase bandwidth capacity than can be achieved through their traditional approach.

The problems being faced by service providers are further exasperated by their legacy network equipment and billing systems which makes innovation challenging. Networks have been built on top of technology put in place ten or twenty years prior in some cases. The result is service provider core networks are exceptionally difficult to modify or improve. Service providers are therefore looking to new innovative solutions that will enable them to deploy capital more intelligently. Developing a fuller understanding of QoE provides one such solution approach. Useful solutions must also be able to interface with legacy equipment and processes, or alternatively, be deployable purely over-the-top with no reliance on any core network integration.

1.1 Cellular Network Issues

The majority of current cellular infrastructure falls under the categories of second generation (2G) or third generation (3G) networks. A new generation of cellular network has been rolled out approximately every ten years since 1981 when first generation (1G) cellular was introduced. The definitions of 1G, 2G, 3G, etc. are based on a set of standards used for mobile telecommunications published by the International Telecommunications Union-Radio Communications Sector (ITU-R). 3G is defined as part of ITU-R's International Mobile Telecomunications-2000 (IMT-2000) specifications[4]. In order for a network to qualify as 3G, it must be able to provide peak data rates of a least 200 kbit/s. ITU-R has since published a definition of 4G in the

International Mobile Telecommunications Advanced (IMT-Advanced) specification[5]. 4G requires non-mobile users to receive speeds up to 1 gigabit per second (Gbit/s).

The cellular industry hoped that 4G networks would provide enough bandwidth increases to address emerging bandwidth requirements. However the costs associated with upgrading networks to 4G are sizable and roll out will take years. Furthermore, state of the art networks aren't truly delivering 4G speeds, instead they are closer to what is being dubbed 3.5G or 3.75G. Telecommunications service providers are also becoming more skeptical that 4G will solve their problems. This is because 3.5G networks provide a more viable option for high quality video consumption. In effect, the bandwidth capacity gains from moving to 3.5G are being offset by user behaviour changes associated with having access to faster networks[5]. As a result of the high capital cost of upgrading to 3.5/4G and the perceived failure of these upgrades to create additional capacity, many service providers are skeptical that networks which rely solely on cellular technology will remain competitive going forward.

1.2 WiFi Network Issues

This situation is leading to innovation. Unable to afford 3G/4G upgrades in the extent required, cellular operators have begun turning to more cost effective smaller-cell technologies to alleviate their bandwidth crunch. Femtocells, picocells, WiMax and WiFi access points, which are all significantly less expensive than traditional cell towers[6], and may provide the answer. According to studies, an area can be blanketed with high-powered carrier-grade WiFi for roughly 10% of what it would cost to cover that same area with Cellular[6]. Hence, companies such as Shaw Communications, are deploying significant WiFi networks despite owning cellular spectrum[7]. Moreover, although expected to bid on the 700MHz frequency in 2013 they have instead opted to pursue a broader WiFi strategy while reducing their cellular position.

WiFi has been defined by the WiFi Alliance as any "wireless local area network (WLAN) products that are based on the Institute of Electrical and Electronics Engineers' (IEEE) 802.11 standards" [8]. In 1985 the US Federal Communication Commission ruled that the radio frequency band that 802.11 is based on would be unlicensed. This deregulation has since motivated the rapid proliferation of WiFi technology.

Despite the cost effective nature of WiFi, to date these networks have failed to reach their full potential. This is largely because large-scale carrier WiFi is challenging from a network perspective due to the frequency of connections and disconnections, and the volume of data that can be transmitted [9]. When dealing with short range radio frequencies such as WiFi’s 2.4GHz, 3.6GHz, and 4.9/5.0 Ghz bands, it isn’t as clear to service providers how access points should be placed or spaced apart to achieve maximum effectiveness[10].

1.3 Network Management System Issues

Neither WiFi nor 4G networks in isolation have been able to fully solve the issues arising from increasing network demands. Service providers, lacking any straightforward low-cost fix to increasing network capacity are now exploring smarter approaches to plan and manage their networks. Wireless service provider network planning and operations practices require augmentation through innovative analytic solutions which are able to more effectively determine which network investments and actions will produce effective customer QoE gains. In order to succeed, these analytic solutions must have the capacity to manage the varied complexities of both 4G and WiFi networks. Combined solutions involving both technologies will be required to cost effectively support modern data demands. Currently, few analytic solutions seek to aggregate both WiFi and Cellular QoE information to provide one centralized network planning and operations platform. This is because the wireless network probes monitoring cellular quality information exist as separate systems from those which manage WiFi. Effective modern solutions will need to integrate diverse sets of information sources.

The industry need for such an integrated platform is motivating changes to the locations in the network where wireless quality monitoring takes place. Cellular network probes are only capable of monitoring cellular network quality. Likewise, WiFi probes only monitor the performance of WiFi networks at their access points. However, by performing network monitoring directly on mobile devices the user's QoE from any wireless IP connection can be assessed. By combining core network monitoring with aggregated on-device user perspective QoE monitoring a deeper visibility into cellular and WiFi networks can be achieved. Moreover, the developed insights can then be used to support internetwork decision processes such as offloading user traffic to WiFi from cellular.

Strong motivation therefore exists to move towards monitoring the quality of wireless networks directly via the QoE of mobile handsets. However the true value of this shift lies in gaining a customer perspective of the network(s). A number of radio propagation and device-side issues ensure that such customer network perceptions simply cannot be extracted from standard network-side QoS monitoring.

Chapter 2

Related Work

The value of device-side QoE measurements and issues in their collection have been explored in several prior research works.

In [11], Yang et al. developed two system models to determine how best to incentivize consumers to participate in mobile device based crowdsourcing. Their research focused on the incentive systems that were available to motivate manual input of information for crowdsourcing QoE. In particular they explored a platform-centric incentive approach and a user-centric incentive approach. The platform-centric approach shared rewards amongst the full group of participants by following the Stackelberg game model[12] in which the incentive platform is the leader and the users are the followers. Their user-centric incentive model took an auction style approach in which each user could bid on unique rewards. They concluded that network crowdsourcing for wireless service providers should ideally require no consumer input or time effort.

Yang et al. focused on determining the best incentive model and left unaddressed how to acquire the large volumes of network data to satisfy a wireless provider’s needs. The incentives that could be offered for any single data input action by a user therefore would likely be too small to provide adequate incentives at the data scales required. This suggests that a more viable approach would be to run in the background of the mobile device and have no user interaction or noticeable impacts on device performance.

Requiring active user intervention has been shown to significantly reduce user participation[11].

In [13], Ickin et al. explored what application and network characteristics are required to create a positive perceived application experience for consumers. This is relevant as consumers experience their networks through the mobile applications they use. If applications underperform, a consumer is more likely to delete the application. Consumers are also largely unable to distinguish the difference between network and application issues[13]. This study focused on measuring the consumer's perceived application experience as well as the application's appropriateness to the user's context and needs. This was done by surveying the application user immediately after application use and then again at the end of the day.

It was found that network throughput, network latency, application interface design, battery usage, and the user lifestyle all significantly influence the perceived experience. However the study concluded that users generally have good enough connections at any given time that the network connectivity should not be considered a core bottleneck to ensuring a good application experience. This conclusion though may change as applications continue to demand more and more network bandwidth to perform adequately. Moreover this conclusion is not consistent with the concerns expressed by network providers.

A challenge in seeking to apply such results more generally is that the study was performed on only fifty participants. This study highlights the need to incorporate device-side application-level information into network planning activities. A network that supports a group of applications well may also poorly support another group of applications. Moreover this suggests opportunities may exist to improve network planning by better understanding mobile device application distributions and usage behaviours across the network.

In [14], by Rosen et al., a study was performed that demonstrates the effectiveness of using mobile devices to crowdsource the performance of WiFi networks. The study showed that on a number of occasions the crowdsourcing approach was able to find issues that were not observable using other existing network side QoS tools. The work concludes by suggesting that the crowdsourced data is best used to supplement the data seen using in-place network side access point management systems.

This study also outlined the effort, cost, and efficiency benefits of using crowdsourcing. However it didn’t seek to address any underlying issues that might lead to a wireless service provider adopting this approach. It also didn’t seek to explore what specific actions could be taken based on the observed data to improve the performance of the wireless network. Rosen et al. though does provide a detailed basis for the argument of why crowdsourcing QoE data is effective for use by wireless service providers in network planning.

The three presented studies do not embody the entire set of related work performed to better understand QoE crowdsourcing. Instead each presented study represents leading research that has taken place in three key areas. Rosen et al. provide a detailed argument for why crowdsourced data is relevant whereas Icken et al. explored how to translate that data set into an understanding of consumer experience. Lastly Yang et al. study the consumer incentive requirements to collect that data set. This report expands on their work by outlining the details of wireless provider QoE challenges, how

QoE data can be collected in sufficient quantities, and how that data set can be used to efficiently produce QoE gains.

Chapter 3

User Experience & Service Provider Success

For service providers the goal of network investments is to have the largest possible positive impact on the end customer's mobile experience or QoE – be it cellular or WiFi, at the minimal cost. QoE has a known and substantial impact on customer retention[15]. According to Amdocs, a multi-national telecommunications solution provider, 70% of service providers cite customer retention as being their foremost strategy for growth[16]. This is not surprising given that in North America average revenue per user (ARPU) has remained relatively unchanged for the past three years. In fact the largest reported gain from 2010 to 2013 was only a 3% growth reported by only one service provider[17] – an economic gain that only keeps pace with inflation[18].

To summarize, for service providers an attractive and cost-effective way of increasing revenue would be by delivering a quality of experience that is high enough to improve customer attraction and retention. Even just maintaining current levels of quality of experience requires upgrading networks to be able to support the yearly observed doubling of mobile device data demands[2]. The end result is that a service provider's survival depends on ensuring that their network upgrades effectively maximize the positive impacts on user quality of experience against their costs. Even single poorly planned network upgrades can result in degradation of user experience, leading to customer loss and decreased revenues. With less cash for upgrades, quality of experience will likely further diminish, creating a downward spiral that would be hard to recover from. Hence WiFi and Cellular service providers are more motivated than ever to understand what it means to deliver a high quality of experience to their consumers.

Traditionally service providers have monitored what can be defined as quality of service (QoS), as opposed to quality of experience (QoE). Quality of service, is generally reported as a composition that is derived from network characteristics such as throughput, latency, jitter, packet loss and other key performance indicators[19]. Quality of service is traditionally monitored using network probes that sit behind cell towers in service provider core networks. Hence quality of service describes a network perspective of wireless services.

A strong argument can be made that this traditional approach is insufficient. In actuality, consumers now experience networks through applications that they use on their mobile devices. A user’s satisfaction with a network depends on how well the applications they use perform on each given network. Quality of Experience denotes the performance of applications being used by consumers on networks. Consumer QoE perceptions are influenced by many additional factors that exist outside of traditional QoS measurements.

In order for service providers to achieve the user experience benefits associated with incorporating Quality of Experience measurements they must first be able to make these measurements. This requires monitoring user experience from the consumer’s perspective directly on mobile handsets as opposed to from the network’s perspective. It also requires accounting for the network requirements required by the specific applications that consumers use eg; video, VoIP calling, on-line games, and web browsing applications.

This application-centric QoE perspective is critical for service providers due to the increasing importance of each of their network investments. Every upgrade must result in improved consumer experience if the service provider is to remain competitive. Capital expenditure budgets are too slim and network upgrades too important to not be optimizing and measuring how the dollars spent are improving customer experience. Service providers are, therefore, shifting from relying solely on QoS to also incorporating QoE as a key performance indicator when making decisions to gain better insights as to how network investments actually impact their customers.

Chapter 4

Device-Side Monitoring

Monitoring QoE information directly on mobile devices produces a data set for wireless service providers that differs from what is achieved with network-side monitoring. However the specific data elements that are achieved depend on how the device-side monitoring is performed. QoE crowdsourcing platforms must therefore be designed differently depending on service provider requirements. Device-side software monitoring libraries are able to track user experience in three main ways:

1. By interacting with the operating system: Operating systems such as Android and Apple's iOS have native APIs that allow developers to access information about the device itself eg: device make, device model, and screen resolution[20][21].

2. By generating synthetic network traffic and then analyzing the network response: This is often called Active Network Testing. In an Active Network Test the monitoring software pings a known server then downloads or uploads a file of known size. The monitoring software tracks how long it takes for these ping, download, and upload events to complete in order to derive information about the network to determine network characteristics such as throughput and latency.

3. By watching how the consumer naturally consumes content: This is often called Passive Network Testing. For example, if the consumer downloads a video, the monitoring software measures the length of time the download took and the size of the file to make an estimation of download throughput. Passive testing is often preferable over active network testing as no additional network traffic needs to be generated. This has battery and data usage savings, however the test results also tend to be less accurate as measurements such as throughput must be inferred as opposed to directly assessed.

4.1 Video QoE

Video QoE monitoring metrics are especially interesting due to the industry gap that they are able to fill. Currently the majority of video quality monitoring is performed using deep packet inspection (DPI) systems. DPI functions by scanning data packets as they traverse through the network[22]. However these DPI systems are unable to monitor the quality of video traffic when that video traffic is encrypted[23]. This is a serious disadvantage. On the other hand, when you monitor video quality directly on a mobile device it is possible to monitor the quality of encrypted video traffic. Mobile device media players decrypt video traffic as it is streamed. By interacting with the media player on the device, the details of this video traffic and the provided video QoE can be monitored.

4.2 Limitations

It is important to note that there are costs associated with using on-device user experience monitoring software. Each additional measured QoE metric has an impact and collecting extraneous information should be avoided.

4.21 Battery usage

Consumers are extremely sensitive about how much battery capacity individual processes consume. If the QoE monitoring software is embedded inside of mobile applications then that application cannot then consume significantly more power or the consumer may become upset and uninstall the application. Location tracking via GPS is one of the largest offenders when it comes to battery consumption[24].

4.22 Memory and CPU usage

Consumers are sensitive to the amount of memory or CPU an application uses because it impacts the overall performance of their device as well as its battery drain rate[25]. However, operating systems such as Android and Apple’s iOS are designed to shut down processes when they run in the background to conserve the device computing resources[26]. QoE monitoring software should not collect unimportant data that may risk increasing CPU and memory usage to a point that leads to automated shut downs by the operating system.

4.23 Privacy Concerns

Ever since CarrierIQ was in the news in 2011 for tracking sensitive consumer activity information with embedded phone monitoring software, wireless service providers have become increasingly concerned about how much information they track about their user base and how that data may be used[27]. The CarrierIQ incident led to many wireless service providers issuing public statements regarding their strong commitments to users. All monitoring software on mobile devices must be compliant with privacy regulations, policies, and statutes. Android and iOS operating systems ensure that consumers must opt-in to any form of tracking. After downloading an application and opening it for the first time, Android and iOS present the consumer with a series of questions about what types of information they are comfortable sharing with the mobile application. If the consumer says no to any specific type of data, Android and iOS then prevent the collection of that data type. However, privacy law compliance is a minimum and it is often appropriate to take extra measures to protect private information. It is important for service providers to also aggregate all collected user experience information to ensure that this cannot be used to identify specific users or the specific user behavioural patterns. It is also important that the service provider only collect the information that is indeed necessary to achieve their customer experience improvement objectives.

4.24 Managing Limitations

There are many advantages and concerns with collecting data on mobile devices to help wireless services providers understand and improve their wireless service quality. It should not be unexpected that service providers therefore require QoE measurements to service a variety of objectives. Certain pieces of data are more (or less) important depending on each carrier's specific concerns, their governing laws, their network maturity, and the intricacies of their user base. It is then important that any QoE monitoring software retain post-deployment customizability and flexibility. This can be accomplished through server-side components that control and manage the deployed base of monitoring software. In particular there must be full control over:

1. What data is collected,
2. How much data is collected and how frequently various QoE tests are made,
3. How frequently the resulting test data sets are uploaded, and
4. Tracking which users have authorized what data collection.

Chapter 5

Distribution

Achieving significant distribution of a on-device QoE measurement suite is a critical challenge to implementing an effective consumer perspective monitoring platform. Clearly, if the results are to be statistically valid, a distribution into a suitably large cross-section of active devices is required. There are a number of methods for getting monitoring software onto consumer-level mobile devices. Many of these approaches involve embedding monitoring code inside of other software. In all cases it is important to be aware of and comply with any jurisdictional requirements such as Canada Anti-Spam Legislation (CASL) which has compliance requirements associated with embedded software systems.

5.1 Chipset Embedding

This involves working directly with a device manufacturer to have the QoE software come pre-installed on chipsets. This ensures that each device sold will contain a consistent monitoring software suite. The downside is that monitoring is not transparent to the consumer. Without reading the terms and conditions of the device carefully the consumer will not be aware that any monitoring is taking place. This can lead to significant privacy concerns and potential backlash. This also would not address currently deployed devices but only future devices from the collaborating manufacturers. Although this approach works well for achieving mass distribution it has a higher potential to result in consumer concerns around privacy. Updating chipset software can also be problematic compared to the ease of updating consumer application over iTunes or Google Play stores.

5.2 Embed in a Carrier Application

Wireless service providers generally offer 5-10 mobile applications over iTunes and the Google Play stores specific to their networks. For example, many offer mobile applications to let consumers track how much data they have consumed from their monthly quota. Wireless carriers could therefore embed the monitoring software inside of their own applications to collect consumer perspective information. However best practice is to notify all application users of the collection to avoid the perception of violating user privacy. The advantage of this approach is that distribution is managed by the service providers. However service provider applications are unlikely to have a large user base compared to more general consumer applications.

5.3 Embed in a Consumer Application

Wireless monitoring software can be embedded inside of more general consumer applications i.e. those not owned by wireless carriers. The data that is collected could then be sold to the wireless carriers to support their network planning efforts. This approach requires motivating the application developer to embed the additional QoE monitoring software, potentially by splitting any resulting data revenues with the application developers. This approach provides large sets of data that can provide value to service providers and other stakeholders. However, the difficulty is managing relationships across many consumer application developers.

5.4 Embed inside of an Ad Network SDK

This approach is similar to directly embedding the software inside of a consumer application. However it has greater distribution potential. Consumer application developers are used to and comfortable with embedding SDKs in their code that show mobile advertisements to their user base. A network monitoring SDK can be paired and integrated with an Ad Networks SDK to achieve broad distribution into thousands of mobile applications on millions of mobile devices rapidly. This approach provides potentially massive distributions while only requiring the management of a few key relationships. The difficulty with this approach is setting up a viable win-win relationship with the Ad Network.

Chapter 6

Comparison to Drive Testing

Wireless service providers have known for some time that they require consumer QoE perspectives to truly understand their networks[28]. However to date it has been difficult to monitor QoE directly on mobile devices due to the non-trivial impacts on the phone battery, CPU and memory. Only since 2013 have smartphone capabilities been advanced enough to support the required monitoring software while not negatively affecting consumer experience[29].

Traditionally service providers have had to rely on drive testing in order to assess wireless quality in the field. Drive testing involves loading expensive network testing and emulation equipment vehicles that are then driven to precise areas to assess wireless network quality. In this manner a map of likely customer QoE can be developed for the carrier's service areas.

The advantages to monitoring QoE directly via smartphones as opposed to by drive testing include:

1. Cost: Drive testing is much more expensive to operate due to the need for network testing equipment and vehicles. Technician are also required to drive the vehicles. These expenses are reduced when monitoring QoE on consumer devices and crowdsourcing the results.

2. Time sensitivity of data: A drive test network audit is useful only for specific periods of time[30]. The addition of buildings, cell towers, and WiFi access points etc. can significantly change radio frequency propagation and radio interference effects with each given environment. It is generally not cost effective to engage in on-going drive testing network audits. Hence outdated information can end up being used to make expensive network decisions. By comparison, embedded device-side QoE clients have enabled low-cost ongoing collection of QoE information - alleviating the problem of stale information.
3. Indoor Testing: A large portion of wireless data is consumed inside of buildings. Drive testing isn't able to map the quality of wireless inside of buildings and as a result much of the required data isn't accessible. Monitoring QoE on a device allows for direct testing wherever the device can go.
4. Reflects the Consumer Experience: Drive testing only emulates consumer network connections. The emulation equipment connects to cell towers then runs through a set of scripts in order to mimic likely consumer behaviours. This is a proxy for actual user behaviours, which therefore lead to the potential that many actual and important behaviours and edge cases un-explored. On-device QoE testing takes place on real consumer devices in locations and at times where consumers are consuming network resources.

Device-side QoE testing is unlikely to fully replace the need for drive testing. Drive testing emulation equipment has the advantage of being able to monitor specific network Key Performance Indicators (KPIs) that cannot be collected on mobile handsets[28]. Hence there will always be a need for some drive testing.

6.1 Network Quality Variations – City Scale

Cellular and WiFi operators send engineers into the field to asses problems such as coverage holes in the network. However, drive testing gives only limited snap shots of the network[31]. These snap shots are often ineffective for network planning because they only remain valid for a limited period of time.

Figures 6.1.1, 6.1.2, and 6.1.3 show example QoE readings on a commercial network for a 3 month period. The readings were taken by embedding network testing code in the background of a commonly used mobile application.

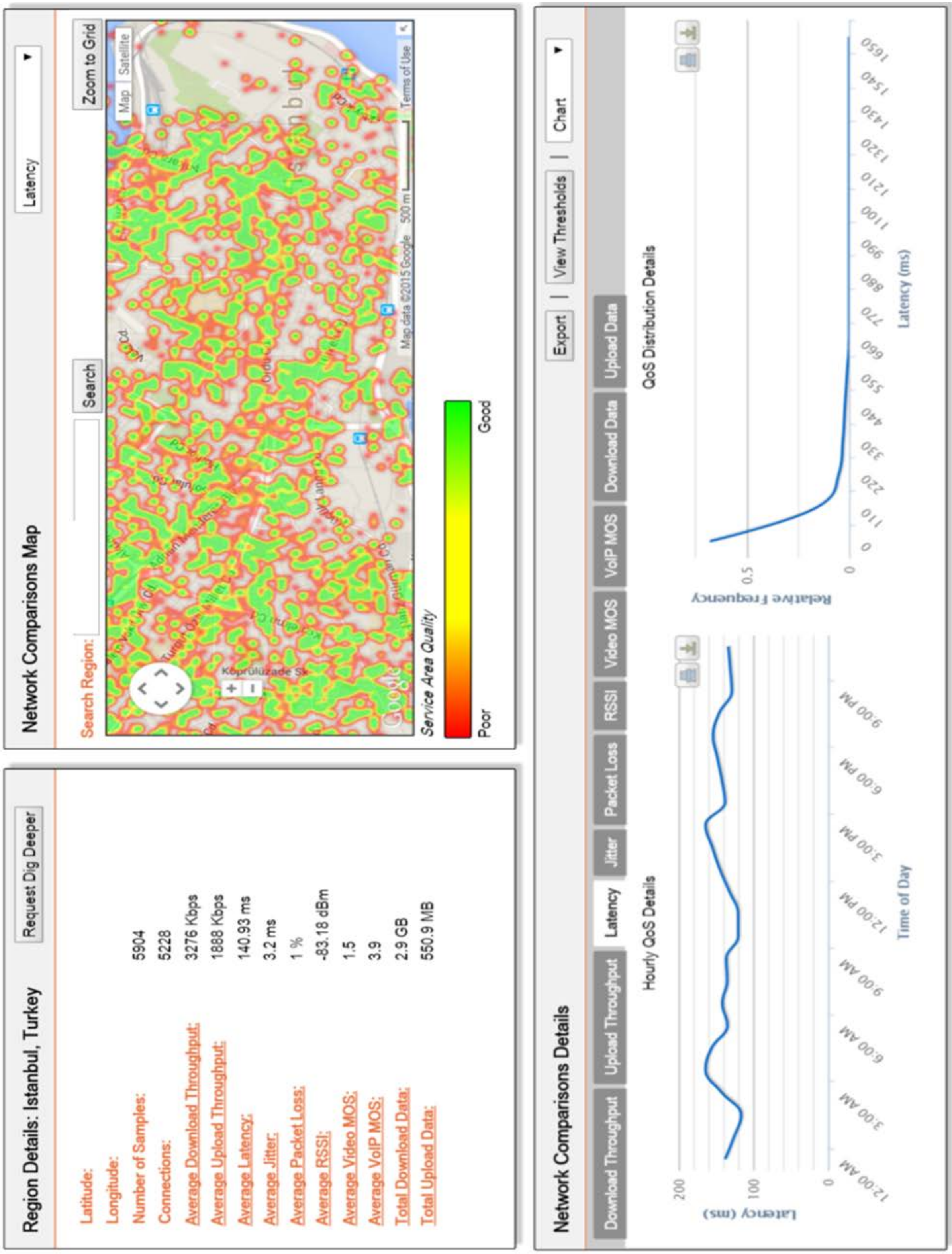

Figure 6.1.1: The results of 5904 QoE readings taken from a commercial network from April 1 to April 15th 2015

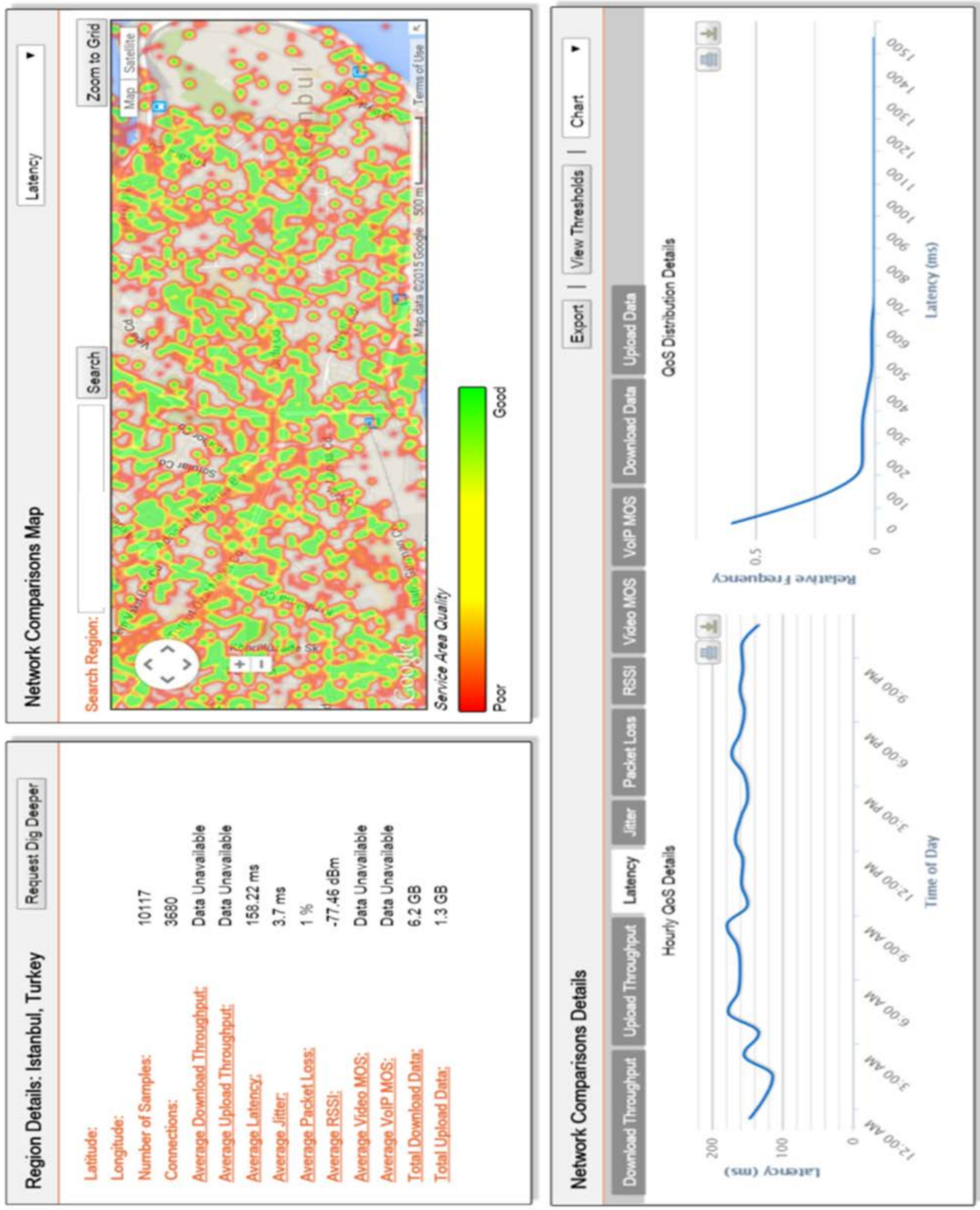

Figure 6.1.2: The results of 10117 QoE readings taken from a commercial network from May 1 to May 15th 2015

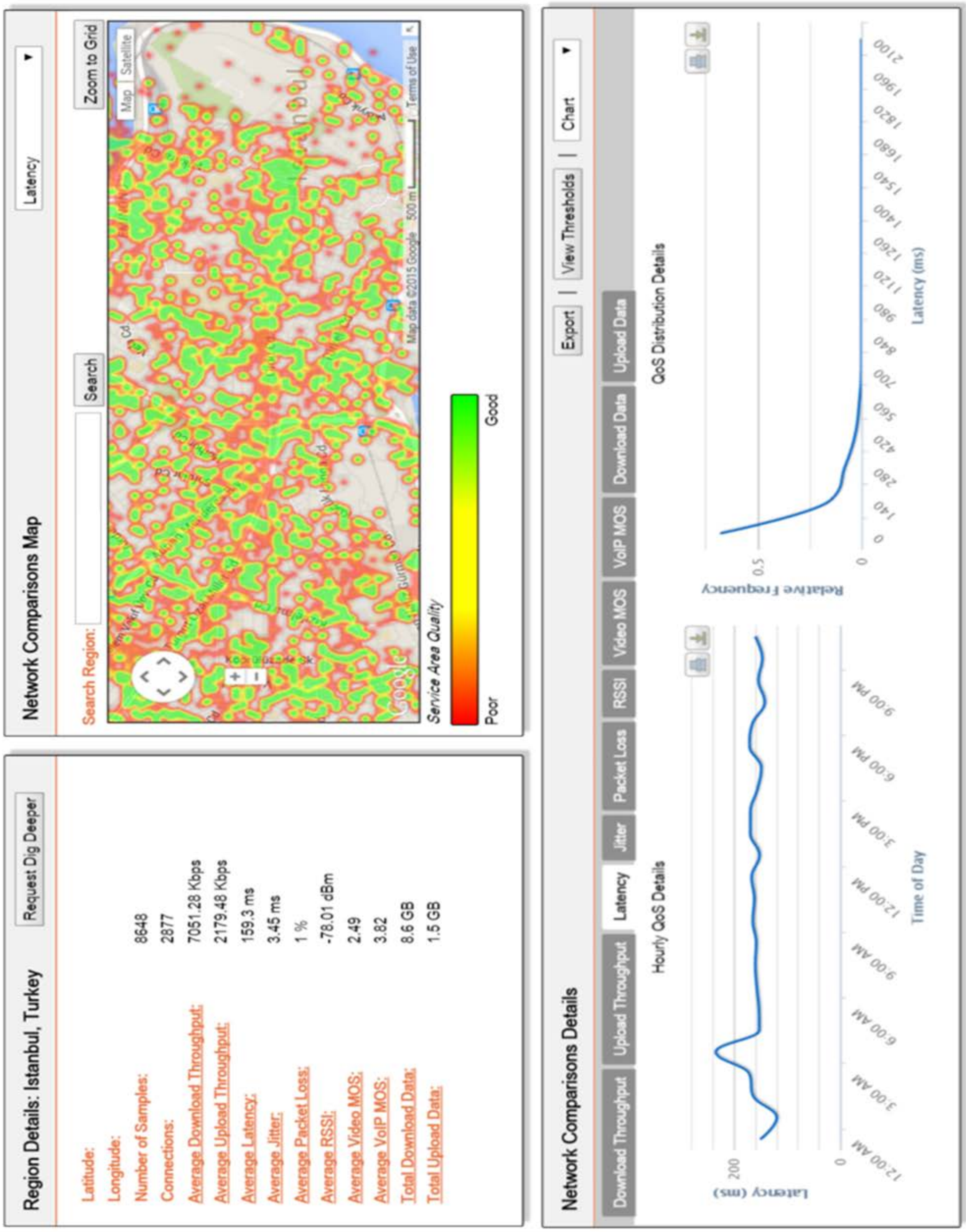

Figure 6.1.3: The results of 8648 QoE readings taken from a commercial network from June 1 to June 15th 2015

	April	May	June	Max Variation	Standard Deviation
Latency (ms)	140.93	158.22	159.3	18.37	10.30
Jitter (ms)	3.2	3.7	3.45	0.5	0.25
Packet Loss (%)	1	1	1	0	0.5
RSSI (dBm)	-83.18	-77.46	-78.01	5.17	3.15

Table 6.1.1: A city-scale comparison of a commercial network from April – June 2015

Table 6.1.1 shows that latency, jitter and RSSI all experienced some fluctuation on a commercial network in between April and June, 2015. The one exception was packet loss as it remained near zero throughout. These observed city scale variations highlight the importance of using up-to-date information for making network planning decisions.

6.2 Network Quality Variations – 2500 Square Meter Grid

Figures 6.2.1, 6.2.2, and 6.2.3 show the results of QoE readings taken on a commercial network over a period of 3 months. The readings are all for the same selected 2500 square meter area.

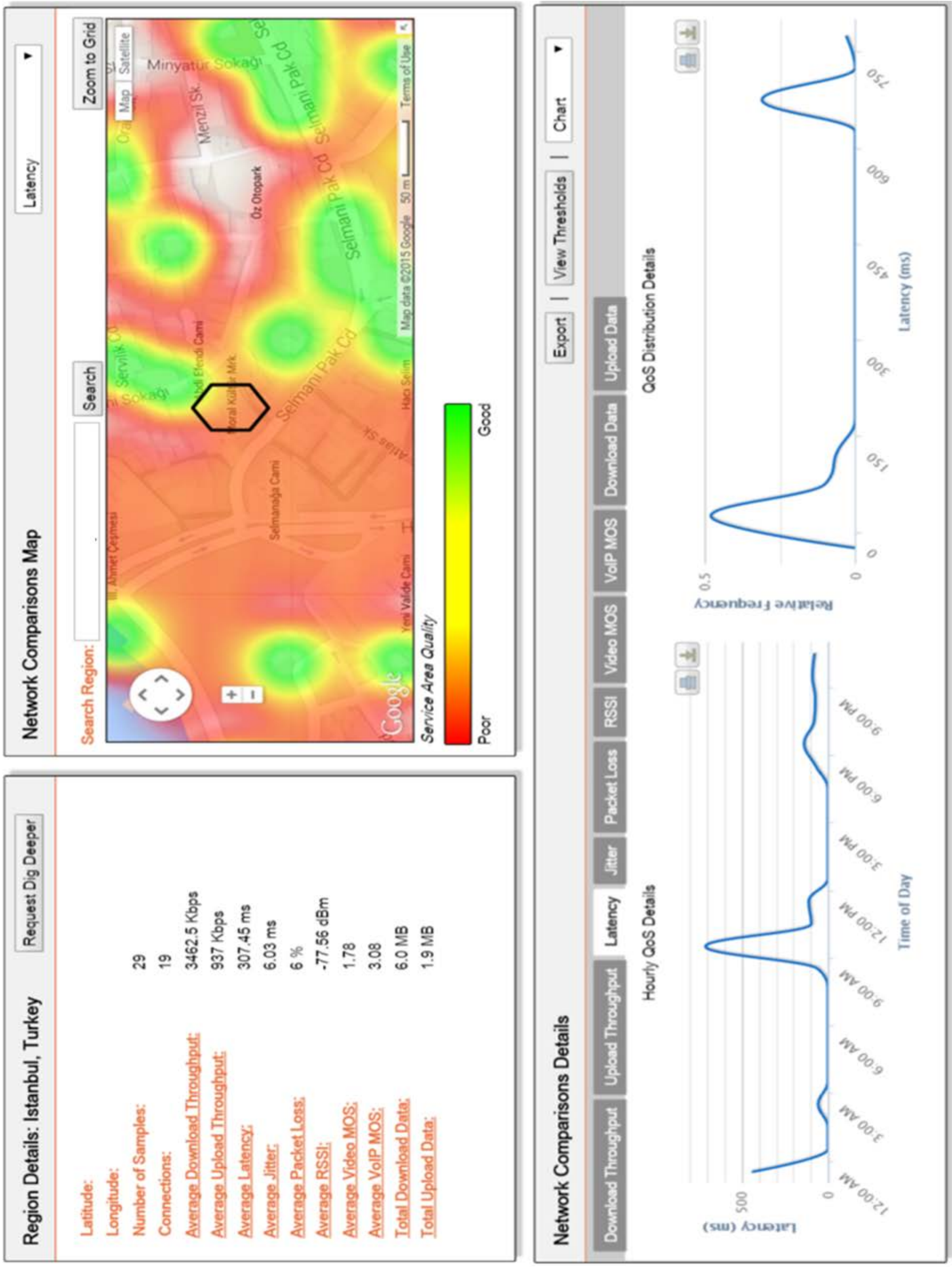

Figure 6.2.1: The results of 29 QoE readings taken on a commercial network from April 1 to April 30th 2015 for a 2500 square meter area.

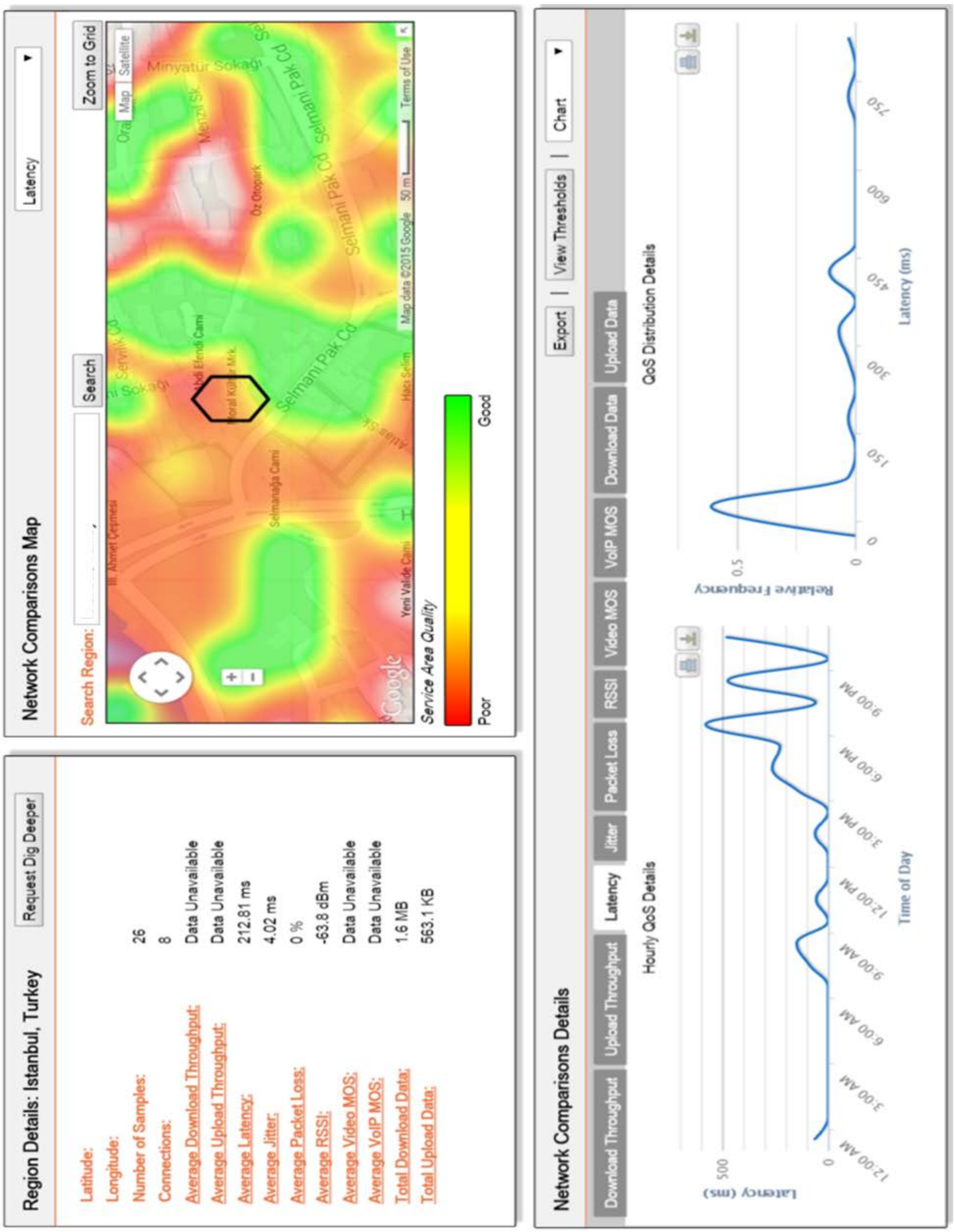

Figure 6.2.2: The results of 26 QoE readings taken on a commercial network from May 1 to May 31st 2015 for a 2500 square meter area.

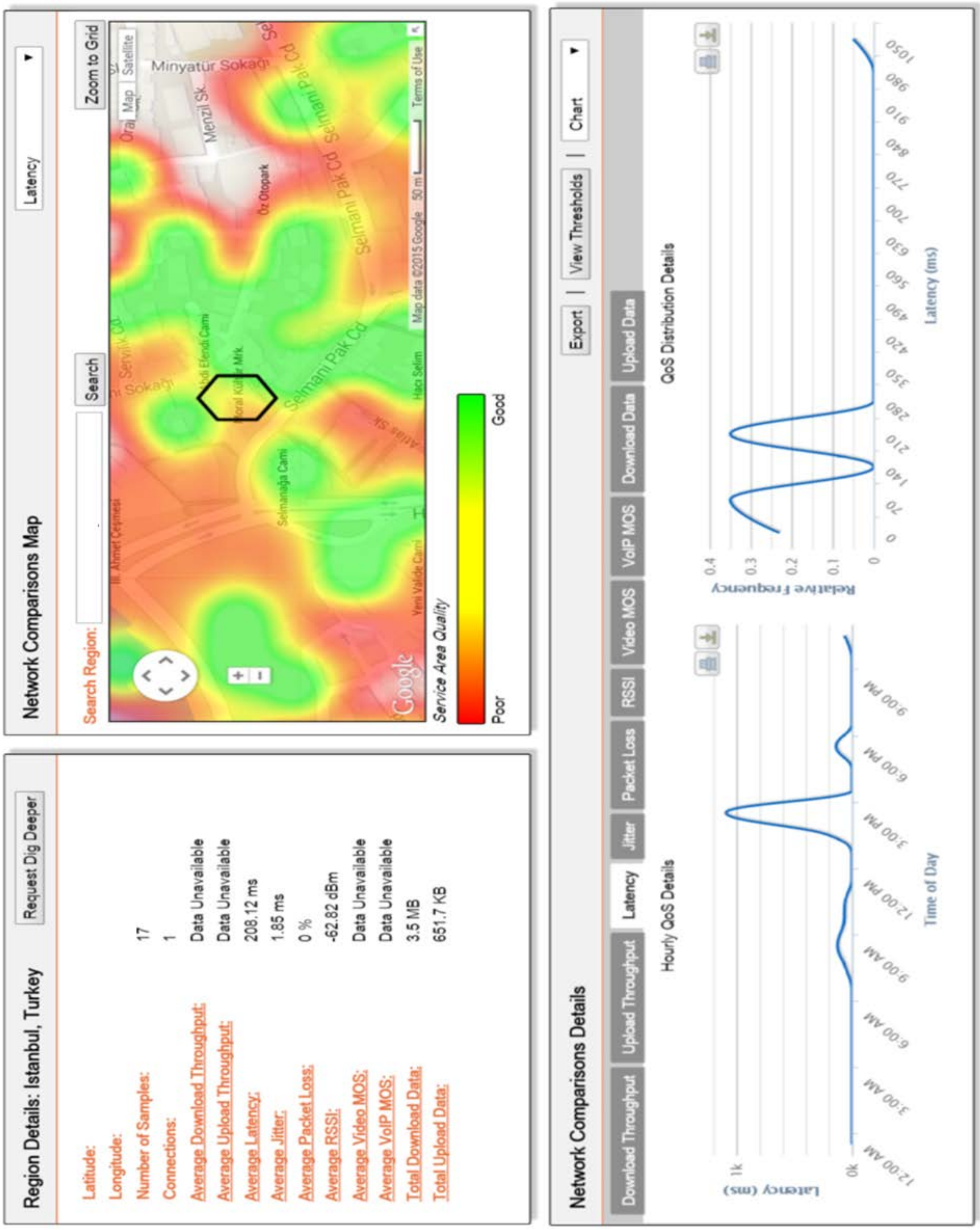

Figure 6.2.3: The results of 17 QoE readings taken on a commercial network from June 1 to June 30th 2015 for a 2500 square meter area.

	April	May	June	Max Variation	Standard Deviation
Latency (ms)	307.45	212.81	208.12	99.33	56.04
Jitter (ms)	6.03	4.02	1.85	4.18	2.09
Packet Loss (%)	6	0	0	6	3.46
RSSI (dBm)	-77.56	-63.8	-62.82	14.74	8.24

Table 6.2.1: A comparison of Turkcell QoE readings from April – June 2015 for a selected 2500 square meter area.

Table 6.2.1 shows that latency, jitter, packet loss and RSSI all experienced fluctuations on a commercial network between April and June 2015 inside of the selected grid area. These observed variations in the selected grid highlight the importance of using up-to-date information for making network planning decisions.

Chapter 7

Crowdsourced QoE Value to Network Planning

Network planning by service providers involves finding the best install sites, optimizing coverage area, and planning for reduced interference[32]. All such activities require a detailed field view. Consumer QoE perspective data collected directly from mobile devices is especially important to wireless service providers for the purpose of network planning. This is because the objective of network activities such as installing a new small cell or WiFi access point is to improve QoE for consumers.

7.1 Small cell site planning

When properly positioned, deep packet inspection systems are able to look at the majority of traffic flowing through wireless networks. As a result they can be used by a wireless carrier to determine when a specific cell site is congested or when a specific cell site may become congested in the near future. However once a carrier knows that a cell site is congested the appropriate response is not always clear. One available option is to install a small cell(s) somewhere in the congested tower's broadcast area to alleviate strain on the tower and, hopefully, improve its performance.

Small cells include picocells, femtocells, and microcells[6], broadcasting in both unlicensed and licensed spectrum spaces and typically having maximum ranges of no more than a couple kilometers. However many are deployed to support ranges of less than two hundred meters[6]. In general, they are primarily used to fill holes in the network and eliminate dead zones without needing to install new macrocells, which can cover up to ten kilometers and require significantly more planning and detailed approval processes to deploy.

Once a wireless carrier has identified a congested, or soon to be congested, cell tower they must then identify the most appropriate location(s) to install small cells. In order to do this the wireless carrier needs to be able to map the signal strength and usage density profile of the cell tower. Placing a small cell in areas of low user density or where the network is not saturated offers little advantage. QoE crowd-sourcing provides a direct means of acquiring the information required to effectively place the small cell. Wireless carriers do currently have network-side tools that allow them to approximate the coverage area of any individual cell tower so that they can identify potential dead zones. However such network-side mapping relies on the network's perspective of coverage and QoE.

7.2 WiFi site selection analytics

Many WiFi operators in North America are cable providers, such as Shaw Communications, Cablevision and Comcast. Such WiFi operators tend not to own and operate cellular networks. As a result the WiFi operators have no visibility of their subscriber when the subscribers are using cellular services. WiFi operators are only able to monitor their subscribers for the limited times when they are connected to and using the WiFi network. This poses a challenge when the WiFi operator attempts to decide where to install a new publically accessible WiFi access point as there is no data available to tell them in what un-serviced areas their subscribers reside.

Device-side QoE monitoring addresses this information gap. When a monitoring client is loaded onto a mobile device, the monitoring client can provide network-agnostic QoE assessments. It is then possible to identify un-serviced WiFi areas that should be prioritized for new WiFi coverage. A new open WiFi access point placed in one of these areas it is likely to be a more effective installation.

This capability is critical for WiFi operators if they are to build out their WiFi service network cost-efficiently and effectively. The cable providers are viewing their subscribed WiFi networks as a core differentiator and the main way by which they will be able to maintain their customer base and reduce churn[36]. Therefore, identifying such high value install sites is a key industry need. Device-side QoE monitoring provides core tools to find and identify such sites.

7.3 Self Organized Networks

Self organized networks (SON) is an emerging technology in the industry[33]. These SON network control systems are installed in networks to dynamically modify the angle and power of cell tower antennas. Hence, service areas can be dynamically tuned to better match user densities and demands.

The primary data input being used by SON systems, to plan the appropriate angles and power levels for antenna, is signal strength. Location based signal strength information, or signal strength maps, allow dead zones and weak signal areas to be identified. Currently drive testing is used to collect such information. However crowd sourcing that same data using device-side QoE monitoring solutions can provide more efficient, more timely, and a more complete solution.

Chapter 8

WiFi Deployments & Data Onloading

Commercial WiFi in North America is mainly being deployed by leading cable providers. In Canada this is being led by Shaw Communications with more than 60, 000 public access points[34]. In the United States the largest WiFi network is operated as a partnership between five of the largest cable operators. Combined they account for 400, 000 access points[35]. Cable companies are well positioned to set up WiFi networks as extensions to their in-place high bandwidth capacity cable network installed in most urban centers. In most cases these cable networks are also underutilized so large amounts of available capacity exists that can service WiFi access. From a network architecture perspective, these cable providers are well positioned to cost-effectively set-up large WiFi networks.

On a business level, cable providers are motivated to deploy WiFi for their subscribers as they are losing customers to cellular providers. These cellular providers are able to offer in-home video services that are on-par with those provided by cable. However the cellular providers can also offer essentially anytime anywhere wireless services through their cellular network. North American cable providers have decided that they will go all-in on deploying city wide WiFi networks in order to have a competitive wireless story[36]. Expanding their WiFi networks is seen as a main defense against losing customers to cellular carriers. However the cable industry’s shift toward a competitive wireless story entails the need to support services such as on-the-go video and VoIP calling. As such services are QoE sensitive. They underline the importance for WiFi operators of the need to better understand their customers' QoE in order to cost-effectively expand their WiFi coverage and service offerings.

The cable industry also works quite differently than the cellular industry. Cable companies have traditionally dominated in their respective geographies with very few territorial overlaps. Hence cable companies tend to collaborate instead of complete. They have jointly funded R&D initiatives such as CableLabs and are together planning how to deploy their WiFi networks effectively. This is allowing them to form alliances between their WiFi networks. All of their networks will then act as one WiFi network. This is destined to become a massive wireless network particularly since cable providers have been actively deploying dual SSID access points into people's homes. Such home access points provide half of their capacity to the home owner, with the other half allocated for use by cable WiFi alliance subscribers. The massive expense of deploying 4G networks will lead to their joint WiFi network becoming comparable, in terms of speed and coverage, to cellular wireless services or even potentially surpassing them.

8.1 Cellular Offload

The massive increases in WiFi coverage are also providing opportunities for struggling cellular providers. Data traffic that is above and beyond what a cellular network can in current networks handle can be offloaded onto available WiFi networks to decrease cellular congestion. In some cases the WiFi network itself may be owned and operated by the cellular provider. As is the case, for example, with AT&T. Alternatively cellular customers could be offloaded onto WiFi networks that are owned and operated by completely separate entities. The cable WiFi alliance, for example, hopes that they can navigate the complex business hurdles required to be able to offload traffic from overloaded cellular operators as another potential revenue source.

At a technical level challenges exist for such offload solutions. Not all cellular traffic can or should be offloaded to WiFi. Whenever a WiFi offloading event takes place, there is a degree of risk that the consumer QoE will be negatively impacted. With current handsets the cellular connection must be broken before the WiFi connection can be established. If the handoff WiFi network is of poor quality or doesn't have sufficient throughput then the consumer will need to re-connect to cellular. This hopping (or ping-ponging) between WiFi and cellular should be avoided. Hence cellular providers only want to move specific customers and specific traffic types to WiFi. High priority customers or high priority traffic may not be good offloading targets. Also WiFi offloading is only needed under prescribed circumstances – mainly peak high congestion network usage times.

In essence cellular providers only want to move consumers to WiFi when a seamless transition will be experienced. To achieve such seamless switches the following must be achieved:

1. Persisted IP address: If someone is streaming a movie on cellular and is switched to WiFi, a persisted IP address is required to ensure that the back-end movie server continues to stream video to that device. If this is not present, the video will need to be re-loaded.

2. Continued access to services: Cellular subscribers access a variety of services through the cellular network. These may include parental controls, the ability to check on the status of their current bill, or even the ability to buy new ringtones. It is important that the consumer is able to continue to access these services over the WiFi network. This is especially important for things like parental controls which need to remain consistent across networks. Without this capability, the consumer experience cannot be managed as effectively and some revenue generating services cannot be offered.

3. Continued QoE: If a consumer is offloaded onto WiFi then the QoE should be equal or better. Offloading onto poorer quality networks is not a viable option as this will diminish the perceived experience. In general, the end-goal is to maintain QoE and service access in a manner that is transparent to the users.

Monitoring network quality from mobile handsets is core to satisfying the third requirement. Network monitoring equipment that sits behind a cell tower or WiFi access point in the core networks can only have visibility to the network within which it sits. In other words, network-side WiFi network monitoring equipment only has visibility into the network quality of WiFi, and network-side cellular network monitoring equipment only has visibility into the network quality of the cellular network. However WiFi offloading by its very nature involves both networks working together. Crowdsourced on-device QoE monitoring allows the concurrent monitoring of both networks, i.e. it provides a network agnostic solution. Hence, on-device QoE monitoring provides the critical pieces of real-time information required to make intelligent offloading decisions.

Existing WiFi offloading standards, such has HotSpot2.0[37] or ANDSF[38] are made up of three main parts:

1. A connection manager: This is the on-device software that facilitates network switches. It sits directly on the mobile device and physically moves traffic between various connections. A connection manager can be seen as the switching mechanism. However it is often controlled by a server-side policy manager which sends instructions to it. Connection managers come natively built into mobile device operating systems, with some vendors having built augmented connection mangers that replace or cooperate with the native connection manager.

2. A policy manager: This is the server-side control for a WiFi offloading solution. It communicates with the connection managers on mobile devices to tell those devices where they should be connected to at any given time. The main responsibility of the policy manager is to distribute current connection policies to the mobile devices.

3. A policy engine: This is the intelligence component of a WiFi offloading solution. The policy engine determines where specifically each consumer should be connected to at any given time and relays this information to the policy manager in the form of policies. It is this component that can make use of network

QoE information to produce appropriate policies. Hence whenever a device makes a connection, a network quality reading would be taken on the device and the results are then provided to the policy engine for analysis. When enough collections have taken place, an appropriate policy may then be generated for the policy manager and the WiFi offloading solution.

Existing HotSpot2.0 and ANDSF policy engines make use of network connection priority lists. These lists ensure that consumers stay connected to their best available, or preferred, networks. For example, the majority of consumers tend to prefer to use their home WiFi network whenever it is available. As a result it is important to ensure that there is a policy in place that gives preference to that home WiFi connection over other visible connection points. Such is the case with the network priority list shown in Table 8.1.1.

Priority Level	**Network**
Priority #1	Home WiFi (SSID Set)
Priority #2	Free WiFi (SSID Set)
Priority #3	Home Cellular Network
Priority #4	Paid Roaming Networks

Table 8.1.1: A sample network priority list being used by policy engines in industry

In traditional policy forms WiFi access points are selected purely based on their network identifier, or SSID. This means that if a consumer enters a building with multiple WiFi access points, each of which uses the same network identifier, there is no way to differentiate between access points that are known to provide enhanced levels of performance and those that do not. Instead each WiFi access point, within a given WiFi network, will be given the exact same priority level based on it having the same SSID.

By adding mobile device QoE data, more detailed policies can be created. This is done by supplying policy engines with more descriptive information as to how each access point is performing and then augmenting the policies to reflect these details. This requires that an API is added to the policy engine that enables it to access the crowd sourced QoE data.

An example of a three tiered network priority list, which has been informed by device perspective network measurements, is illustrated in Table 8.1.2. In this example Tier 1 access points provide better wireless QoE than Tiers 2/3 and Tier 2 access points provide better QoE than Tier3.

Priority Level	**Network**
Priority #1	Tier 1 Home WiFi (BSSID Set)
Priority #2	Tier 2 Home WiFi (BSSID Set)
Priority #3	Tier 3 Home WiFi (BSSID Set)
Priority #4	Tier 1 Free WiFi (BSSID Set)
Priority #5	Tier 2 Free WiFi (BSSID Set)
Priority #6	Tier 3 Free WiFi (BSSID Set)
Priority #7	Home Cellular Networks
Priority #8	Paid Roaming Networks

Table 8.1.2: A sample network priority list that has been augmented with device-side QoE data

The enhanced network priority list shown in Table 8.1.2 ensures that the best current quality access points are used when choices are presented. This is an augmentation of the network priority list shown in Table 8.1.1. Should a Tier 1, Tier 2, and Tier 3 quality home access point all be available at the same time, a connection will be establish with the Tier 1 access point because the network priority list differentiates between access points based on quality and sets priority levels accordingly. This selection of the Tier 1 access point for a connection, instead of the Tier 2 or Tier 3 access points which may share the same SSID, is possible when QoE Tiers are introduced to network priority lists. The expansion of the policy is possible within the current framework of HotSpot2.0 and ANDSF as these standards allow for 250 distinct priority levels[37][38].

However, network priority lists constructed as shown in Table 8.1.2 do not guarantee that a positive consumer experience will result from a data offloading event. The network priority list depicted in Table 8.1.2 shows access points ranked into Tiers based on the network QoE that they are able to deliver. However it is possible that none of the options in the network priority list are able to provide sufficient network QoE to be appropriate offloading candidates. One of the requirements for an offloading event to be perceived as a seamless network switching experience by the mobile device user is that the candidate network for offloading data provide equal or better QoE than the user's current network. As such, more advanced network priority lists utilize additional network QoE information from mobile devices that describes the user's current network QoE. The network priority list indicates which quality Tiers are acceptable for offloading events and which are not. When such a more fine grained approach is utilized it is much more likely that a new connection enforced by a connection manager will provide a seamless user experience for the device user.

A sample of a three tiered network priority list which has been informed by device perspective network measurements to make it clear which quality tiers are acceptable for offloading events is depicted in Table 8.1.3.

Priority Level	**Network**
Priority #1	Tier 1 Home WiFi (BSSID Set) Acceptable – Based on current QoE levels
Priority #2	Tier 2 Home WiFi (BSSID Set) Acceptable – Based on current QoE levels
Priority #3	Tier 3 Home WiFi (BSSID Set) Unacceptable – Based on current QoE levels
Priority #4	Tier 1 Free WiFi (BSSID Set) Acceptable – Based on current QoE levels
Priority #5	Tier 2 Free WiFi (BSSID Set) Unacceptable – Based on current QoE levels
Priority #6	Tier 3 Free WiFi (BSSID Set) Unacceptable – Based on current QoE levels
Priority #7	Home Cellular Networks Acceptable – Based on current QoE levels
Priority #8	Paid Roaming Networks Acceptable – Based on current QoE levels

Table 8.1.3: A sample network priority list that indicates which quality Tiers are appropriate for offloading events

The amount of traffic on cellular networks is growing at roughly 80-100% per year according to Cisco[2]. This is making cellular operators motivated to seek solutions to their growing congestion levels. One of the most promising solutions is WiFi offloading as WiFi networks can be deployed at a fraction of cellular's cost. However, in order for the public to accept the use of WiFi offloading it needs to occur seamlessly. Seamless offloading events can be made possible by incorporating mobile device monitoring software, but device-side QoE information is required to inform connection policy. Specifically the quality of the consumer's current connection, as well as the quality of candidate networks must be monitored, understood, and dynamically updated.

Chapter 9

Conclusion & Future Work

It is critical that wireless service providers continue the emerging operational shift towards using Quality of Experience as a key performance indicator for their networks. Understanding the customer's perspective of what wireless quality is received, by taking direct mobile device measurements, has several near and long term benefits, whereas the traditional approach of only monitoring quality from the network's perspective can lead to misinformed network decisions and investments.

Traditional drive testing to determine what is happening out in the field is expensive and provides quickly outdated information. Moreover user behaviours must be emulated reducing accuracy. A switch to crowdsourcing network QoE from the field using mobile devices can allow portions of drive-testing budget to be reallocated into improved network infrastructure.

Having access to crowd sourced views of network quality, as experienced by actual consumers, helps to ensure that each network investment is effectively applied. Without having access to an abundant source of Quality of Experience information, service providers have higher potential to make misinformed decisions on where they should be improving the network or performing maintenance.

When service providers make decisions motivated by the consumer's perspective of network quality, customer Quality of Experience improvements can arise. QoE information that has been crowdsourced from mobile devices provides a more complete and accurate view of network quality. This helps the operator to focus their efforts on enhancements that will have meaningful impacts. As a result utilizing device-side QoE information leads to having a more satisfied customer base which helps reduce network churn [15].

Looking forward, there are longer-term benefits to making this switch. Cellular and WiFi networks are becoming increasingly interoperable. Several wireless service providers are deploying both technologies. In other cases roaming agreements are being discussed between separate WiFi and Cellular network owners. Coordinating how consumers transition between these two very different network technologies, to ensure a seamless experience, requires a device-side QoE monitoring solution as it is only device-side QoE monitoring clients which have real-time visibility into the quality of all utilized networks.

Due to the inefficiencies of drive-testing it is difficult for SON platforms to gain access to their required levels of field data[39]. Crowdsourcing QoE by monitoring on consumer devices provides a potentially more viable approach to collecting the volumes of on-going field data that is required to effectively inform Self Organizing Network platforms.

It can be concluded that augmenting QoS metrics with QoE data and starting to monitor network performance directly on mobile devices is an important transition for wireless services providers. The augmented view that is achieved by incorporating QoE into network planning and network operations processes leads to decisions that are more likely to have meaningful and positive impact on the quality of the consumer experience.

Incorporating QoE then allows wireless service providers to be more competitive at a lower cost and will ultimately lead to a better wireless experience for everyday consumers who rely on their wireless connectivity for many aspects of their lives.

Device-side QoE measurements are becoming core to building effective and efficient network operations strategies. However it is unlikely that service providers will solely rely on device-side QoE measurements. Drive testing, deep packet inspection, and network probes still have some unique advantages. For example, although expensive, drive testing is quite effective at collecting lots of information about a specific region quickly, whereas crowdsourcing can at times take longer to collect that amount. The advantage to using deep packet inspection and network probes is that these systems see a much higher percentage of network traffic than is achieved with device-side QoE monitoring. Deep packet inspection and network probe system are, as a result, more effective at measuring and predicting levels of network congestion.

Using mobile devices to crowdsource QoE will reduce service provider reliance on drive testing, deep packet inspection, and network probes. As such carrier spending on non-QoE network monitoring is likely to decrease. Ultimately the level of success experienced by platforms for crowdsourcing QoE will depend on the amount that carriers can reduce their spending on these other network monitoring services and platforms. Future work should focus on determining how much carrier spending on other platforms can be reduced by device-side crowdsourcing so that carrier return on investment can be determined.

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