California Public Utilities Commission

Spring 2012
Mobile Broadband Field Testing
Initial Staff Report

BROADBANDUSA
CONNECTING AMERICA'S COMMUNITIES

August 2012

Edmund G. Brown, *Governor*

CALIFORNIA
PUBLIC UTILITIES
COMMISSION

COMMUNICATIONS DIVISION

BROADBAND, POLICY & ANALYSIS BRANCH

Robert Osborn, CPUC
Ken Biba, Co-Founder and CTO, Novarum
Owen Rochte, CPUC
Principal Authors

Michael Morris
Supervisor
VIDEO FRANCHISING AND BROADBAND DEPLOYMENT

Rob Wullenjohn
Program Manager
BROADBAND, POLICY AND ANALYSIS

Michael Amato
Acting Director
COMMUNICATIONS DIVISION

Paul Clanon
Executive Director

Acknowledgments

We would like to thank the following organizations for making this study possible:

- The National Telecommunications and Information Administration (NTIA), who provided the grant money to do this study.
- Ken Biba, Co-founder and Chief Technology Officer of Novarum, for devising the testing methodology and for providing overall guidance on test design and results interpretation.
- The Computer Science and Information Technology program at California State University, Monterey Bay, for designing, building, and supporting the mobile testing applications used for this study.
- The Geographical Information Center at California State University, Chico, and the dedicated field testing team who performed the actual tests.

Table of Contents

Executive Summary

The California Public Utilities Commission (CPUC) is the California recipient of an $8,000,000 State Broadband Data and Development Grant, awarded by the National Telecommunications and Information Administration (NTIA) under the American Recovery and Reinvestment Act ("ARRA"). The Grant funds certain broadband mapping and planning projects through October, 2014. Approximately $1,500,000 of the total grant is for a project to both create a mobile app that can be used by the public to measure and report actual mobile broadband connection quality, and for drive tests to be conducted by the CPUC at six month intervals to measure service quality in urban and rural areas, and on tribal lands within the state. Pursuant to the Grant, the CPUC must deliver a testing summary report for each round of testing. This report is intended to fulfill that requirement.

The purpose of this Report is to present the methods, procedures, results and initial findings associated with the Commission's first semi-annual drive test. In May 2012, the CPUC launched its first drive test to study mobile broadband quality across the state. Testers drove over 35,000 miles to take measurements at 1,200 locations (34% urban, 11% tribal and 55% rural). Since this was the first of a series drive tests to be conducted over several years, it is premature to draw long-term conclusions about any of the four major operators (Verizon, AT&T, T-Mobile and Sprint).

However, preliminary results suggest the following:

- The rollout of Long Term Evolution Networks (LTE)[1] in urban areas was clearly evident and contrasted starkly with the considerably slower throughput in rural and tribal areas.
- Verizon and AT&T covered the most locations and had the highest average throughputs, with Verizon outperforming AT&T at the higher speeds, but AT&T delivering a much wider geographic distribution of mid-range speeds across the 1,200 locations we tested.
- The number of locations meeting the combined 6 megabits per second downstream / 1.5 megabits per second benchmark[2] on mobile was still very limited.

1 Mobile Broadband Testing

Broadband access technologies fall into two categories: wireline and wireless. Wireless broadband access is provided in two forms: fixed and mobile. In California, mobile broadband is provided by cellular phone service providers, also known as "terrestrial mobile wireless carriers." The principal mobile wireless carriers in California are Verizon Wireless, AT&T Mobility, Sprint, and T-Mobile, although there are others that may be available, such as MetroPCS, US Cellular, etc. The tests include areas where carriers

[1] Further analysis is being done to quantify the area and number of households covered by LTE.

[2] FCC 11-161, REPORT AND ORDER AND FURTHER NOTICE OF PROPOSED RULEMAKING, establishes a benchmark of 6 megabits per second downstream and 1.5 upstream for broadband deployments in later years of Connect America Fund Phase II. The same benchmark is used for certain California Advanced Services Fund grant applications.

offer roaming. These carriers offer voice as well as data services, but for this study we only measured mobile broadband data service elements.

As defined by the FCC, mobile service qualifies as “broadband” if the downstream throughput is 768 kilobits per second or higher and upstream throughput is 200 kilobits per second or higher. For this study, we collected measurements even when they fell below this threshold. This included locations in California where no effective service was available for any mobile operator.

Mobile broadband field testing is part of a larger broadband mapping project funded by a grant to the California Public Utilities Commission (CPUC) from the National Telecommunications Information Administration’s (NTIA) State Broadband Data & Development Grant Program. The purpose of this program is to map broadband Internet access in all 50 states to facilitate efforts by the public and policy makers to increase broadband access. The CPUC collects broadband data from providers in California two times a year and provides that data to the NTIA. This data feeds into the National Broadband Map as well as the more feature-rich California Interactive Broadband Map (http://www.broadbandmap.ca.gov).

As part of the mapping project, the CPUC plans to conduct mobile broadband field tests twice a year. In order to do so, the CPUC contracted with California State University, Chico to hire and manage a team of testers to perform speed and availability tests of the four major carriers (Verizon, AT&T, Sprint, and T-Mobile) at 1,200 locations throughout the state. A map of these locations may be found in Appendix C – Test Locations. The breakdown of 1,200 locations was 34% urban, 11% tribal, and 55% rural, based on Census 2010 definitions[3].

We used open source tools for our tests, and tests were performed using both commercially available smartphones and USB modems. The first round of tests ran from May 7, 2012 to June 1, 2012 and covered over 35,000 miles of roads and highways. A follow on subset of the tests were re-run in AT&T LTE coverage areas because the initial testing used non-LTE capable devices. The second round of tests is scheduled for September, 2012.

Our results from the first drive tests are summarized in this report and will also be incorporated as subsequent layers in the California Interactive Broadband Map. The CPUC also plans to make the raw data from these tests available to the public online.

2 Mobile Test Application

The CPUC contracted with California State University, Monterey Bay to develop an open source mobile testing application that collects mobile broadband measurements in real-world conditions. This means testing a number of different traffic types and testing them on servers physically located on opposite coasts of the United States in order to take into account each carrier’s varying backhaul networks.

[3] The “urban” category includes both “urbanized areas” (UAs) of 50,000 or more people and “urban clusters” (UCs) of at least 2,500 and less than 50,000 people. “Rural” encompasses all population, housing, and territory not included within an urban area. The “tribal” category is the same as referenced in Appendix D – Test Routes.

The application uses iPerf[4], which is an open source network testing tool that creates TCP (Transmission Control Protocol, which is used to upload and download files and E-mail), and UDP (User Datagram Protocol, which is used for real-time streaming applications like streaming video and Voice over Internet Protocol, or VoIP) data streams and measures the performance of each. CSU Monterey Bay developed a Java user interface that runs on both Android and the netbook version of Windows operating systems. The data created by the test is uploaded by the tester to a cloud-based database server. Details of the record format of the test results are included in Appendix F – Data Record Format.

Testers ran the testing application in a stationary environment inside an automobile. Each tester was equipped with a netbook, an external GPS antenna, and a smartphone and USB modem for each of the four carriers. Tests were done sequentially, first by getting a valid GPS reading from the GPS receiver connected to a netbook, then by running the tests using the data cards for each carrier. Finally, the smart phone tests were performed. Testers uploaded the results at each location to the cloud-based database server. In cases where the upload failed at the tested location (generally due to inadequate speeds), the test results remained on the netbook or smart phone until the tester was able to find a location where sufficient network coverage allowed the data to be uploaded.

In cases where there was no signal whatsoever, that result was also stored on the netbook or smartphone for later upload. The testing application ran 6 tests measuring TCP and UDP. The tool also ran ping tests to measure end-to-end latency. At the end of testing, we had close to 1,200 results each for the netbook and the smartphone for each of the four carriers. Details on the test sequence are included in Appendix A – Test Application.

At a subset of locations, testers ran a separate test using an open source tool called “Glasnost” in order to measure the presence of carrier rate limiting or “traffic shaping.”

This paper focuses exclusively on TCP results for netbook and smartphones using both West and East coast servers. Analysis of the UDP test results, as well as those for Glasnost, will be addressed in a later Report.

2.1 Limitations of Mobile Testing

The following caveats should be taken into consideration for any mobile testing, including the testing summarized in this report. Radio communications is not an exact science. Planning and operating networks takes into account the probability of a user’s location and the forecasting of aggregate demand for a cell site, both of which may vary, depending the time of day, location, and topography of the test location, network loading and congestion, and device hardware and software limitations. In addition, test results show end user experience at a specific time and specific location and do not necessarily indicate that an end user experience at one location will be similar to that of a nearby location.

[4] See Appendix A – Test Application for how it was used in the testing application. Information on iPerf may be found at: http://code.google.com/p/iperf/

3 Preliminary Analysis

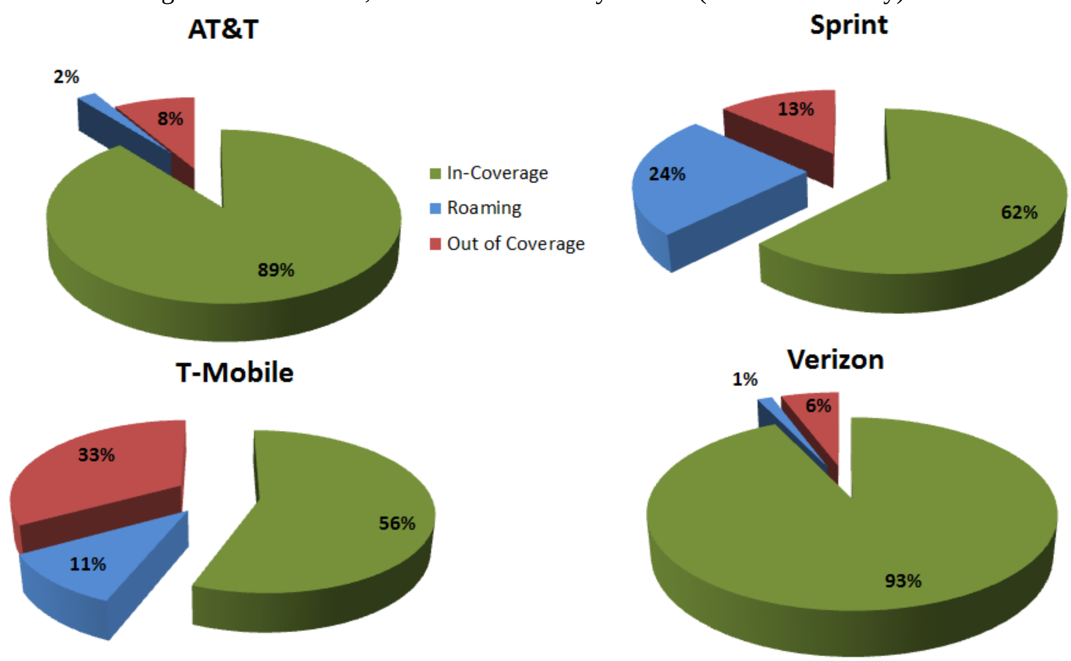
The following results are preliminary since they were based on a single round of tests. As we complete subsequent rounds of testing at the same locations (the next round is scheduled for September 2012), we will be able to draw more conclusions about each carrier's network in terms of changes in its coverage and performance over time. Details on analyzing the data are listed in Appendix G – Data Processing.

3.1 Mobile Coverage

The following chart shows a breakdown of each carrier's coverage based on all 1,200 locations tested. Test locations falling outside a carrier's coverage area[5] that showed a positive TCP result were considered to be roaming locations. As stated previously, more than half of the testing locations fell within rural areas. In terms of number of tested locations with valid results[6], Verizon and AT&T had the largest network footprint. T-Mobile appeared to have the least coverage of the four, but we will see later that in urban areas that T-Mobile did cover, they managed to deliver significant throughput in many locations.

The chart below shows results for downstream only. The results for upstream were consistent with those for downstream.

Chart 1: Coverage Breakdown of 1,200 Test Locations by Carrier (Downstream only)



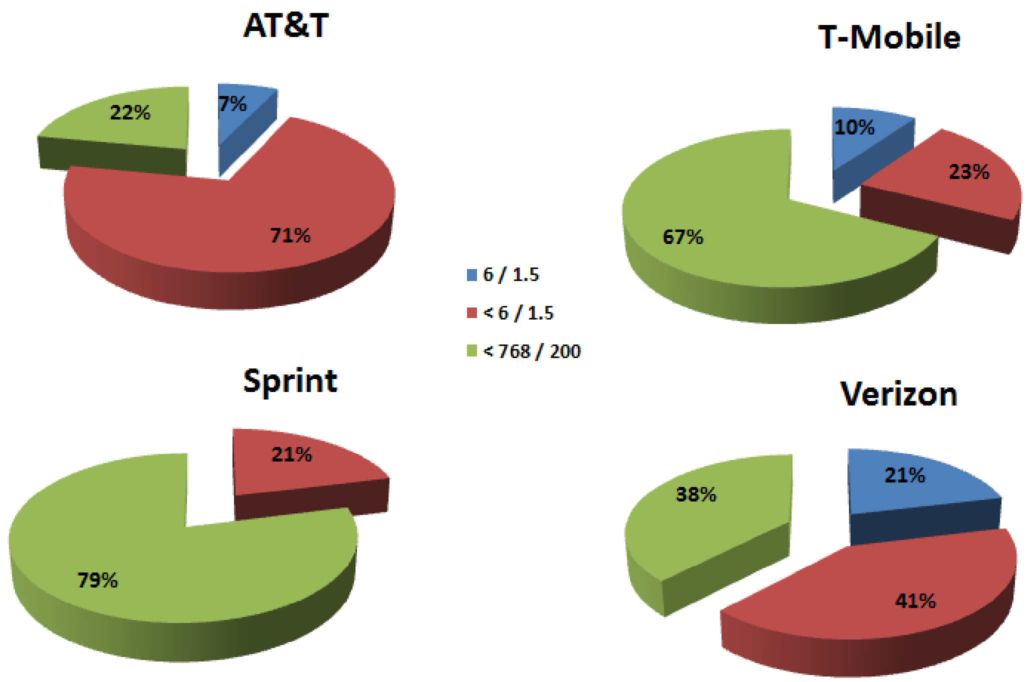
[5] Each carrier's coverage area was determined from mobile broadband availability data that each carrier submitted to the CPUC under the NTIA's State Broadband Data and Development Grant Program.

[6] A result was considered valid if a single TCP test resulted in a positive value or zero rather than one of the Abnormal Value Descriptions listed in Appendix F – Data Record Format.

3.2 Locations Meeting the 6 Mb/s / 1.5 Mb/s Threshold

The calculations below included only locations that fell within each carrier's coverage or roaming area, as described in Section 3.2.

Chart 2: Locations Meeting ≥ 6 Mb/s Downstream and ≥ 1.5 Mb/s Upstream Threshold



Among the four providers tested, only AT&T and Verizon have deployed LTE (Long Term Evolution) networks in California. T-Mobile, which has held off on deploying LTE, had more locations meeting the 6 Mb/s down, 1.5 Mb/s up threshold than AT&T. One possible explanation is that, while T-Mobile lacks the breadth of coverage of AT&T or Verizon, they have upgraded many of their urban locations to high speed HSPA+, which does very well at achieving higher speed throughputs without having to upgrade to LTE. Sprint has not yet launched LTE in California, and, because it is a CDMA network instead of a GSM network, HSPA+ is not an option because it is not a CDMA technology. Sprint does sometimes use WiMAX, but results showed few examples of this. Most of their network appeared to support primarily 3rd Generation network speeds, and until they launch LTE, it will probably be difficult to reach the 6 Mb/s down, 1.5 Mb/s up threshold.

We will see in Section 3.6 that the stark disparity between urban versus rural and tribal locations suggests that mobile broadband is still not a practical substitute for fixed broadband outside urban areas.

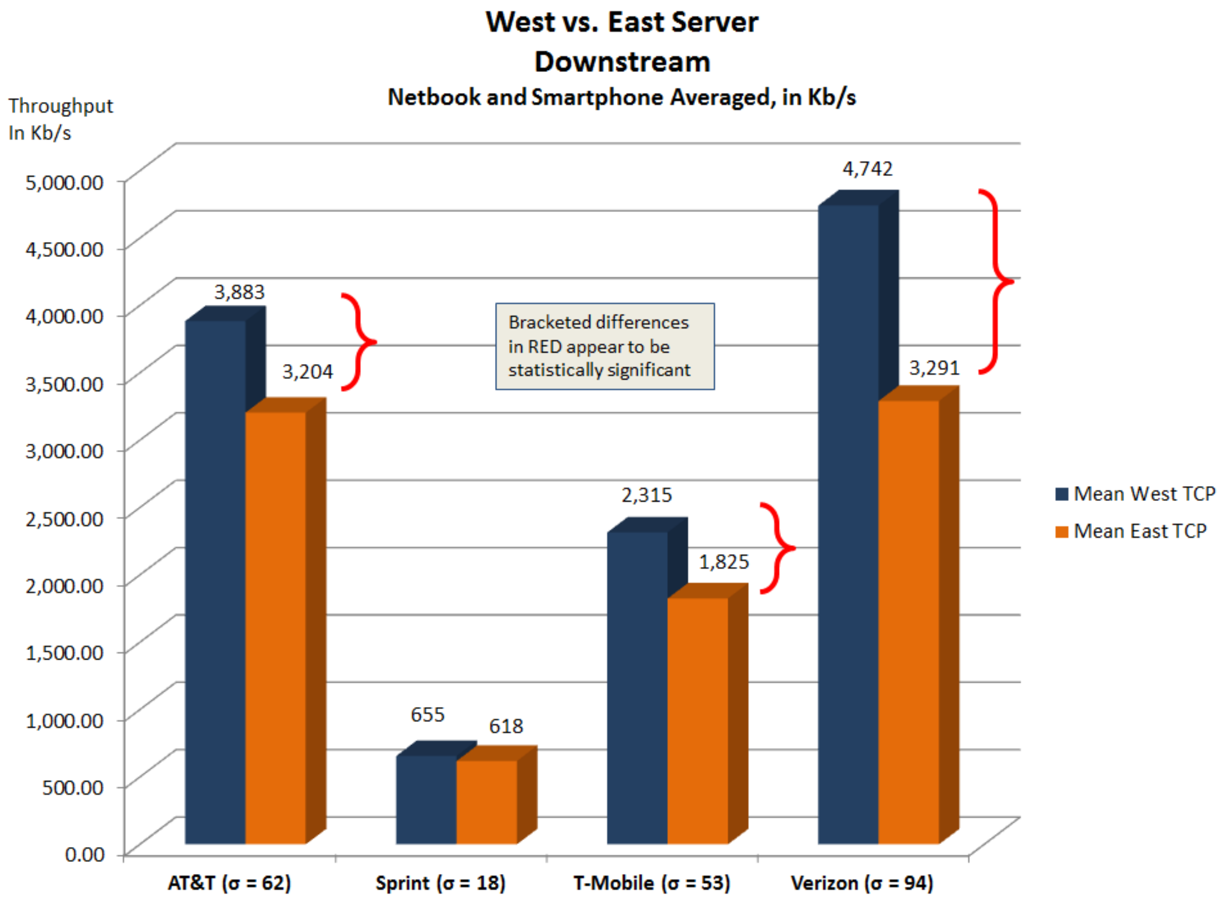
3.3 West versus East Server – Understanding Backhaul Differences

The mobile testing application ran a series of tests using servers located on opposite coasts of the United States. One Amazon server was located in San Francisco, and the other in Virginia. The purpose was to understand how each carrier performed given different backhaul requirements.

The "backhaul" is the part of the network that connects base stations to routers and switches, and then routers and switches to other routers and switches. Each carrier has a unique backhaul network, and neither we, nor the end user, know how it is designed. Nor should we care. However, it is possible that one carrier's backhaul network, given its physical proximity to the mobile tester, could have an advantage over another carrier. By requiring our test to connect to both coasts of the United States, we wanted to see how performance differed.

The testing application ran a TCP upload for 10 seconds, then a TCP download for 10 seconds. It did this twice using the West coast server. The application then ran the same tests again twice for the East server. The results for the downstream throughput are summarized below. Here, netbook and smartphone results are averaged. Results for upstream were less dramatic but they mirrored those of the downstream. The calculations below included only locations that fell within each carrier's coverage and roaming areas, as described in Section 3.2.

Chart 3: West vs. East Server Throughput Differences (Downstream only)

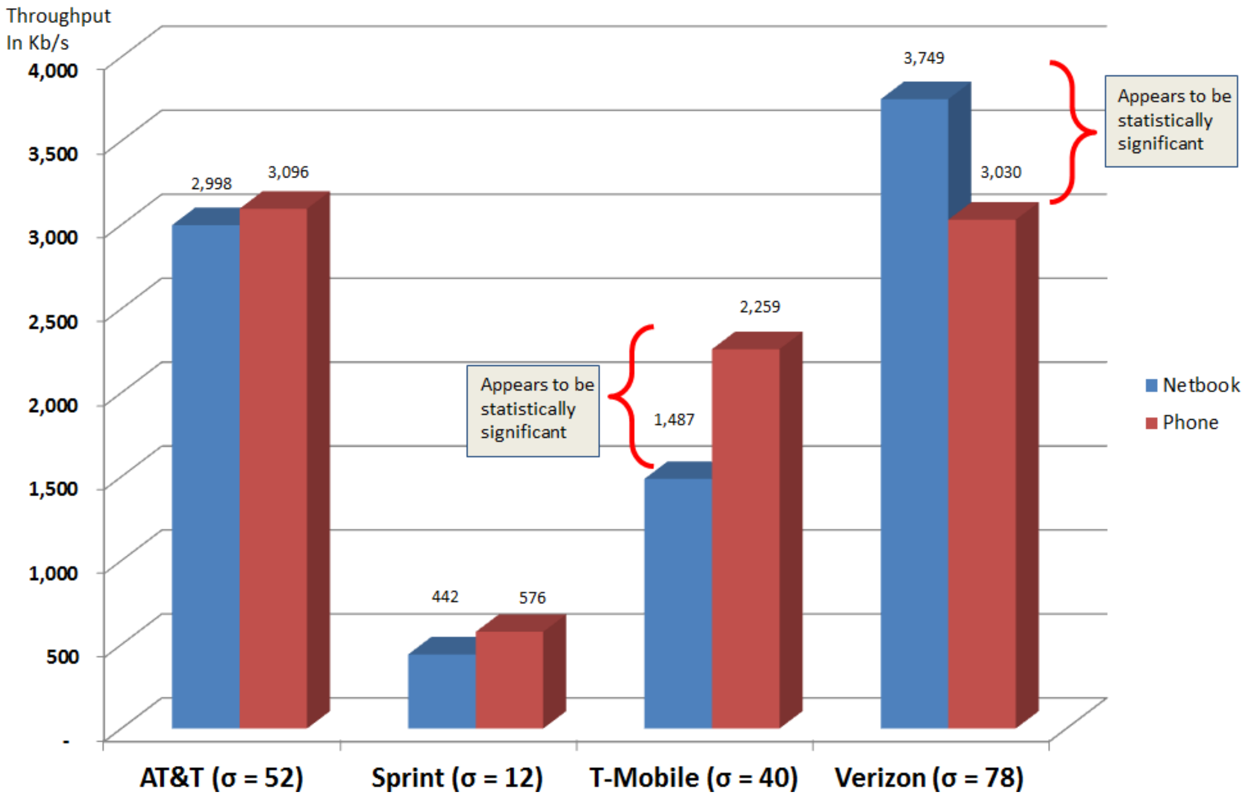


As shown in the results above, we detected no statistically significant difference in throughput for Sprint using West and East coast servers. However, we did detect differences for AT&T, T-Mobile, and Verizon. On first glance, it might appear that the difference was attributable to network design, but it is important to note too, as we will see later, that the mean and median throughputs for AT&T and Verizon were significantly higher than the others. It may be the case that, as throughput increases, the limiting factor in end user performance is the backhaul network rather than the radio access network.

3.4 Netbook versus Smartphone – Understanding Device Differences

Comparing results of 1,200 tests for the netbook, which connected to the internet via carrier-provided USB modem, with those of the smartphone, we noticed slight performance differences. The calculations below included only locations that fell within each carrier's coverage and roaming areas, as described in Section 3.2.

Chart 4: Netbook (USB Modem) vs. Smartphone (Downstream only, West & East server results averaged)



Of the four carriers, there appeared to be a statistically significant difference in netbook versus smartphone performance for T-Mobile and Verizon downstream. For upstream, the picture was slightly different with AT&T (netbook, 1,497 Mb/s vs. smartphone, 1,083 Mb/s, σ = 32) and Verizon (netbook, 2,602 Mb/s vs. smartphone, 2,173 Mb/s, σ = 54) appearing to show statistically significant performance differences.

3.5 Urban, Rural, and Tribal Throughput Averages

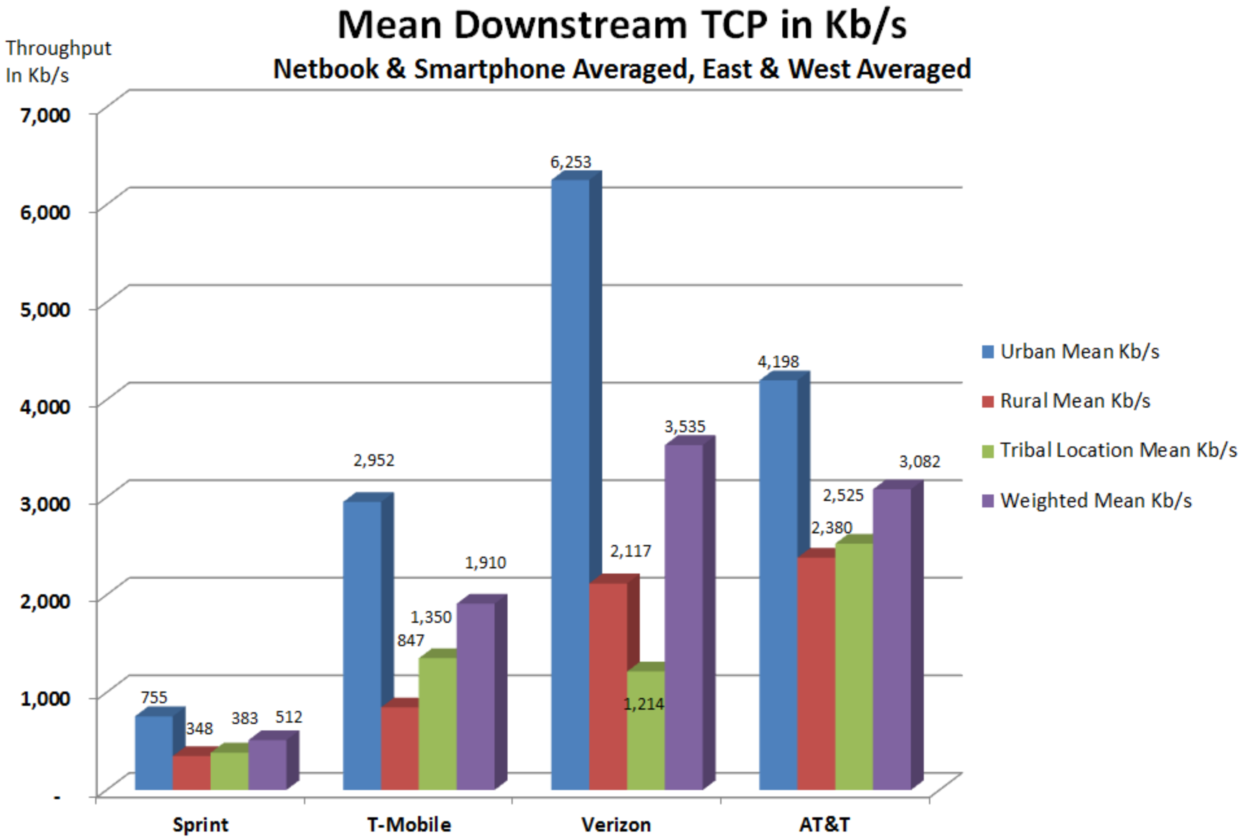
When comparing average throughput by location type, we found it was important to look at both the mean (statistical average) and median (middle point) to see how the carriers differed. As shown in the chart below, there appeared to be significant throughput differences between urban locations compared to rural and tribal locations. The definitions for "urban" and "rural" in this analysis relied on the Census 2010 definition[7] rather than the methodology used for location selection reference in Appendix D – Test Routes. The difference between urban versus rural and tribal was exacerbated by the fact that T-Mobile, Verizon, and AT&T have upgraded their networks to support higher throughput primarily in urban locations.

[7] See footnote 3 in Section 1

Verizon and AT&T appeared to be close in terms of overall ***mean*** downstream throughput (purple bar). But, as shown in the ***median*** downstream in Chart 6, Verizon's overall mean is influenced significantly by its LTE deployment in non-rural locations, whereas AT&T appears to have better overall throughput across more locations.

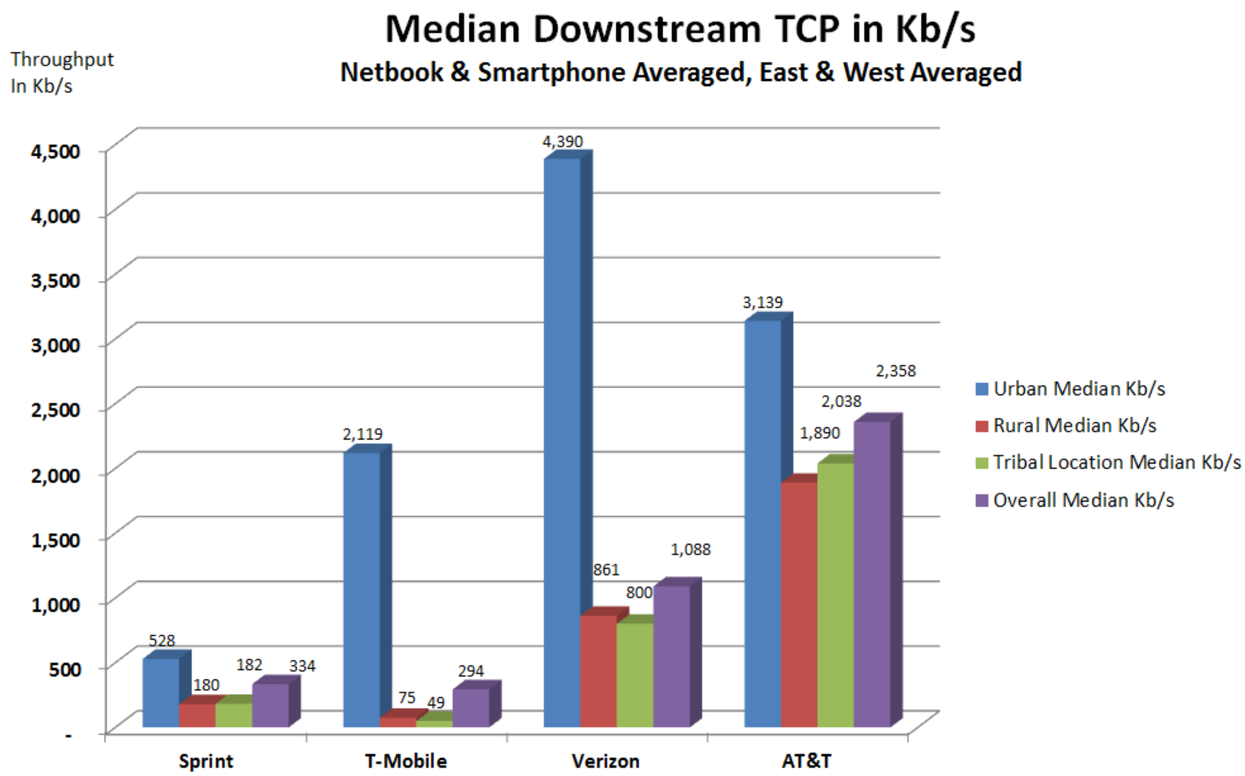
The mean and median calculations below included only locations that fell within each carrier's coverage and roaming areas, as described in Section 3.2.

Chart 5: Mean Downstream Throughput by Location Type



As shown in Chart 6 below, the median throughput showed a very different picture. Verizon's median throughput (blue bar) was high in urban locations, but its overall median (purple bar) was less than half that of AT&T's due to AT&T's strength in the middle range for rural and tribal locations.

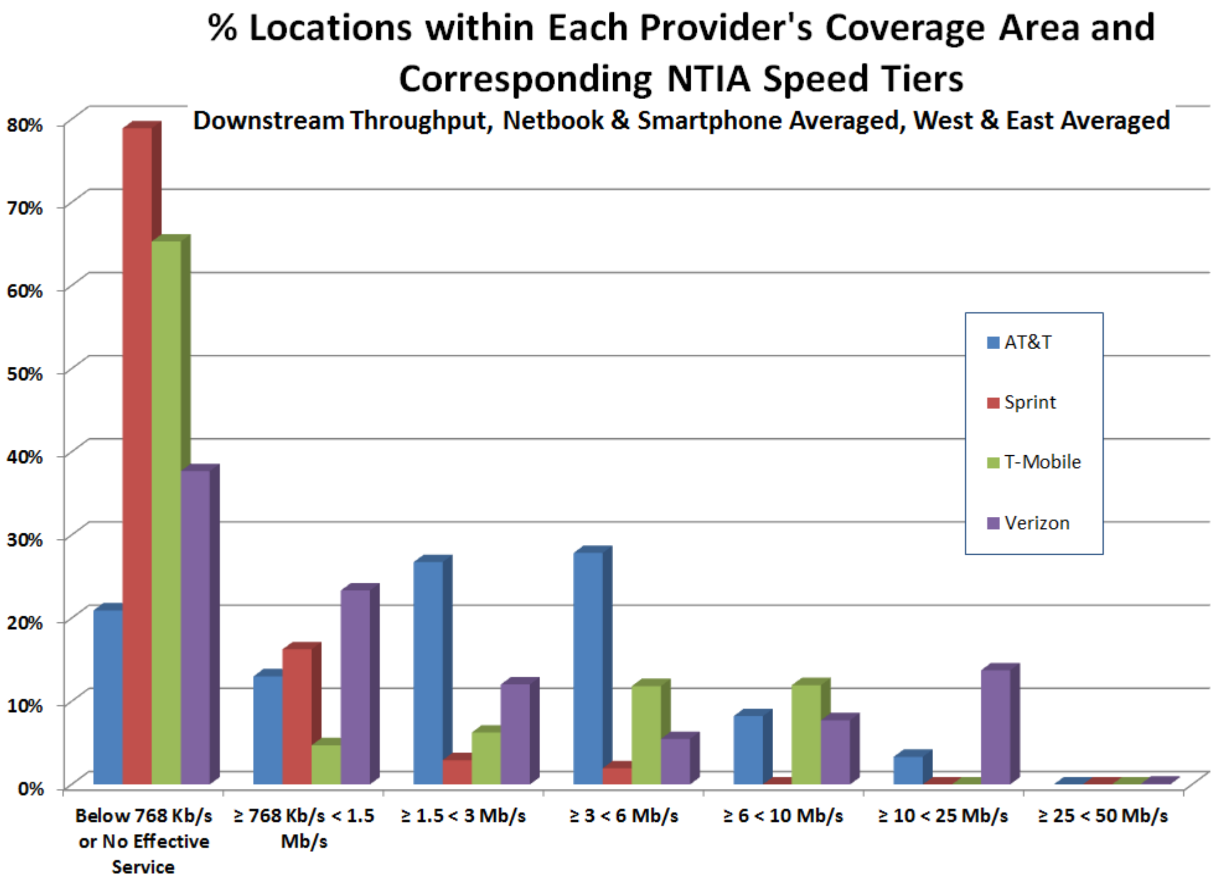
Chart 6: Median Downstream Throughput by Location Type



3.6 Distribution of Speed Tiers and Percent of Locations

To better understand the breadth and distribution of throughput over all of the locations where carriers provided coverage, we grouped downstream throughput into speed tiers used by the National Telecommunications and Information Administration (NTIA) for the National Broadband Map. The CPUC's California Interactive Broadband Map also relies on these speed tiers. The calculations below included only locations that fell within each carrier's coverage and roaming areas, as described in Section 3.2.

Chart 7: Histogram of Speeds by Carrier



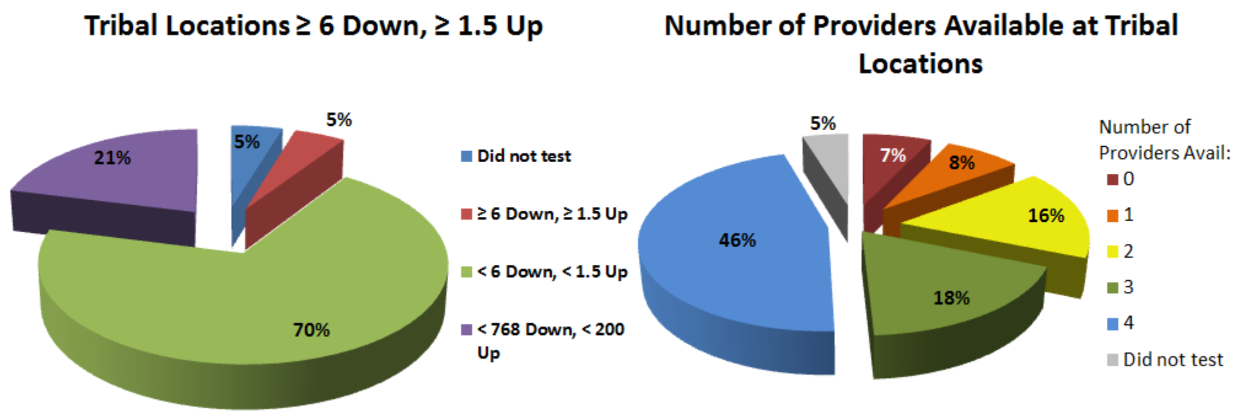
As mentioned in Section 3.3, Sprint has yet to launch LTE, and this was reflected in the great majority of locations tested using Sprint devices falling below downstream throughput of 1.5 Mb/s. At the other end of the spectrum, over 20% of the locations within Verizon's coverage area showed that carrier's ability to deliver downstream throughput greater than or equal to 6 Mb/s, while that for AT&T was only 10% of covered locations. Where AT&T showed particular strength was in the mid-range – greater than or equal to 1.5 Mb/s. Of the locations within AT&T's coverage area, which, as we saw in Section 3.2 was roughly the same coverage percentage as Verizon's, 66% showed downstream speeds greater than or equal to 1.5 Mb/s, whereas for Verizon, it was 40%, meaning that 60% of the locations for Verizon showed less than 1.5 Mb/s downstream.

3.7 Tribal Areas –Locations and Number of Carriers

Tribal locations were tested at the entrance or near the entrance of the property. Because of this, the user experience was not necessarily the same as what might be found inside the tribal areas. Of the 128 tribal locations planned, 5% were not tested because of geographic impediments. Using the same method in Section 3.3, only 5% of the locations tested met the 6 Mb/s down, 1.5 Mb/s up threshold, with more than

2/3 coming in lower than the threshold and 1/5 qualifying as un-served, which is defined as less than 768 Kb/s down and 200 Kb/s up. The number of carriers available at each location is shown in the graph on the right. Test results for each of the 128 Tribal locations are included in Appendix H – Test Results by Tribal Location.

Chart 8: Tribal Locations Meeting Combined ≥ 6 Mb/s Downstream and ≥ 1.5 Mb/s Upstream Threshold



4 Conclusion

As stated in the Executive Summary, these results were only the first in a series drive tests to be conducted over several years, so it is premature to draw any long-term conclusions. However, it seems clear at this early stage that we can conclude, 1. The large gap in throughput between non-rural versus rural and tribal locations (Section 3.6) demonstrates that the rollout of Long Term Evolution Networks (LTE) has been focused primarily in higher density, urban areas. We expect this gap to narrow in the coming years as LTE becomes the standard for all mobile carriers. 2. Based on results shown in Sections 3.2, 3.6, and 3.7, Verizon and AT&T covered the most locations and provided the highest average throughputs, with Verizon outperforming AT&T at the higher speeds, but AT&T delivering a much wider geographic distribution of mid-range speeds across the 1,200 locations tested. 3. The number of locations meeting the combined 6 Mb/s per second down and 1.5 Mb/s up threshold were still limited. Section 3.3 shows the disparity among mobile carriers in the number of sites meeting the threshold, and the disparity between non-rural (urban) compared to rural and tribal locations supported this conclusion.

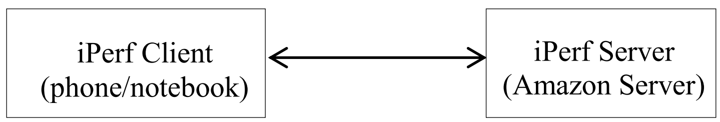
Appendix A – Test Application

TESTING APPLICATION IMPLEMENTATION: IPERF FOR TCP AND UDP MEASUREMENTS

The user interface is written in Java and runs on both the Android and Windows operating systems.

IPerf is a software tool to measure the network throughput and performance. It is developed using a client-server model as in Figure 1. The client software in a client device requests an either TCP or UDP data connection to the server side software. After the connection is established, the tool measures the throughput between the two ends. In the project, we set up the iPerf server software on two Amazon Linux machines at the East and West coasts, respectively.

Figure 1



In the project, the iPerf tool measures TCP upload bandwidth, TCP download bandwidth, UDP jitter, and UDP datagram loss rate. For the TCP upload, the client software makes a connection to the server side software and sends data streams to the server side for 10 seconds. After that, the server side software sends data streams from the server to the client for download bandwidth. Note that the original iPerf tool uses two separate connections for the upload and download measurements, respectively. But because many client devices and network operators do not allow for the server side software to make a new connection with the client device, we keep the connection used for the upload measurement and use it for the download measurement as well. By this technique, we can avoid the firewall blocking at the client device. As other measurement parameters, the tool uses 64.0 Kbytes window size (-w 64k), which is the amount of data that can be buffered during a connection without a validation from the receiver, and executes four threads concurrently (-P 4) at both sides, which can increase the data volumes to be exchanged between the client and server.

For the UDP jitter and datagram loss rate measurement, the iPerf sends data to the client side for either one or five seconds. Note that there's no data streams from the server to the client in the UDP measurement. As other parameters, we use 220K buffer length (-l 220) and 88K bits/sec bandwidth (-b 88k) to send data. The following shows all measurements in a single testing:

- TCP upload (10 seconds) and download (10 seconds) measurement to the West server (twice)
- TCP upload (10 seconds) and download (10 seconds) measurement to the East server (twice)
- UDP jitter and datagram loss (1 second) to the West server (three times)
- UDP jitter and datagram loss (1 second) to the East server (three times)
- UDP jitter and datagram loss (5 seconds) to the West server (one time)
- UDP jitter and datagram loss (5 seconds) to the East server (one time)

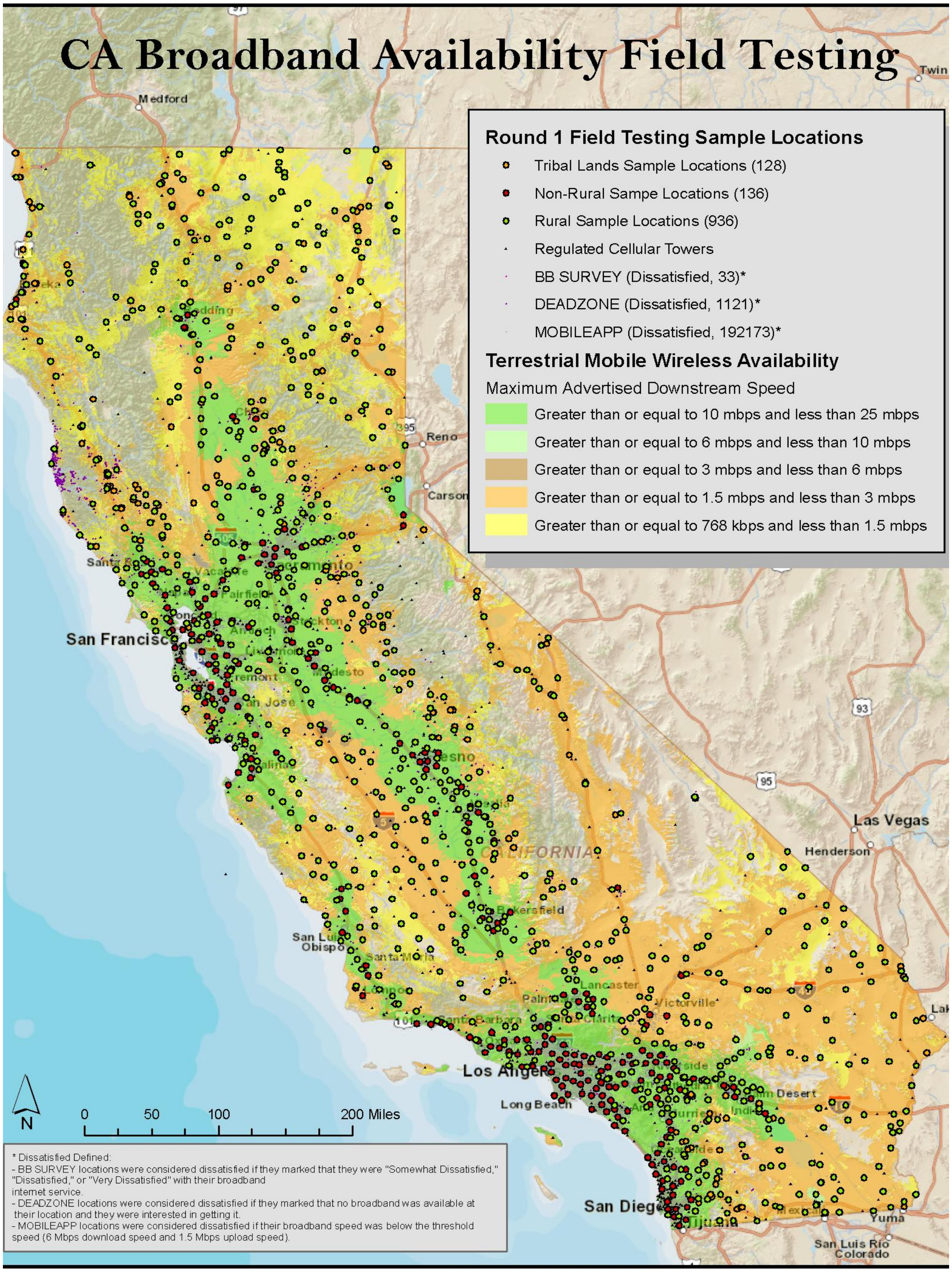
Test	Explanation
Minimum, maximum, and average packet Round Trip Time (RTT); packet loss rate during the RTT	To understand how long it takes to send & receive data and amount of data that can be lost during transmission
User Datagram Protocol (UDP) jitter & loss	Both of these measurements assess the quality of UDP. UDP is the network protocol used for streaming media such as video and voice over internet protocol (VoIP). Jitter measures the degree to which the UDP signal becomes distorted during transmission. Loss is the amount of message that gets lost during transmission.
Transmission Control Protocol (TCP), upstream and downstream throughputs	TCP is the network protocol used for E-mail. Expressed in kilobits per second, these measurements tell how quickly the user can send (upstream) and receive (downstream) TCP messages.

Appendix B – Test Equipment

EQUIPMENT USED FOR MOBILE TESTING

Equipment	Type	Technology	Quantity
Asus Netbook	Netbook	Not Applicable	8
BU-353 GPS	GPS receiver	Not Applicable	8
AT&T HTC ONE X Android	Smart phone	LTE, HSPA+, UMTS	8
AT&T USB Momentum	USB Modem	LTE, HSPA+, UMTS	8
Sprint HTC EVO 4G Android	Smart phone	EVO, 1XRTT	8
Sprint Sierra Wireless 250U USB	USB Modem	EVO, 1XRTT	8
T-Mobile Samsung Galaxy SII Android	Smart phone	HSPA+, UMTS	8
T-Mobile Jet 2.0 4G Laptop Stick	USB Modem	HSPA+, UMTS	8
Verizon Droid Charge 4G LTE Android	Smart phone	LTE, EVO, 1XRTT	8
Verizon Pantech USB Modem UML290	USB Modem	LTE, EVO, 1XRTT	8

Appendix C - Test Locations



Appendix D – Test Routes

Routes were generated using ESRI's Network Analyst extension. Test locations were divided between Chico and Northridge testers based on closest location, then adjusted to make distribution equal between the two groups of testers (600 points to Chico, 600 to Northridge). Then, locations were divided into logical zones based on regional geographic considerations. Routes were designed to minimize drive time given the constraints of an 8-hour work day, idle time due to testing, a lunch break, and returning home for weekends. The Northridge routes had the additional constraint of one vehicle needing to return home each day. Routes from each zone were divided between each driver in an effort to equalize total drive time for each driver.

TRIBAL SAMPLING

Tribal Lands sampling locations were defined as a point along the California Road Network, as classified in the 2010 census road inventory, which fall within Tribal Lands. One sample location was randomly generated for each Tribal Land containing features from the California Road Network using spatial analysis software. Each point represents a location currently known to have mobile wireless broadband coverage. A total of 128 sampling locations were generated for Tribal Lands.

NON-RURAL SAMPLING:

Non-Rural sampling locations were defined as a point along the California Road Network, excluding MTFCC Class Code S1400, as classified in the 2010 census road inventory. All points in this category fell within Non-Rural Lands, and outside any Tribal Lands. All sampling locations were randomly generated at a minimum distance of five miles using spatial analysis software and represented a location known to have mobile wireless broadband coverage. A total of 136 sampling locations were generated for Non-Rural Lands.

RURAL SAMPLING:

Rural sampling locations were defined as a point along the California Road Network as classified in the 2010 census road inventory. Rural points were first allocated to 2010 Census Designated Places (2010 CDP) that were outside any Non-Rural and Tribal Lands and were randomly generated at a minimum distance of five miles using spatial analysis software. Remaining sampling locations were allocated to Rural areas not within any other lands (Tribal, Non-Rural, and CDPs) and were randomly generated at a minimum distance of ten miles using spatial analysis software in areas where no sampling locations existed from the initial Rural distribution. All sampling locations represented a location known to have mobile wireless broadband coverage. A total of 936 sampling locations were generated for Rural Lands.

Notes: 1. Minimum distances were determined by the largest distance (tested in five mile increments) the software allowed for the amount of points within the sampling area being calculated. 2. California Roads Network: Sampling locations were controlled to highway ramp (S1630), secondary roads (S1200), and local neighborhood road/rural road/city street (S1400), as classified in the 2010 census road inventory. 3. All road classes were weighted equally in the distribution process.

Appendix E - Operator Technologies & Frequencies

Carrier	2G MHz	3G MHz	4G MHz	3G Technology	4G Technology
AT&T	850, 1900	850, 1900	700, 1700/2100	GSM/HSPA+	LTE (FDD)
Sprint	1900	1900	2500, 1900 PCS, 800	CDMA/EV-DO	WiMAX (Clearwire) LTE (Sprint, FDD; Clearwire, TDD)
T-Mobile USA	1900	1700/2100, 1900	1700/2100	GSM/HSPA+	LTE (FDD) - launch in 2013
Verizon	800, 1900	800, 1900	700	CDMA/EV-DO	LTE (FDD)

Notes:

1. All frequencies listed are in megahertz (MHz)
2. Paired frequencies are listed with "/" where the first number represents the uplink frequency, and the second the downlink frequency

Acronyms

GSM	Global System (for) Mobile (Communications)
HSPA+	High Speed Packet Access Plus
CDMA	Code Division Multiple Access
LTE	Long Term Evolution
FDD	Frequency Division Duplex
TDD	Time Division Duplex

LTE DEPLOYMENT STATUS IN CALIFORNIA

As of the writing of this paper, only two of the four major carriers have deployed LTE in California: Verizon and AT&T. Sprint has not yet announced plans to launch LTE in California. T-Mobile has said it plans to install "LTE Advanced" Release 10 equipment in 37,000 base station sites and launch in "18 or 19 of the top 25 markets in 2013." Some of those markets may be in California.

VERIZON

Verizon has deployed LTE in 15 markets: Bakersfield, Fresno, Los Angeles, Modesto, Oakland, Sacramento, Salinas/Monterey/Seaside, San Diego, San Francisco, San Jose, San Luis Obispo, Santa Barbara, Stockton, Visalia/Porterville, Yuba City/Marysville.

AT&T

AT&T has deployed LTE in San Francisco, Oakland/East Bay, San Jose/South Bay, Los Angeles, and San Diego.

Appendix F – Data Record Format

DATA FIELD DESCRIPTION		
Column Name	**Example(s)**	**Description**
Tester	3	ID number of a tester who conducted the testing
Location ID	1020	Location number assigned by GIC
Date	5/30/2012	Test starting date. We use the "05/30/2012" date format.
Time	15:48:08	Test starting date.
Provider	Verizon, AT&T, T-Mobile, Sprint	Network provider.
Operator	Verizon, AT&T, T-Mobile, Sprint	Network operator.
Network	EHRPD, LTE, UMTS, HSDPA, etc.	A specific network type. At the moment, the information is available at the phone testing only. Netbook testing is always NA.
Latitude	37.323429	
Longitude	-122.036079	
Device ID	WBBDTest1 (netbook), 99000024385563 (phone)	A unique number of a testing device.
Client Type	Phone or Netbook	
ePktMin	154.062	Minimum RTT (Round Trip Time) of packets to the East server (in ms)
ePktMax	270.189	Maximum RTT (Round Trip Time) of packets to the East server (in ms)
ePktAvg	184.525	Average RTT (Round Trip Time) of packets to the East server (in ms)
ePktLoss	0	Packet loss rate (%) during the RTT test to the East server.
wPktMin	83.702	Minimum RTT (Round Trip Time) of packets to the West server (in ms)
wPktMax	218.218	Maximum RTT (Round Trip Time) of packets to the West server (in ms)
wPktAvg	118.374	Average RTT (Round Trip Time) of packets to the West server (in ms)
wPktLoss	0	Packet loss rate (%) during the RTT test to the West server.
eUDP Jitter1	14.606	Jitter for the first UDP measurement to the East server (in ms). There are total four UDP jitter measurements to the East server such as eUDP Jitter2, eUDP Jitter 3, and eUDP Jitter 4.
eUDP Loss1	0	UDP datagram loss rate for the first UDP measurement to the East server (in %). There are total four UDP data gram loss rate for each measurement such as eUDP Loss 2, eUDP Loss 3, and eUDP Loss 4.
eUDP Period1	1	UDP test period for the first UDP measurement to the East server (either 1 sec or 5 sec). There are total four UDP measurements to the East server such as eUDP Period 2, eUDP Period 3, and eUDP Period 4.

wUDP Jitter1	17.412	Jitter for the first UDP measurement to the West server (in ms). There are total four UDP jitter measurements to the West server such as wUDP Jitter2, wUDP Jitter 3, and wUDP Jitter 4.
wUDP Loss1	0	UDP datagram loss rate for the first UDP measurement to the West server (in %). There are total four UDP data gram loss rate for each measurement such as wUDP Loss 2, wUDP Loss 3, and wUDP Loss 4.
wUDP Period1	1	UDP test period for the first UDP measurement to the West server (either 1 sec or 5 sec). There are total four UDP measurements to the West server such as wUDP Period 2, wUDP Period 3, and wUDP Period 4.
wTCP_UP1	478.9	TCP upload speed to the West server at the first measurement. (in kbps). Technically, our tool has four threads to collect the TCP upload and download speed. So, the values in TCP upload and download fields are the addition of the four threads.
wTCP_DOWN1	1156.3	TCP download speed to the West server at the first measurement. (in kbps).
wTCP_UP2	567.8	TCP upload speed to the West server at the second measurement. (in kbps).
wTCP_DOWN2	889.1	TCP download speed to the West server at the second measurement. (in kbps).
eTCP_UP1	346.2	TCP upload speed to the East server at the first measurement. (in kbps).
eTCP_DOWN1	914.8	TCP download speed to the East server at the first measurement. (in kbps).
eTCP_UP2	278.5	TCP upload speed to the East server at the second measurement. (in kbps).
eTCP_DOWN2	448.2	TCP download speed to the East server at the second measurement. (in kbps).

ABNORMAL VALUE DESCRIPTION

Value	Description
no effective service	If a test failed the connectivity test (ping to our west server for four seconds), our post-processing script generates "no effective service".
ERROR: QUIT BY USER	A user quitted the testing. So, the raw should be removed for the data analysis.
NA at ePktMin, ePktMax, ePktAvg, ePktLoss, wPktMin, wPktMax, wPktAvg, wPktLoss	The testing result didn't provide the corresponding round trip time (RTT) value. In many cases, it means that the ping command had bad connections (or 100% loss.)
timeout	Our measurement tool spends 120 seconds to measure a TCP upload and download to a server. If our tool fails to get the TCP testing result within 120 seconds, it generates "timeout", which usually occurs in a weak signal location.

connect_error1	While a TCP testing, our measure tool fails to finish the TCP testing with an internal software error message "write1 failed". There are many reasons of this error. -- We are investigating the exact reason. Weak signal could be one of the reasons.
connect_error2	While a TCP testing, our measure tool fails to finish the TCP testing with an internal software error message "write2 failed". There are many reasons of this error. -- We are investigating the exact reason. Weak signal could be one of the reasons.
connect_error3	While a TCP testing, our measure tool fails to finish the TCP testing with an internal software error message "connect failed". There are many reasons of this error. -- We are investigating the exact reason. Weak signal could be one of the reasons.

Appendix G – Data Processing

In order to produce the analysis in this Report, the data were processed as follows:

- **Averaging two devices (data card and smartphone results):** in the event either device's TCP test results showed one of the Abnormal Value Descriptions listed in Appendix F – Data Record Format, while the other device yielded numerical TCP results, the Abnormal Value Description result was treated as a zero. This meant that the average throughput for a location where one device produced a result while the other did not was effectively half of that of the device that successfully delivered a throughput greater than zero. Example: USB modem throughput was 14 Mb/s, while smartphone result was "no effective service." The throughput for that location for that carrier was 7 Mb/s.
- **Elimination of duplicate "no effective service," "timeout," etc. results for a single device:** in cases where initial ping test failed, testers were instructed to run the test again up to 3 times. In cases where the ping test failed all 3 times, the results would show one or several of the Abnormal Value Descriptions listed in Appendix F – Data Record Format for all of the tests. In this case, the result for that testing location was "no effective service." In the event one of the ping tests succeeded, the TCP tests results were used and the other failed ping test results were excluded from the analysis. If some or all of the TCP tests for a location with a successful ping test showed one or several of the Abnormal Value Descriptions, the TCP results with those Abnormal Value Descriptions were treated as zero Kb/s throughput, and were included in the calculations used for this analysis.
- **GPS coordinates normalized to average:** tests were intended to be conducted for all four carriers at the exact same location. Due to minor differences in GPS readings as well as practical problems of testers sometimes being unable to conduct all tests as the exact same location due to local conditions, GPS coordinates for all tests performed at each location were averaged to a single set of LAT / LONG coordinates.
- **No GPS signal:** in cases where no GPS data was collected due to the inability of the phone to register a GPS signal, the normalized GPS coordinate was assigned to the test result based on the location ID.
- **Carrier information missing:** the test automatically recorded Provider as well as Operator identification information from the carrier's network. In cases where both Provider and Operator fields were blank, we cross referenced the unique device ID to the carrier in order to determine the correct Provider field entry.
- **Location ID entered manually by tester:** while each tester used a checklist to monitor which sites had been tested, in some cases testers entered an incorrect location ID. To correct for this, we looked at the GPS coordinates of any duplicate location IDs from different testers and assigned the correct location ID based on the LAT / LONG coordinates from the device. In very few cases, there was an incorrect location ID with no GPS coordinate, in which case the unique device ID was cross referenced to the list of sites being tested by each tester to try to determine the correct location ID for that test. In cases where this was not successful, the test result was excluded from analysis.

Appendix H – Test Results by Tribal Location

Tribal Location	Population 2010	Avg. UP Mb/s	Avg. DOWN Mb/s	Number of Carriers	Sq. Mileage
Agua Caliente 1	24,545	964	1,887	4	49.49
Agua Caliente 2	24,545	747	1,676	4	49.49
Alturas	-	778	1,157	3	0.04
Auburn 1	-	547	782	4	1.66
Auburn 2	-	3,315	4,354	4	0.11
Barona	640	343	625	4	9.37
Benton Paiute 2	76	606	1,538	1	0.23
Berry Creek	150	1,031	2,654	2	0.11
Big Lagoon	17	83	48	1	0.01
Big Pine	499	419	901	3	0.43
Big Sandy	118	-	-	0	0.40
Big Valley	139	674	708	4	0.19
Bishop	1,588	521	725	4	1.37
Blue Lake 1	47	696	1,022	4	0.05
Blue Lake 2	47	576	1,889	4	0.05
Bridgeport	35	382	447	2	0.06
Cabazon	1,670	979	2,092	4	6.03
Cahuilla	187	904	259	4	29.08
Capitan Grande	-	643	2,332	3	25.05
Cedarville 1	2	467	886	2	0.02
Cedarville 2	2	559	883	2	0.02
Chemehuevi	308	233	263	1	48.30
Chicken Ranch	4	390	194	4	0.01

Cold Springs	184	-	-	0	0.16
Colorado River	1,687	333	188	4	75.61
Colusa	76	306	715	4	0.40
Cortina	21	86	645	2	1.19
Coyote Valley	144	593	420	4	0.13
Dry Creek	-	344	665	4	0.13
Elk Valley 1	91	766	1,609	3	0.14
Elk Valley 2	91	734	2,344	3	0.14
Enterprise	1	-	-	0	0.07
Fort Bidwell 1	-	-	-	0	0.13
Fort Bidwell 2	94	119	49	2	5.38
Fort Independence	93	583	1,751	3	0.87
Fort Mojave 1	234	625	612	3	0.08
Fort Mojave 2	16	249	408	4	9.76
Fort Yuma	2,189	654	1,128	4	67.29
Greenville	33	508	1,492	4	0.11
Grindstone	164	448	861	3	0.13
Guidiville 1	-	556	1,852	4	0.00
Guidiville 2	52	421	1,427	3	0.07
Hoopa Valley	3,041	-	-	0	142.16
Hopland 1	16	585	802	3	0.12
Hopland 2	16	189	256	2	0.12
Inaja and Cosmit	-	-	-	0	1.35
Ione Band of Miwok	5	93	123	2	2.12
Jackson	-	483	602	3	0.46
Karuk	433	598	2,209	4	1.50
La Jolla	476	454	488	2	13.58

Laytonville	212	400	453	3	0.30
Lone Pine	212	853	1,678	3	0.37
Lookout	11	231	307	2	0.06
Los Coyotes	98	152	98	1	39.44
Lytton	-	6,221	9,579	4	0.01
Manchester-Point Arena	212	334	1,576	3	0.59
Manzanita	78	227	45	1	7.22
Mechoopda	3,106	838	1,711	4	1.31
Middletown	56	360	565	4	0.19
Montgomery Creek	12	822	1,925	3	0.12
Mooretown 1	141	819	1,694	4	0.05
Mooretown 2	141	626	2,080	4	0.05
Morongo 1	-	849	1,456	4	0.06
Morongo 2	913	867	746	4	53.76
North Fork 1	49	399	655	3	0.26
North Fork 2	11	125	92	1	0.10
Pala	1,315	328	670	4	20.46
Paskenta	-	784	2,786	4	3.35
Pechanga	346	2,207	3,848	4	7.05
Picayune 1	57	812	1,295	4	0.11
Picayune 2	57	863	1,228	4	0.11
Pinoleville	129	730	3,364	2	0.16
Pit River	4	785	1,871	3	0.42
Quartz Valley 1	117	79	52	1	0.95
Quartz Valley 2	117	-	-	0	0.95
Ramona	13	335	425	4	0.86
Redding	34	1,278	2,753	4	0.04

Redwood Valley	238	327	595	4	0.42
Resighini	31	199	275	2	0.34
Rincon	1,215	778	2,276	4	6.20
Roaring Creek	14	776	1,581	3	0.13
Robinson 1	16	661	1,322	4	0.04
Robinson 2	191	213	426	4	0.28
Rohnerville	38	227	433	4	0.07
Round Valley	327	862	1,183	1	24.55
Rumsey	77	798	1,393	2	0.76
San Manuel	112	629	778	4	1.05
San Pasqual	1,097	1,513	2,734	4	2.25
Santa Rosa 1	652	2,461	4,801	4	0.63
Santa Rosa 2	71	573	964	2	17.15
Santa Ynez	271	400	619	4	0.24
Santa Ysabel	660	163	141	2	47.14
Shingle Springs	102	3,535	5,514	4	0.27
Smith River 1	101	902	1,412	3	0.26
Smith River 2	101	791	1,561	3	0.26
Soboba 1	482	1,261	2,963	4	9.35
Soboba 2	482	720	1,563	4	9.35
Stewarts Point	78	481	525	2	0.07
Sulphur Bank	61	634	1,287	4	0.08
Susanville 1	312	800	888	4	1.57
Susanville 2	237	501	978	4	0.10
Sycuan	211	922	1,759	4	1.29
Table Bluff	103	697	3,111	4	0.12
Table Mountain	64	671	2,710	3	0.21

Timbi-Sha Shoshone 1	24	59	36	2	0.52
Timbi-Sha Shoshone 2	-	657	1,042	2	2.69
Torres-Martinez	5,594	434	951	4	49.52
Trinidad 1	61	648	856	3	0.09
Trinidad 2	71	755	1,327	4	0.04
Tule River 1	-	579	1,304	2	0.08
Tule River 2	1,049	-	-	0	84.28
Tuolumne	185	1,235	2,841	1	0.59
Upper Lake	87	213	322	2	0.74
Viejas	1,040	818	1,250	4	5.05
Woodfords	214	-	-	0	0.61
XL Ranch	60	738	1,107	3	15.32
Yurok	1,238	487	594	2	88.43
La Posta 1	55	1,078	1,864	4	6.44
Sherwood Valley 1	14	605	1,719	4	0.22
Sherwood Valley Rancheria	154	25	-	1	0.55