CalSPEED Mobile: California's Mobile Broadband Divide

Persistent, Substantial and Growing as Rural and Tribal Users Stay Behind

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CalSPEED Mobile[1] measured mobile broadband quality for the four major mobile carriers in California - AT&T, Sprint, T-Mobile and Verizon - from 2012 thru 2017 - documenting the transition of mobile broadband from 3G to 4G LTE. Uniquely among broadband measurement systems, CalSPEED Mobile knows the geography of measurement, mapping mobile broadband throughout California.

One of the unmistakeable conclusions from CalSPEED measurements is the persistent and substantial mobile broadband quality divide between rural users and urban users.

Limited carrier choices	Only half (AT&T and Verizon) of the mobile broadband carriers offer substantial rural service outside of urban centers and transportation corridors.
Limited broadband coverage	Under 10% of rural CalSPEED measurement locations achieved the 25/3 broadband standard.
Lower throughput	Rural users consistently obtain only about ~70% of throughput of urban users.
Lower quality service	Rural users consistently obtain a fraction of quality (latency, jitter and packet loss) of urban users. For the critical metric of TCP connection failure, rural users experience over 5x worse service.

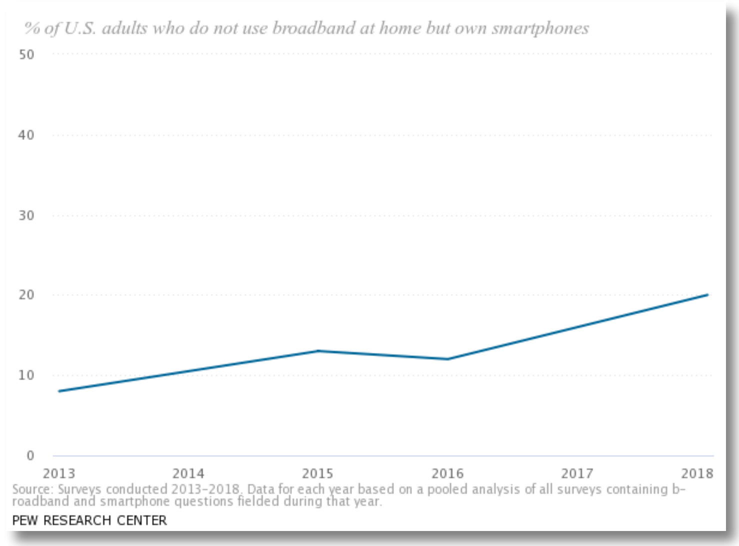
[1] Ken Biba, "CalSPEED Mobile: A Final Report on California Mobile Broadband - Six Years of Mobile Broadband Measurement", Novarum, January 2019

Technology transition	CalSPEED Mobile measures the transition from 3G mobile service to 4G LTE. The physical limitations of new 5G infrastructure suggests the 5G transition will only increase the rural mobile broadband deficit.
Tribal users better service	Both rural and tribal users have lower quality service than urban users. Tribal users have incrementally improved service over rural users.

1. Calibrating the Mobile Internet Experience

Each of us relies on the Internet to research school papers, find a job, find and buy new products, read the news and increasingly to entertain ourselves. The Internet is not only becoming our newspaper, but also our phone, radio and television. How we do our jobs, raise our families, educate ourselves and our children, interact as responsible citizens, and entertain ourselves are all influenced by the quality of the Internet service we obtain. And ever increasingly, that service is not on our desk, but in our hand (or wrist!) wherever we go.

A Pew Research study[2] emphasizes that increasingly the Internet is mobile, rather than fixed.



Knowing the quality of mobile broadband is a vital piece of our modern ecosystem much in the same way as we research the brand of car we drive or the type of house we own. With multiple mobile Internet providers, an independent third party assessment of this quality allows consumers and policy makers to make informed choices.

CalSPEED is an open source, non-proprietary, network performance measurement tool and methodology created for the California Public Utilities Commission, funded originally via a grant from the National Telecommunications and Information Administration and then through the California Advanced Services Fund. CalSPEED uses a methodology pioneered by Novarum. The software measurement system is created and maintained by a team at California State University Monterey Bay, led by Professors Sathya Narayanan and YoungJoon Byun. CalSPEED mapping and measurement field operations are managed by the Geographic Information Center at California State University at Chico. Statisticians at CSU Monterey Bay assist the team with detailed geographic and statistical analysis of the dataset.

Unlike many speed tests that offer just a horse race between carriers, CalSPEED tries to understand the quality of the mobile user broadband experience. It calibrates a number of metrics of the user Internet experience and not only presents them as numbers - but maps them onto the state of California.

[2] "Mobile Fact Sheet", Pew Research Center, February 2018, http://www.pewinternet.org/fact-sheet/mobile/

CalSPEED has measured mobile broadband in California for six years with twelve rounds of mobile broadband measurement over the entire state. It has collected close to 40,000,000 measurements, at the same locations, across California of the four major mobile broadband carriers: AT&T Mobility, Sprint, T-Mobile and Verizon Wireless. CalSPEED now turns its attention to measuring residential wired and WiFi[3] broadband.

This paper identifies the measured digital divide between rural and tribal users and their urban compatriots. The divide is real, persistent and substantial. And the coming transition to 5G mobile service will likely only increase this divide. The CalSPEED methodology has been rigorously analyzed with respect to other available mobile measurement tools[4] and is discussed in greater detail in Appendix A.

[3] Ken Biba, "WiFi Internet in California - for Every Household", Novarum, January 2019.

[4] Ken Biba, "Comparison of CalSPEED, FCC and Ookla", Novarum, Inc., September 2014.

2. Overall Mobile Broadband Context

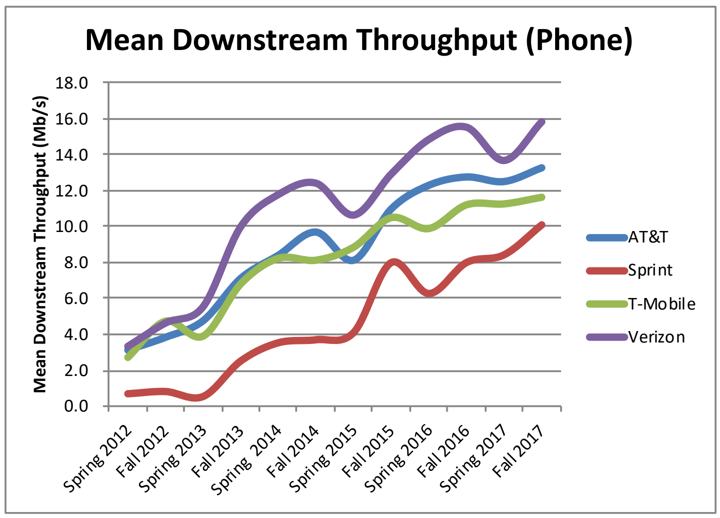
CalSPEED Mobile tracked the mobile broadband transition from 3G service in 2012 to 4G LTE service in 2017. Four major carriers deployed service footprint in California - AT&T, Sprint, T-Mobile and Verizon. The full Final Report documents the full trends, but let's look at the summary of overall California mobile broadband.

Mobile broadband quality improves overall

Mobile Internet quality has seen dramatic overall improvement from 2012 thru 2017:

- A 4x improvement in average throughput
- A 2x improvement in average latency
- A 1.6x degradation in packet loss rates
- A 1.7x improvement in packet jitter
- A 1.5x improvement in TCP connection reliability.

These changes have enabled the widespread deployment, across the state, of advanced communication services including voice over IP and streaming video.



Mobile broadband highly variable

Mobile broadband varies substantially by carrier (2x), infrastructure technology (10x), age of the user device (2x/3 years), location within state (10x) and destination information server (2x). But not much by time of day nor during a communication session (25%).

Mobile broadband is traffic shaped

Mobile broadband quality appears shaped, for all carriers, to have the following qualities:

- Capped maximum throughput upstream and downstream
- Improved median and average throughput
- Substantially degraded performance outside of the regional Internet.

Mobile broadband coverage is modest

Broadband coverage at the 25 Mb/s down, 3 Mb/s standard is available at ~13% of all CalSPEED measurement locations at the end of 2017. At the degraded "mobile broadband" standard of 10 Mb/s down and 1 Mb/s up, "coverage" improves to ~50% for all carriers.

But whichever way broadband is defined, rural users see about 50-75% of the service availability, at that standard as do urban users.

The End of 4G, the Hype of 5G, but 2G Lingers On

4G LTE has achieved high penetration for both urban and rural users. Some legacy 1G and 2G service areas remain particularly for rural users of Sprint, T-Mobile and Verizon. Notably there was no legacy 1/2G service detected for AT&T in California.

Urban users may see substantial increase in performance (possibly 5-10x) and decrease in latency (possibly 2x) from the deployment of 5G that will make interactive and streaming services even more effective. These are unlikely to be available to rural and tribal users where population density and geography make 5G millimeter wave deployments uneconomical or physically impossible.

It is likely that the current mobile broadband digital divide between urban and rural/tribal users will not only widen, but widen dramatically.

Older Devices Mean Slower and Lower Quality Internet

CalSPEED measurements were largely made with the latest generation user devices in order to assess the deployed infrastructure. But CalSPEED has also measured with a variety of other devices in parallel.

What can be learned from this data?

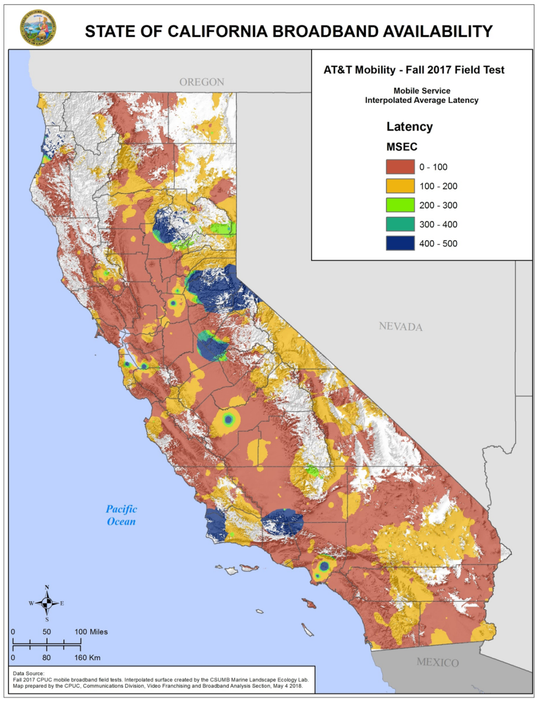
- Different devices can have dramatically different performance.
- This difference could easily be ~25%/year which means a 3 year old user device (a phone with 3 year old technology) can easily be a factor of 2 lower in performance than a state of the art device.

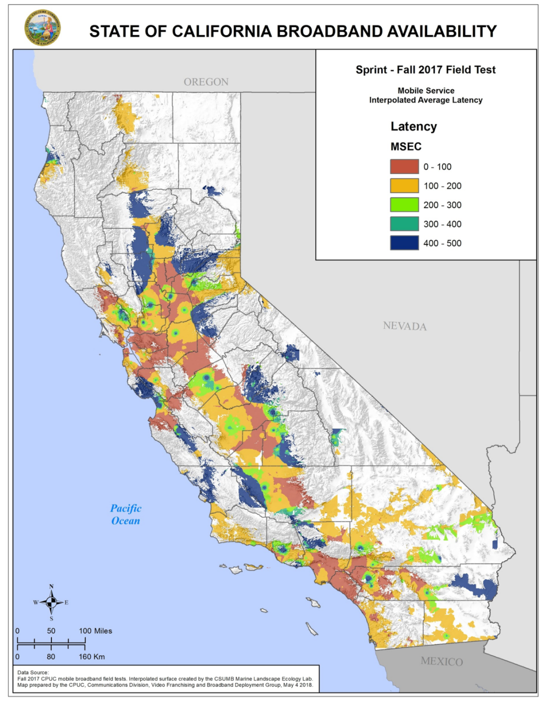
Many users do not choose, or cannot afford, the latest technology. These users will not have the performance and quality of service documented by CalSPEED - but rather something substantially less. These user device choices amplify other differences of carrier and location.

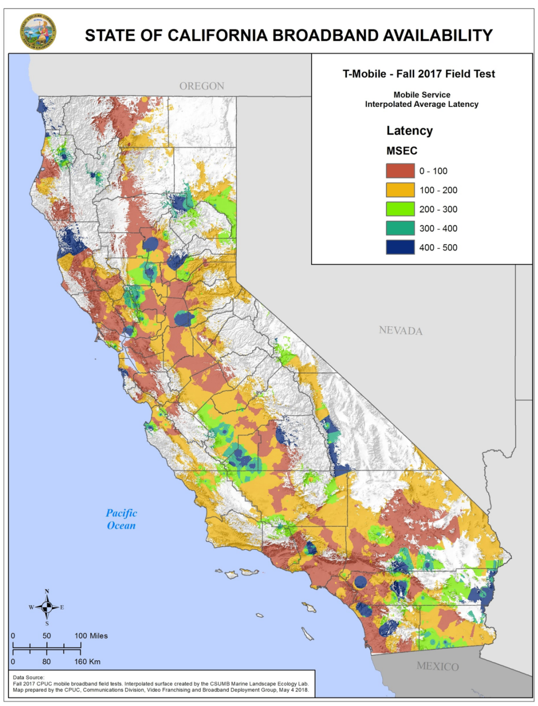
The Signal is Not the Message

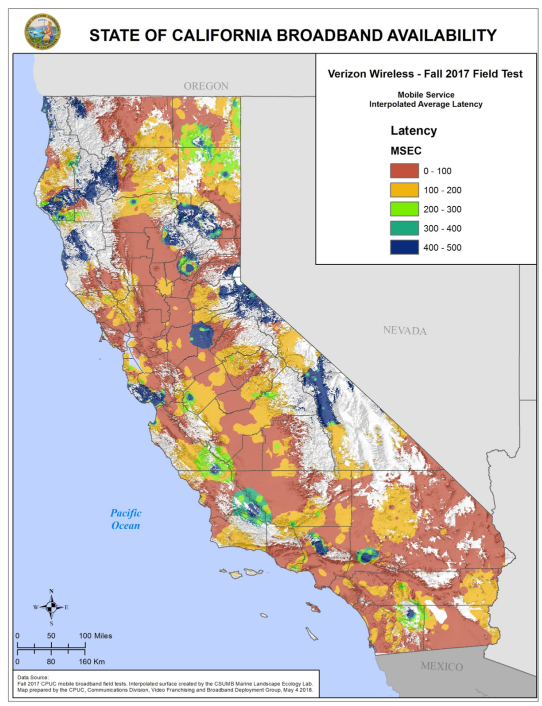
The signal bars on a smartphone are not a good predictor of mobile performance. At best, RSSI explains about 20% of the variation in throughput (Verizon urban), and at worst, explains 0% of the variation in throughput (AT&T urban). At best, SNR explains about 45% of throughput variation (Sprint rural) and at worst, about 6% of throughput variation (AT&T rural).

There is little ability of signal strength to predict Internet performance.



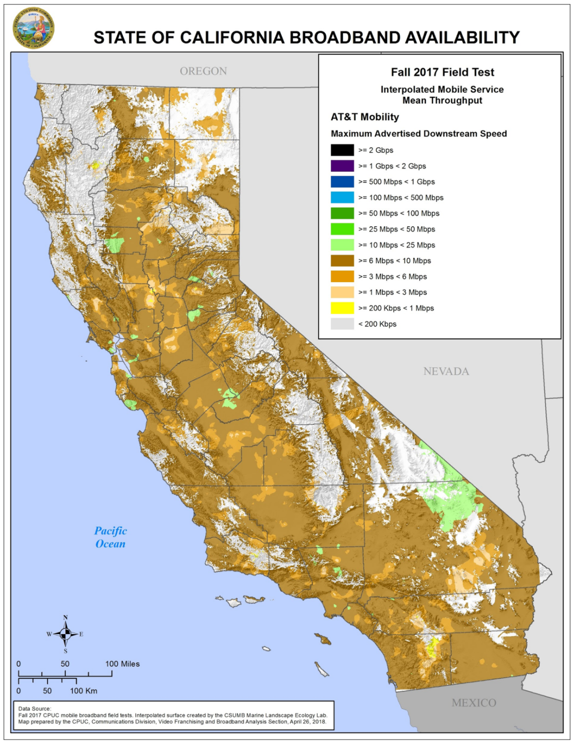


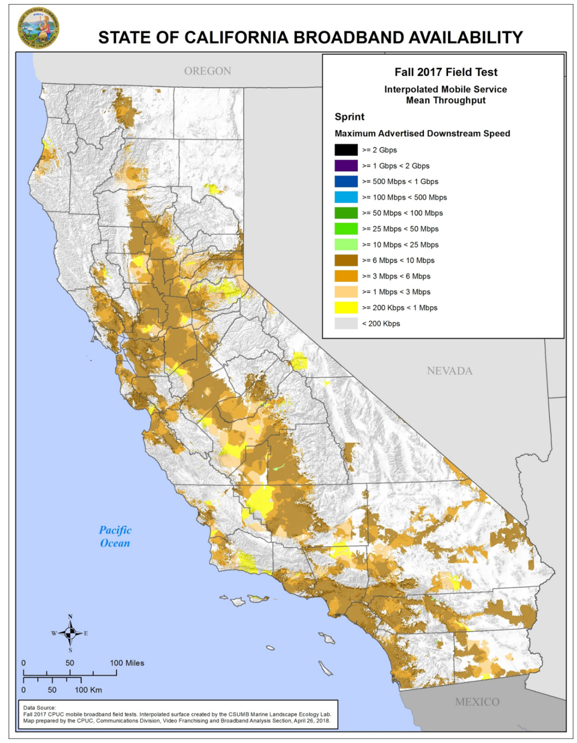


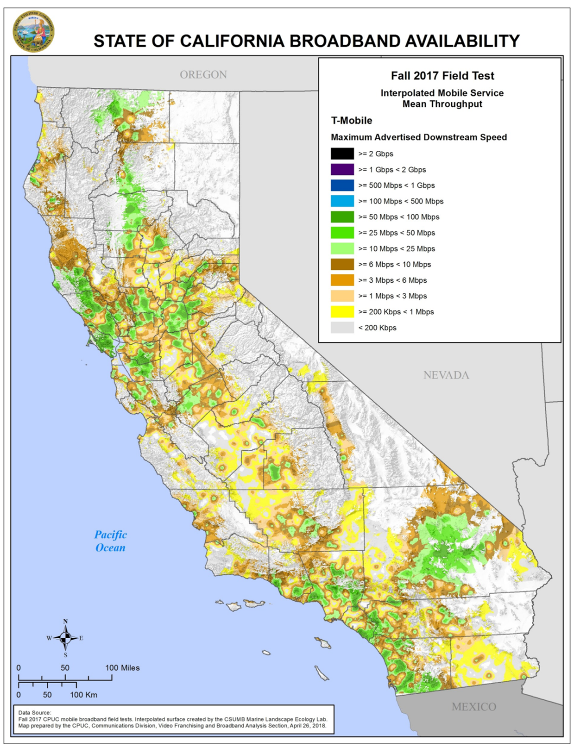


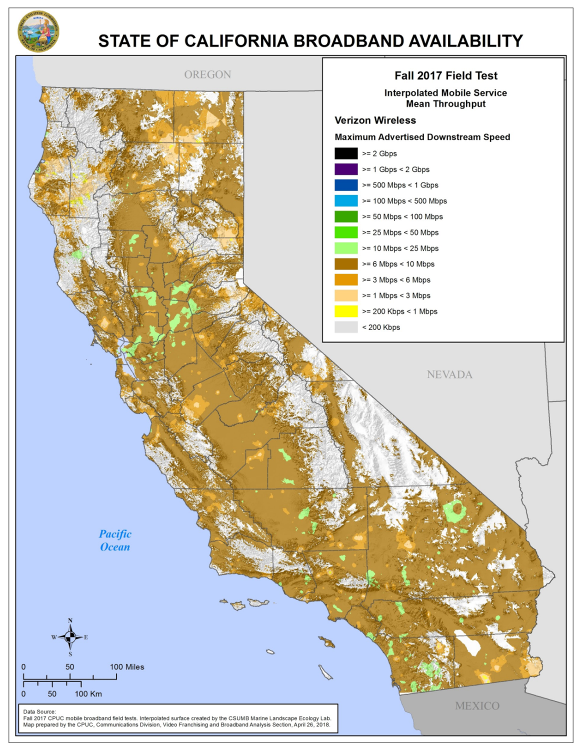
A unique feature of CalSPEED are maps of broadband quality. Such maps allow correlation with other geographic data and give visual evidence of the extent and quality of broadband service.

For example, the following maps of mean downstream throughput graphically illustrate the geographic coverage of each of the major carriers and the quality of their service.



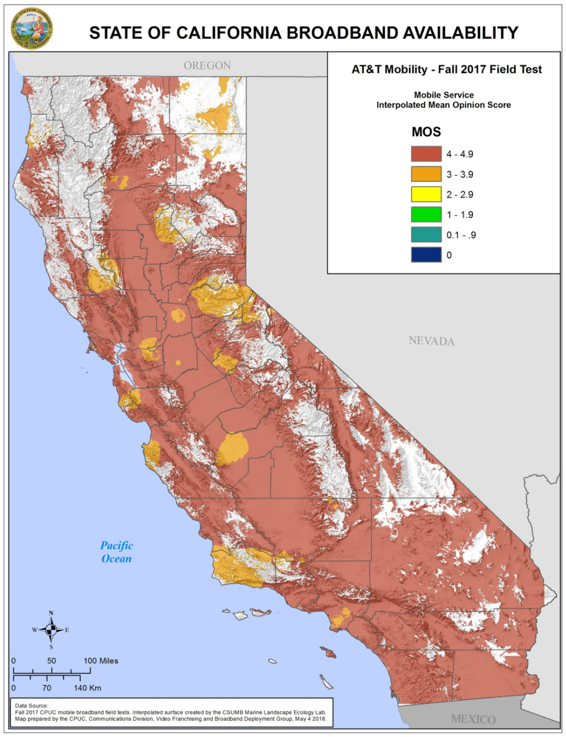




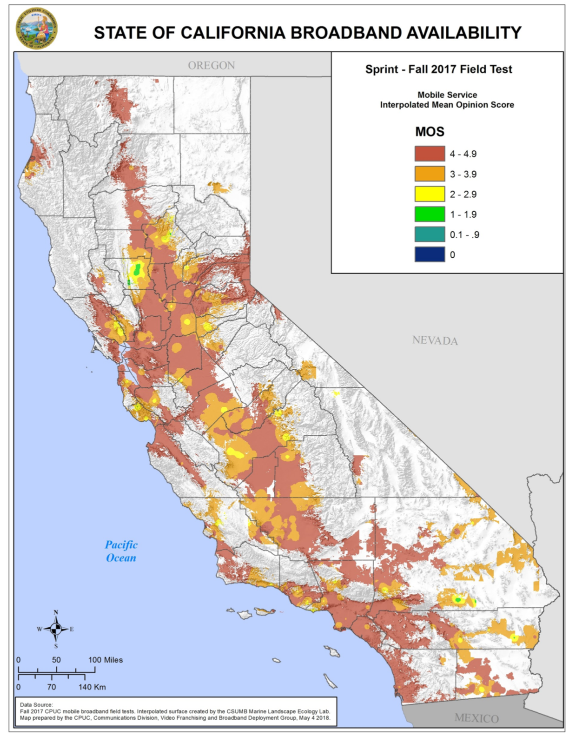


Similar maps visualize latency.

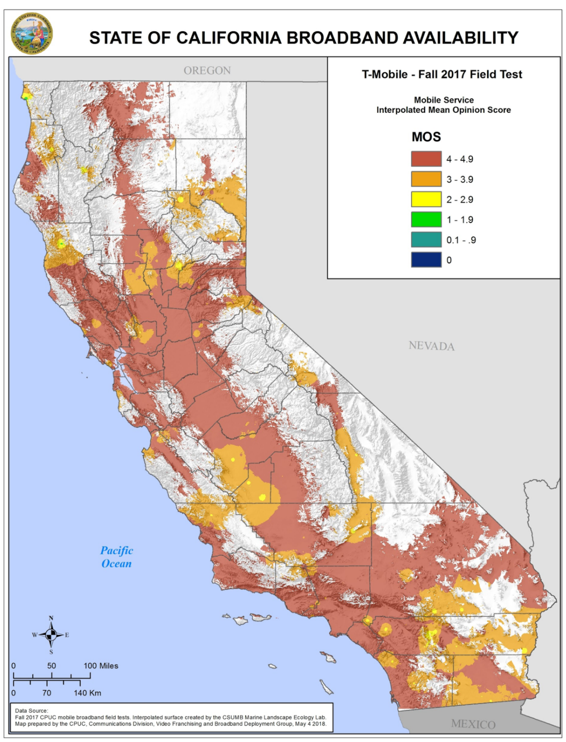
CalSPEED created composite metrics for more advanced services such as over-the-top digital voice - measuring VoIP quality via a synthetic Mean Opinion Score from throughput, latency, jitter and packet loss. The following VoIP maps illustrate the estimated extent of high quality digital voice service.



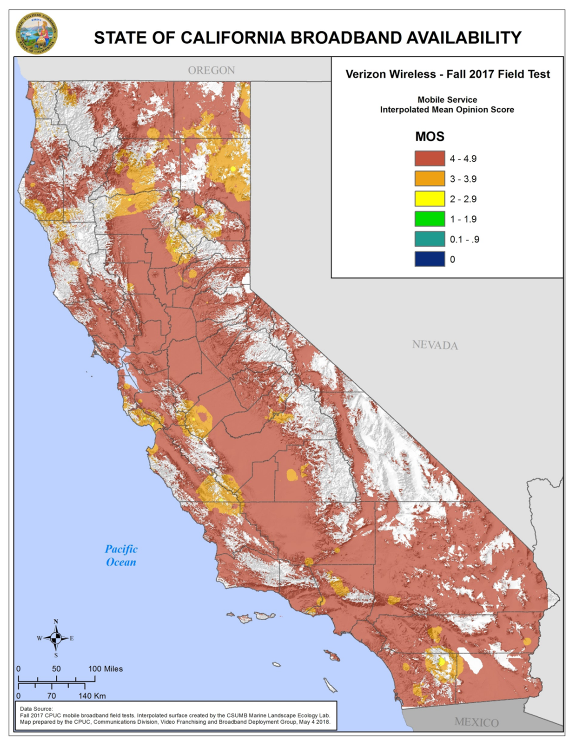
STATE OF CALIFORNIA BROADBAND AVAILABILITY
AT&T Mobility - Fall 2017 Field Test
Mobile Service
Interpolated Mean Opinion Score
MOS
4 - 4.9
3 - 3.9
2 - 2.9
1 - 1.9
0.1 - .9
0
OREGON
NEVADA
MEXICO
Pacific Ocean
N
S
E
W
0 50 100 Miles
0 70 140 Km
Data Source:
Fall 2017 CPUC mobile broadband field tests. Interpolated surface created by the CSUMB Marine Landscape Ecology Lab.
Map prepared by the CPUC, Communications Division, Video Franchising and Broadband Deployment Group, May 4 2018.



STATE OF CALIFORNIA BROADBAND AVAILABILITY
Sprint - Fall 2017 Field Test
Mobile Service
Interpolated Mean Opinion Score
MOS
4 - 4.9
3 - 3.9
2 - 2.9
1 - 1.9
0.1 - .9
0
OREGON
NEVADA
MEXICO
Pacific Ocean
N
S
E
W
0 50 100 Miles
0 70 140 Km
Data Source:
Fall 2017 CPUC mobile broadband field tests. Interpolated surface created by the CSUMB Marine Landscape Ecology Lab.
Map prepared by the CPUC, Communications Division, Video Franchising and Broadband Deployment Group, May 4 2018.



STATE OF CALIFORNIA BROADBAND AVAILABILITY
T-Mobile - Fall 2017 Field Test
Mobile Service
Interpolated Mean Opinion Score
MOS
4 - 4.9
3 - 3.9
2 - 2.9
1 - 1.9
0.1 - .9
0
OREGON
NEVADA
MEXICO
Pacific Ocean
N
S
E
W
0 50 100 Miles
0 70 140 Km
Data Source:
Fall 2017 CPUC mobile broadband field tests. Interpolated surface created by the CSUMB Marine Landscape Ecology Lab.
Map prepared by the CPUC, Communications Division, Video Franchising and Broadband Deployment Group, May 4 2018.



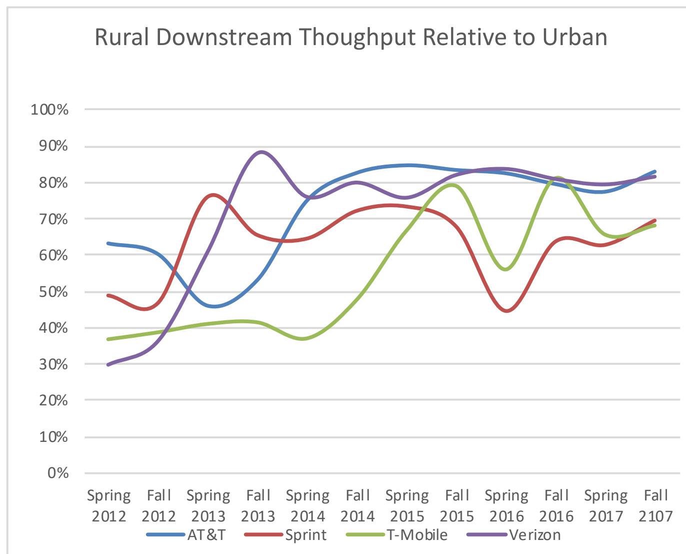
STATE OF CALIFORNIA BROADBAND AVAILABILITY
Verizon Wireless - Fall 2017 Field Test
Mobile Service
Interpolated Mean Opinion Score
MOS
4 - 4.9
3 - 3.9
2 - 2.9
1 - 1.9
0.1 - .9
0
OREGON
NEVADA
MEXICO
Pacific Ocean
N
S
E
W
0 50 100 Miles
0 70 140 Km
Data Source:
Fall 2017 CPUC mobile broadband field tests. Interpolated surface created by the CSUMB Marine Landscape Ecology Lab.
Map prepared by the CPUC, Communications Division, Video Franchising and Broadband Deployment Group, May 4 2018.

3. Persistent Rural/Urban Mobile Broadband Divide

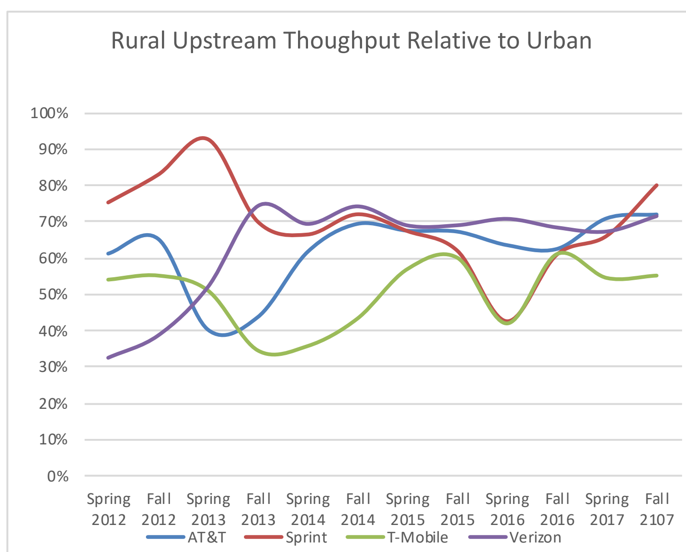
The six years of CalSPEED mobile broadband measurement documents that rural mobile broadband networks consistently (by approximately 1/3) underperform urban networks - both in performance and quality - for all carriers. The data strongly suggests that this underperformance has continued for years and trend lines suggest little improvement. The coming technology change to 5G will likely only further degrade rural and tribal relative to urban since both 5G technology and deployment economics bias towards urban deployment.

Let's examine each of these metrics. There are strong differences between carriers, and it is important to note that the best rural mobile broadband coverage is delivered by AT&T and Verizon.

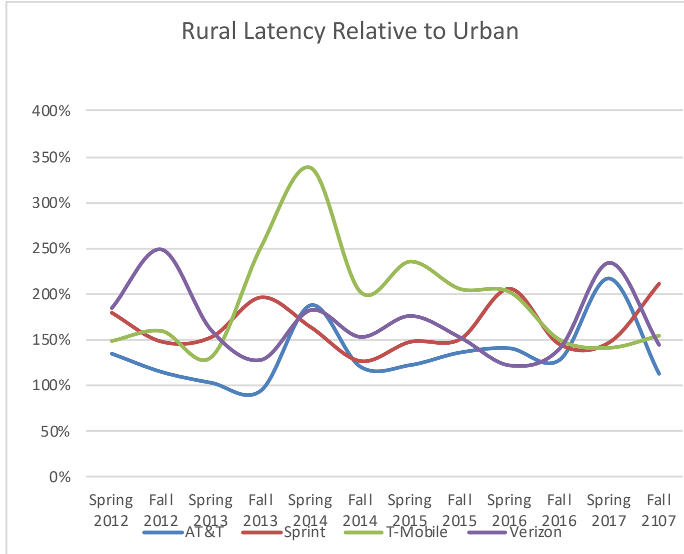
Rural mean downstream TCP throughput is consistently only 80% (and for Sprint and T-Mobile sometimes as little as 50%) of urban.



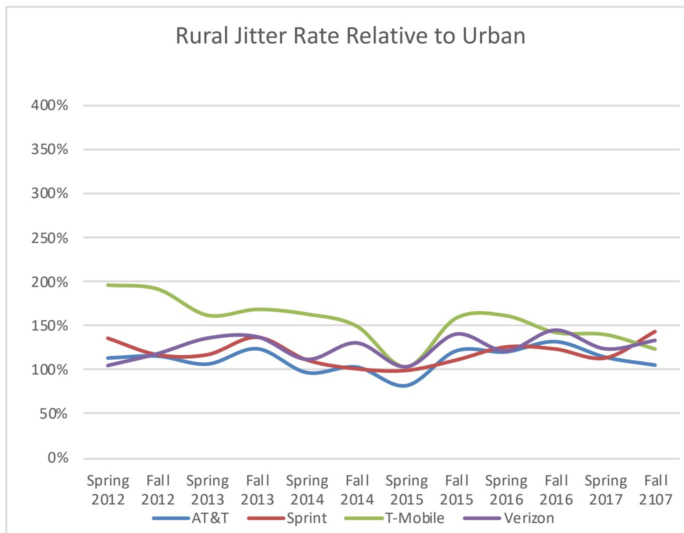
Rural mean upstream TCP throughput is consistently only 60-70% of urban.



Rural mean latency is variable but consistently at least 50% worse than urban.

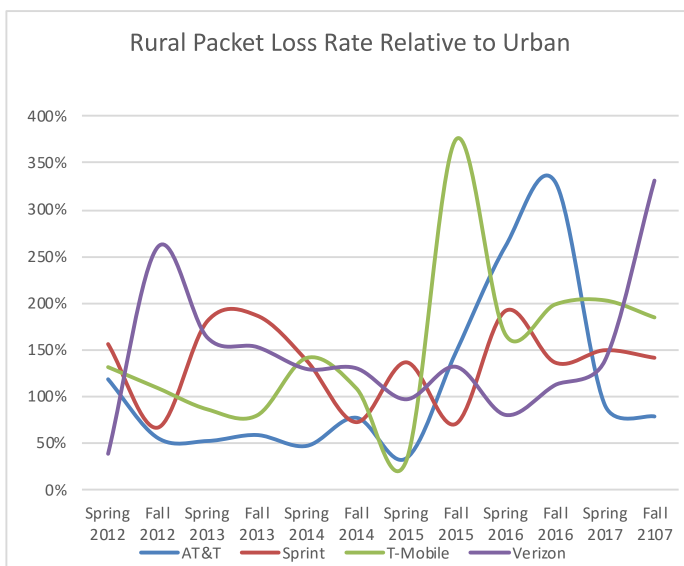


Rural mean jitter is consistently at least 20% worse than urban.

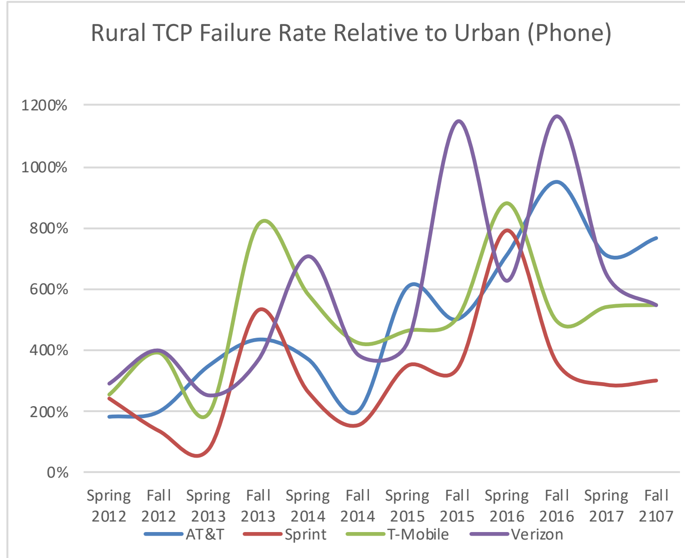


Rural packet loss is consistently 100-200% worse than urban. There is arguably a modest trend for worsening packet loss.

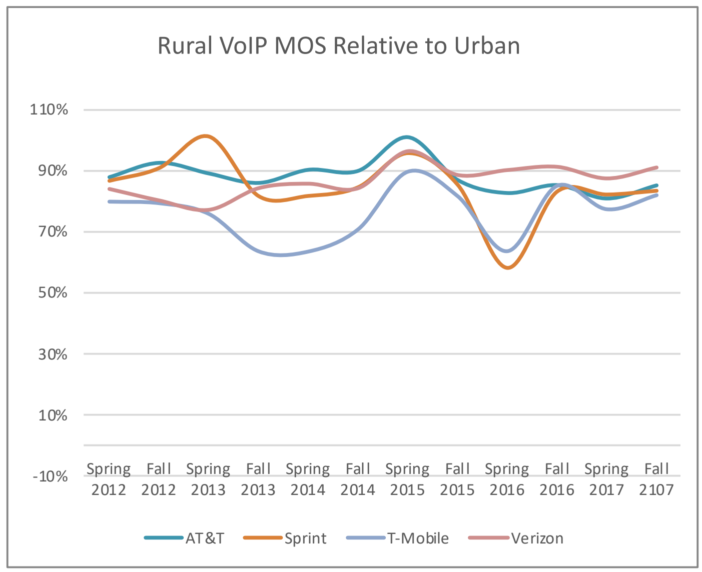
The poor performance of rural latency, jitter and packet loss strongly implies that advanced network services such as streaming voice and video will perform materially worse in rural than urban areas.



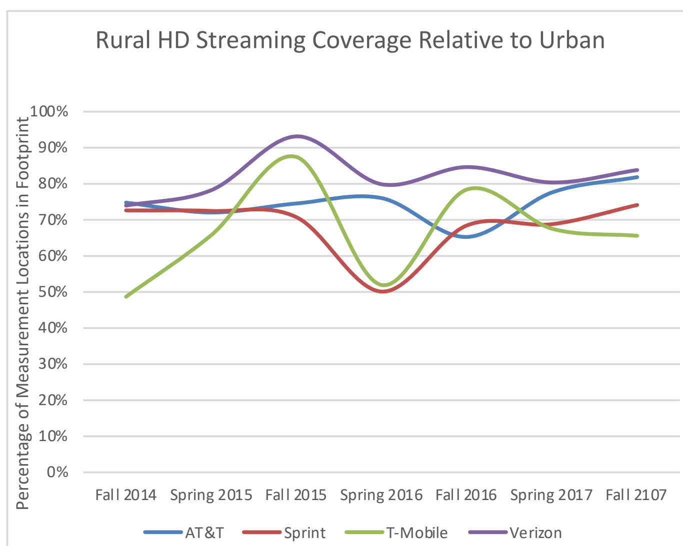
Rural TCP connection failure rate is consistently >5x worse than urban with indications that this disparity is getting worse. For rural and tribal users of all carriers, about 1 in 5 of all TCP connection attempts fail and must be retried.



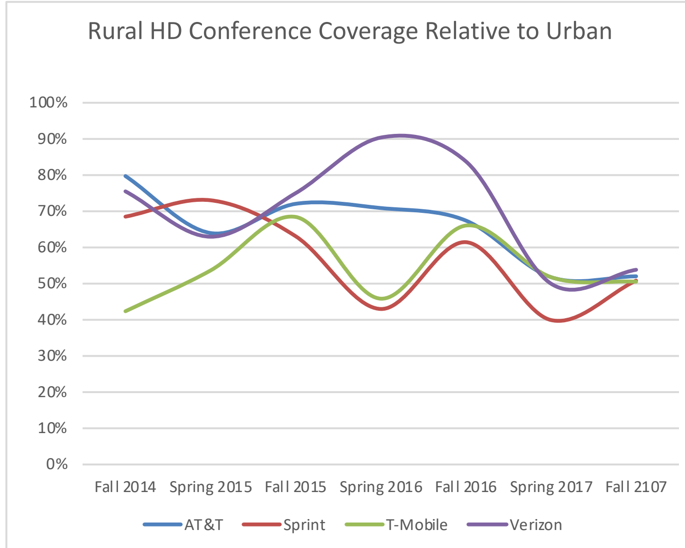
Rural OTT digital voice coverage is consistently only 85% of urban.



Rural high definition (HD) streaming video coverage is consistently 60-80% of urban. Rural users will encounter no HD streaming availability 2.5x more frequently than urban users.

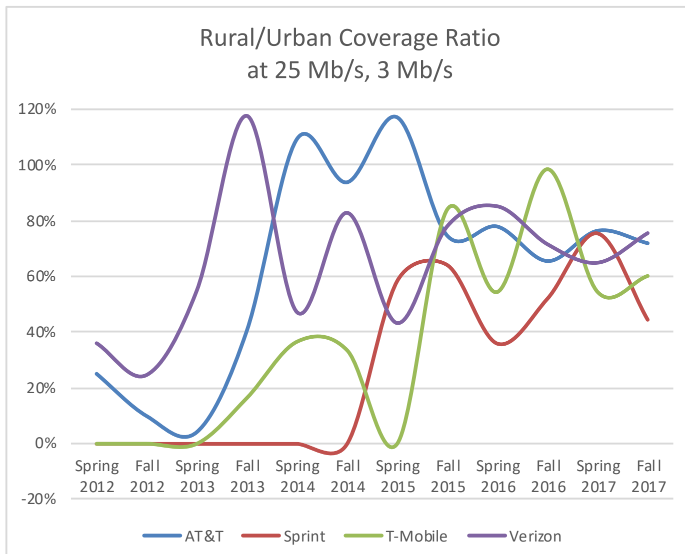


Rural HD interactive video coverage is consistently 60-80% of urban with a significant trend towards worsening. Rural users will encounter no HD conference availability 1.5x more frequently than urban users.

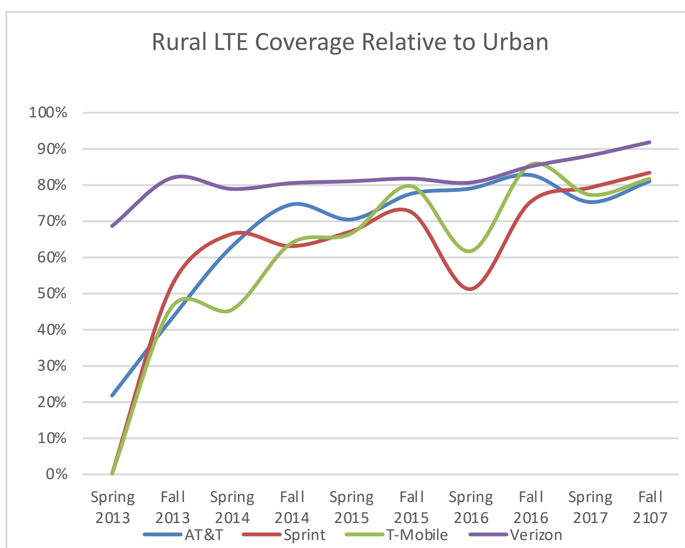


Rural mobile broadband coverage at the standard of 25 Mb/s down and 3 Mb/s up is consistently 60-80% of urban.

Under 10% of rural CalSPEED measurement locations achieved the 25/3 broadband standard.

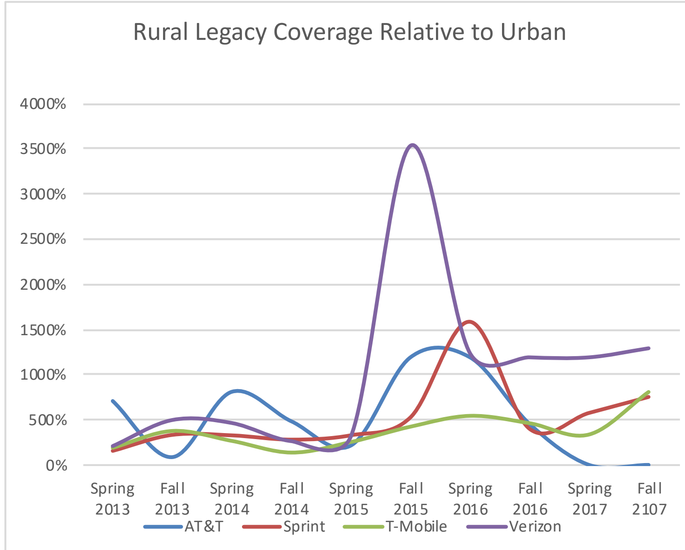


Rural LTE coverage is consistently less than 85% of urban (with the significant exception of Verizon). This has substantial implications for the use of mobile broadband as a replacement for wired broadband in rural areas and for the capability of public safety services.



Rural mobile broadband consistently has more than a 5x use of legacy 1G and 2G mobile broadband technology than urban.   It is much more likely for a rural user to encounter very poor legacy mobile broadband service than an urban user.

A notable change in Spring 2017 is the effective elimination of legacy rural coverage for AT&T. Sprint, T-Mobile and Verizon still have remnants of legacy technology deployed and in daily use.



4. Comparing Rural and Tribal Mobile Broadband

It is often assumed that tribal mobile broadband Is similar to rural coverage. While there are strong similarities, there are distinct differences.

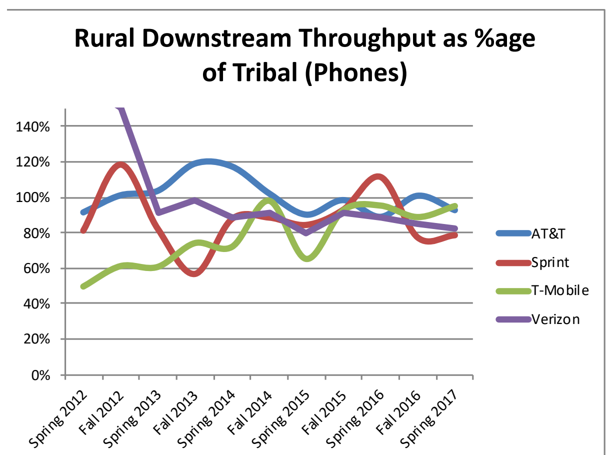
Note that while CalSPEED has intentionally measured mobile broadband for tribal users, this measurement has limitations. First, CalSPEED sampled roughly only 10% of the locations for tribal users as rural users and secondly, many of the sampling locations were not allowed to be on tribal lands, but were measured on adjacent land.

Looking at correlation analysis of the major metrics, rural and tribal users have very similar experiences.

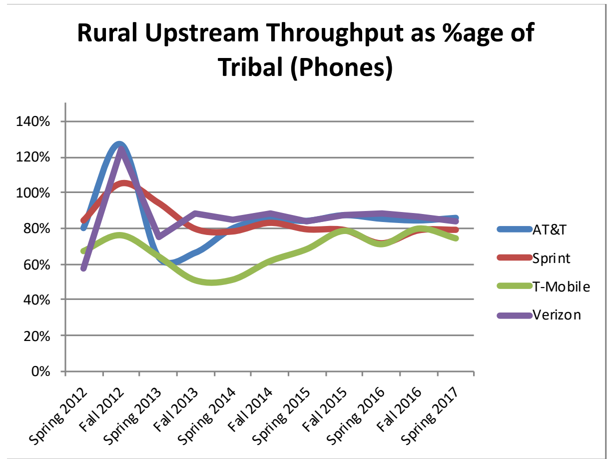
Pearson Correlation						
	Upstream	Downstream	Latency	Jitter	Packet Loss	TCP Failure
AT&T	99%	98%	53%	85%	16%	66%
Sprint	99%	98%	75%	68%	24%	88%
Mobile	98%	96%	70%	89%	60%	73%
Verizon	99%	99%	46%	83%	36%	93%

Let's compare these metrics more thoroughly. Tribal users have improved mobile broadband service to rural users, but still substantially inferior to urban users.

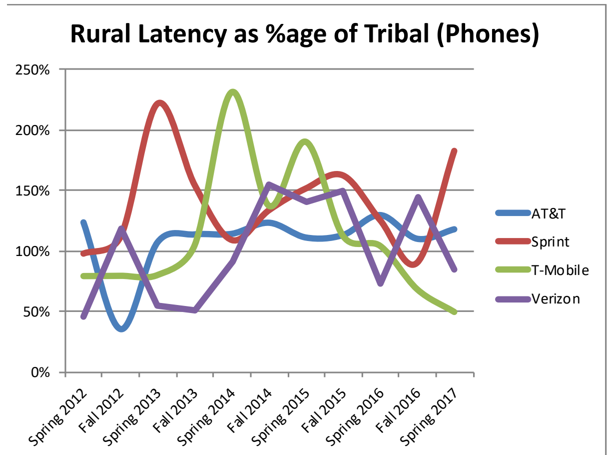
Mean TCP downstream throughput, while similar shows that rural users, on average, get poorer service than tribal users.



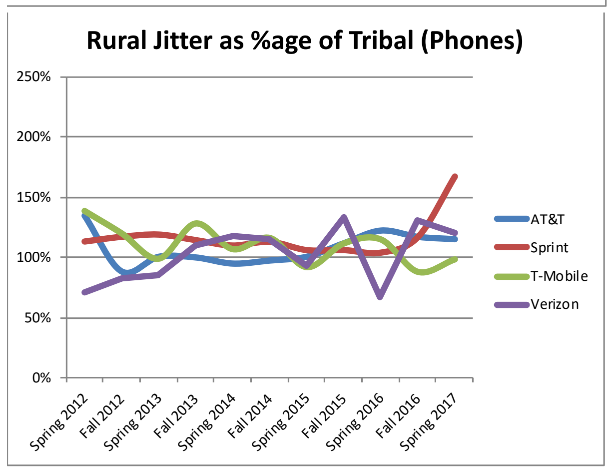
Mean TCP upstream throughput is closely correlated but tribal users get, on average, materially better service.



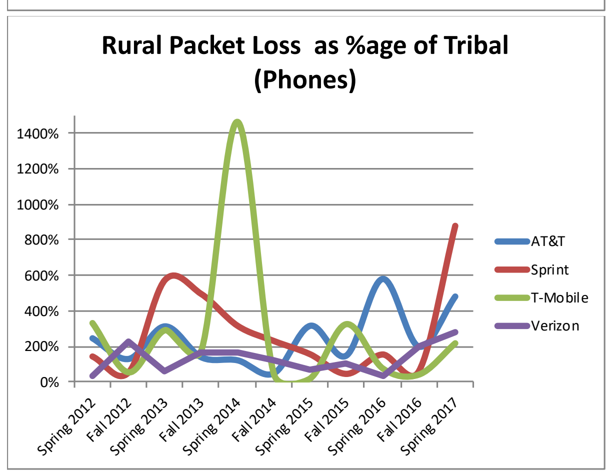
There is much variation in latency, but again rural users see a worse service than tribal users.



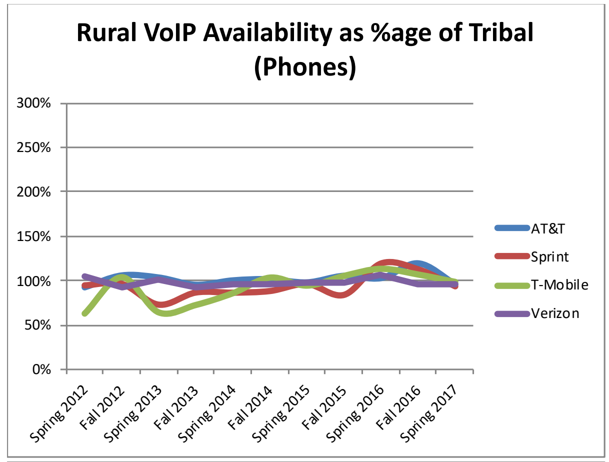
Rural users see more jitter than tribal users.



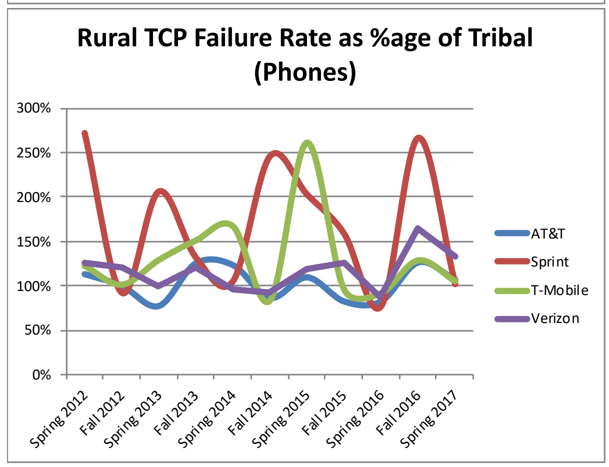
Rural users, at the end of 2017, saw ~4x the packet loss of rural users on the networks with the most extensive rural and tribal coverage.



VoIP service at or above a MOS score of 4.0 is about the same for rural and tribal users.



Rural users see a materially great rate of TCP connection failure than tribal users.



9. Particular Rural Challenges

Lower quality mobile broadband service continues Internet challenges for rural users.

Fewer carriers	Only two of the four major California carriers have a substantial rural coverage footprint. Two carriers have a coverage footprint that only includes urban areas and major transportation corridors.
Lower raw TCP throughput	All four carriers offer lower TCP throughput, on average, to rural users than urban users. This simply means that email, web access, video streaming and other common Internet tasks will take longer and be less efficient for rural users than for urban users. Businesses will be incrementally less efficient. Fewer rural users, with lower availability, will have access to modern mobile broadband performance.
Lower quality	The higher jitter, longer latency, higher packet loss that characterize rural mobile broadband all make advanced services - Voice over IP, video streaming, video conferencing - all have poorer quality and availability to fewer users.
Lower connection reliability	TCP connection attempts fail over 5x more frequently for rural users than urban users. For users of the highest coverage mobile broadband carriers - 1 in 5 TCP connection attempts will fail - unless reattempted automatically by the application or manually by the user. In either case, the rural user experience is less productive and more - annoying - than an urban user.
Older device population	Pew Research, in 2018, found that 26% of rural users used a legacy voice-primary cellphone rather than a smartphone (much less a modern smartphone) compared to only 13% of urban users. While Pew did not ask the question about the generation of smartphone, a reasonable inference is that the age of rural user smartphones trends older than urban users. CalSPEED suggests that a 3 year old smartphone has half the performance of a current smartphone based on the underlying change in mobile broadband technology. A slower upgrade cycle for rural user smartphones would substantially compound the 3/5ths quality deficit of the mobile infrastructure. Lower performance user devices with a lower performance infrastructure suggest an average rural user experience about half that of urban users.

5G

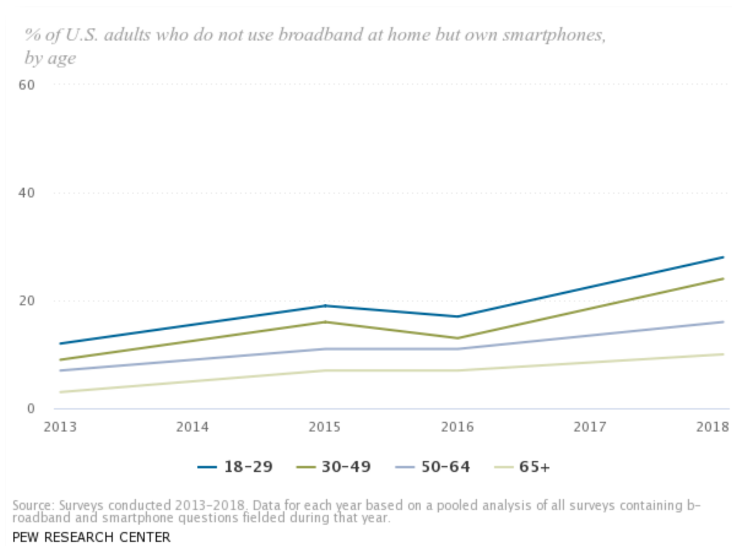
The technology evolution of 5G is in two parts: an incremental improvement in 4G LTE performance in existing high coverage frequency bands and the possibly dramatic increase in performance and quality with access to new bandwidth in millimeter wave bands.

Millimeter wave has unique physical properties that make its widespread use in less densely populated areas economically challenging, delaying deployment if deployment is possible at all.

This likely lack of high performance rural millimeter wave service and the still incomplete rural 4G LTE deployment strongly suggests that the performance and quality divide for rural users will only increase with 5G service to urban users.

Applications designed for these new high performance 5G services will be delayed in their availability, if at all, to rural users.

The quality of mobile broadband has substantial impact on such diverse Internet applications as education, entertainment and emergency services.   Pew Research documents that increasing numbers of US adults rely exclusively on smartphones for Internet rather than residential broadband.



Carriers have begun a process of using mobile (and sometimes fixed wireless) broadband as the preferred alternative over upgrading legacy DSL wire or installing new cable or fiber, so mobile broadband is often the only alternative for high performance rural broadband.

Education increasingly requires access to Internet resources for research and pedagogy and increasingly making use of video resources[5].   High performance broadband is mission critical for this purpose.   Lower performance means lower availability and lower productivity.

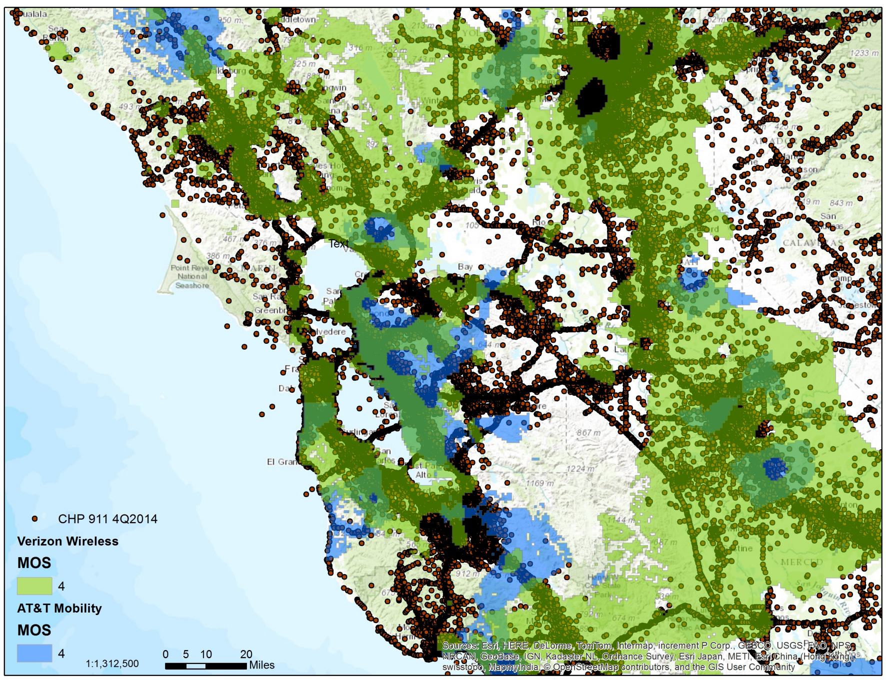
[5] Kahn Academy, https://www.khanacademy.org

Digital streaming media, for entertainment and for communication (e.g. digital voice over IP, FaceTime) is increasingly replacing conventional telephone, broadcast, cable and satellite video. High quality broadband is mission critical for these services. Lower quality means lower availability to users.

Emergency services compound the combination of performance and quality. In particular, let's look at the impact on two emergency services, arguably more important in rural areas - 911 and response to fire threat.

911 Service

CalSPEED integrated its Fall 2014 estimated maps of high quality (MOS >= 4.0) voice over IP service availability for the two highest coverage mobile carriers (AT&T and Verizon) with geo mapping of 911 calls from the California Highway Patrol in San Francisco Bay Area.



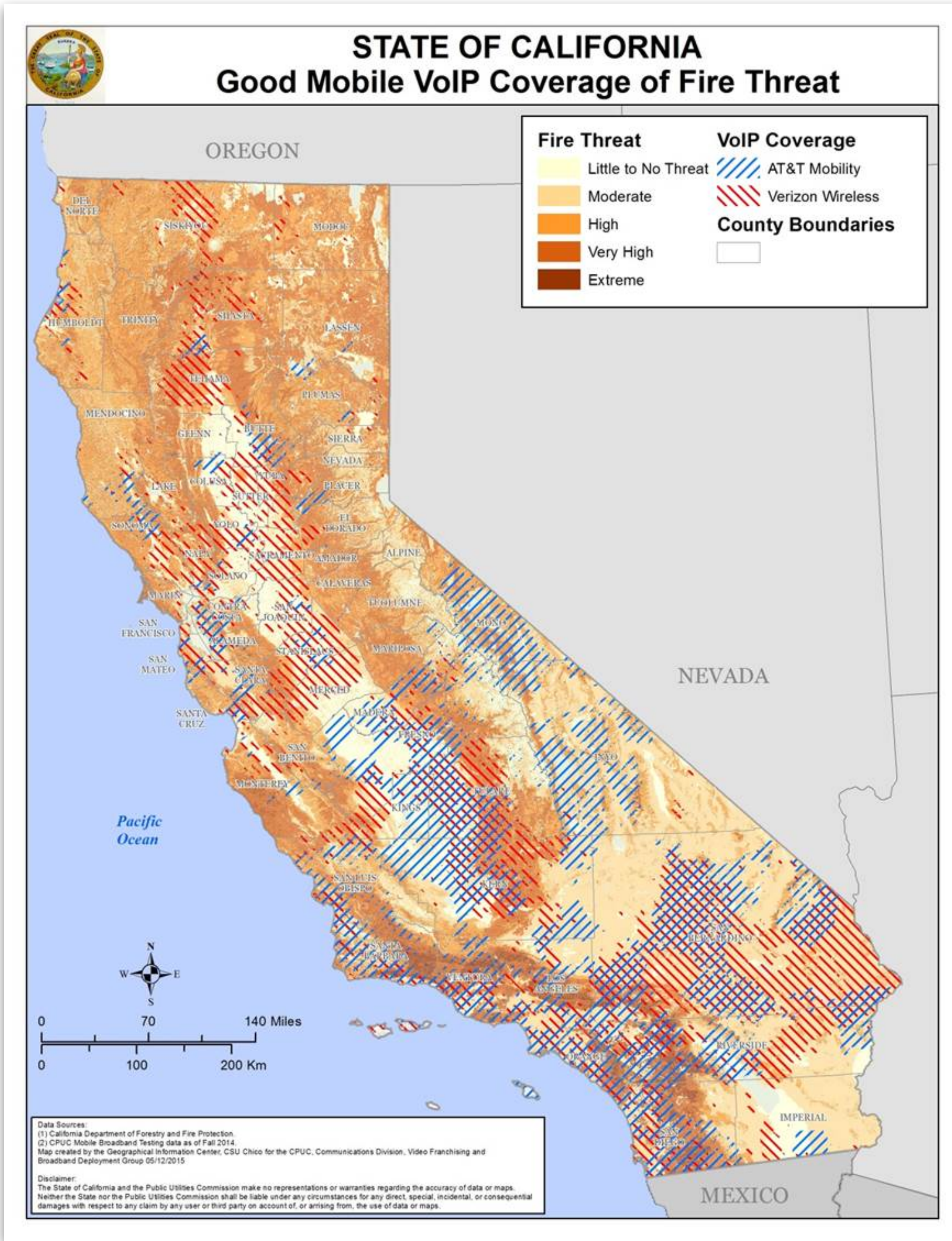
For this portion of California, a mix of heavily urban and rural, AT&T provided about 52% good quality VoIP coverage to locations of 911 calls.   Verizon provided about 65% good quality VoIP coverage.

AT&T Mobility "Good" VoIP Coverage			
Number of Calls Without	Percent of Calls Without	Number of Calls With	Percent of Calls With
3,297,260	48.09%	3,559,394	51.91%

Verizon Wireless "Good" VoIP Coverage			
Number of Calls Without	Percent of Calls Without	Number of Calls With	Percent of Calls With
2,399,405	34.99%	4,457,249	65.01%

High Risk Fire

Correlating maps of fire threat with maps of Fall 2014 estimated VoIP coverage gives an estimate of the likelihood of making a digital voice call in a high fire threat area of the state. The following composite map overlays good VoIP quality for AT&T and Verizon (MOS >= 4.0) with fire threat.



Now let's look at what this correlation reveals. For the leading carriers, AT&T and Verizon, over 80% of the Very High risk fire areas are without good quality estimated VoIP coverage.

FIRE THREAT		Verizon Wireless Good VoIP Coverage			AT&T Mobility Good VoIP Coverage		
Threat Rank	Total Area (Sq. Miles)	Area Without	Area With	Percent Area Without	Area Without	Area With	Percent Area Without
Extreme	3,059	2,351	709	77%	1,397	1,663	46%
Very High	40,090	33,242	6,848	83%	32,706	7,384	82%
High	33,313	27,763	5,549	83%	27,613	5,699	83%
Moderate	56,911	37,956	18,955	67%	38,945	17,965	68%
Little to No Threat	24,780	16,014	8,766	65%	16,491	8,289	67%

10. Conclusions

Limited carrier choices	Only half (AT&T and Verizon) of the mobile broadband carriers offer substantial rural service outside of urban centers and transportation corridors.
Limited broadband coverage	Under 10% of rural CalSPEED measurement locations achieved the 25/3 broadband standard.
Lower throughput	Rural users consistently obtain only about ~70% of throughput of urban users.
Lower quality service	Rural users consistently obtain a fraction of quality (latency, jitter and packet loss) of urban users. For the critical metric of TCP connection failure, rural users experience over 5x worse service.
Technology transition	CalSPEED Mobile measures the transition from 3G mobile service to 4G LTE. The physical limitations of new 5G infrastructure suggests the 5G transition will only increase the rural mobile broadband deficit.
Tribal users better service	Both rural and tribal users have lower quality service than urban users. Tribal users have incrementally improved service over rural users.

Appendix A: CalSPEED: Capturing the End to End User Experience

How CalSPEED Measures

CalSPEED performs the following sequence of measurements to gather its information:

1. ICMP ping to the West server for four seconds for connectivity checking. If the ICMP ping fails, CalSPEED presumes that there is no effective connectivity to the Internet and records that result.
2. iPerf TCP test (4 parallel flows) to the West server - both downstream and upstream.   CalSPEED uses four parallel flows to ensure that the maximum capacity is measured during the test.   A throughput value is captured for each second of each flow.
3. ICMP ping to the West server for 10 seconds to measure latency to the West server.
4. UDP test to the West server. CalSPEED constructs a UDP stream of 220 byte packets to emulate a VoIP connection with 88kb/s throughput.   This UDP stream is used to measure packet loss, latency and jitter.
5. iPerf TCP test (4 parallel flows) to the East server to measure downstream and upstream TCP throughput. A throughput value is captured for each second of each flow.
6. ICMP ping to the east server for 10 seconds to measure latency to the East server.
7. UDP test to the East server to measure packet loss, latency and jitter with a simulated VoIP data stream.

CalSPEED uses two identical measurement servers on the opposite ends of the US Internet.   One hosted in the Amazon AWS near San Jose, CA and for many California users has performance like a CDN server.   The second measurement server is in the Amazon AWS in Northern Virginia.

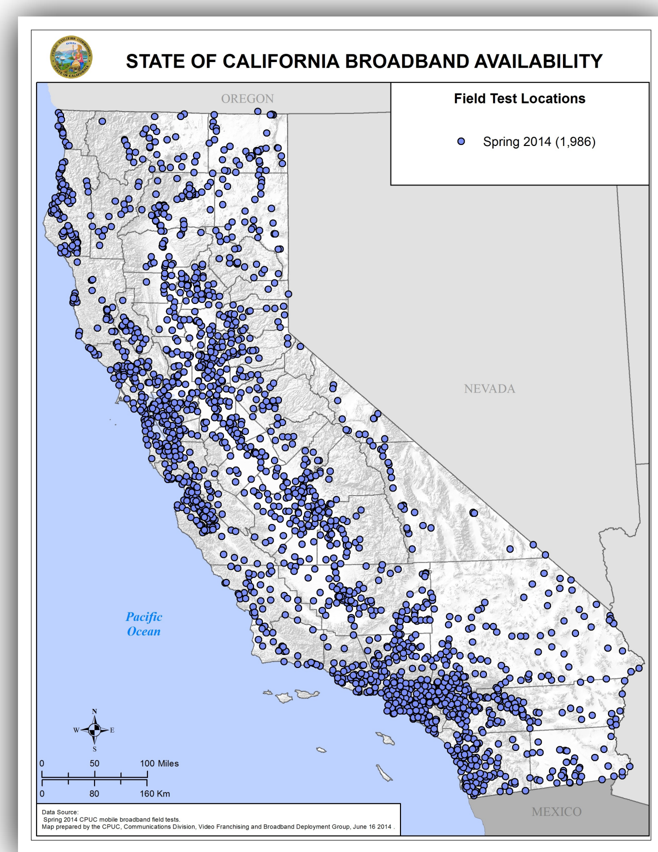
CalSPEED uses two device measurements - a current smartphone and current USB datastick for laptops. Both are upgraded for each measurement round to match the latest wireless technology deployed by each carrier.

Open Source. CalSPEED is an open source network performance measurement tool that is in turn based on an industry standard open source performance measurement tool - iPerf[6].   iPerf provides the foundation network measurement engine for both the TCP and UDP protocols.   CalSPEED packages this engine in both Windows and Android client tools for measuring and recording mobile network performance.

End-to-End User Experience. A foundation assumption of CalSPEED, uniquely among network measurement tools, is an attempt to replicate the end to end user experience.   In particular, CalSPEED recognizes that the Internet resources that a typical user accesses are scattered across the entire Internet … and despite the use of content delivery networks to speed Internet performance by caching frequently accessed content, are not always “local” to the user.   Many measurement

6 http://en.wikipedia.org/wiki/Iperf

tools focus on evaluating just the local radio access network - the last few miles - and not the backhaul network to the ultimate server resource used. CalSPEED instead tests the complete network path, from the client device, through the local access network, through the Internet backbone, to several ultimate server destinations.



While it is impossible to measure all Internet servers, CalSPEED emulates this user experience with two fixed servers - one physically located in Northern California and the other in Northern Virginia - both in the Amazon AWS cloud. CalSPEED reports performance both to each individual server and the average between them. Not only does this method measure the different local access methods, but provides a network interferometry that gives insight into the different backhaul strategies chosen by carriers. We find carrier unique up to 2:1 differences in end to end latency and jitter and material difference in upstream and downstream throughput between the two servers.

These differences in fundamental network performance illustrate that location matters - Internet performance delivered to the user - the Internet user experience - will vary based on where on the Internet the desired server is located. And desired servers are scattered across the Internet, not just close to every user. Measurement to a local server only results in an overly optimistic expectation of service quality than a typical user will actually experience.

CalSPEED measures a complete portfolio of network metrics including end-to-end packet latency, bidirectional TCP throughput, UDP packet loss and jitter.

Just the Facts. CalSPEED does not filter any of its results - throughput, coverage, latency or other network metric - rather uses the results of all tests performed and recorded. We believe that just like the user experience with sometimes failing web page loading, all results are valid representing the user experience. Other testing systems filter results in a way that biases results to give a more optimistic expectation of network performance than a user will typically experience.

Not Just for Crowds. Crowdsourcing is a fashionable method for collecting data at scale - but it has an inherent selection bias of only collecting data from where it is chosen to be used by those people who choose to use it. Where there is no crowd there is no data. And even where there is is data, it is biased towards who collected it, why, when and where.

CalSPEED has two complementary methods of testing - the first is a structured sampling program of

1986[7] measurement locations scattered throughout California (tribal, rural and urban) that are each periodically (every six months) visited and methodically measured with CalSPEED on both the latest Android phones and a USB network device on a Windows based netbook for each of the four major carriers. The use of multiple contemporary user devices gives a good snapshot of the best user experience.

The second method is the independent use of CalSPEED to provide crowdsourced data. The structured sampling program avoids selection bias of when and where measurements are made, giving a full map that covers the entire state, including places not often visited by smartphone users but having mobile broadband service. The crowd sourced data adds additional detail to areas where there are people who choose to use the test and adds additional detail about the range of the installed base of phones (particularly legacy mobile devices) and the performance those user devices are seeing. The structured measurement program uses the most current user devices available at the time of each round of field measurement and thus gives a snapshot of the latest deployed network technology. Older user devices, with older wireless technology still in use by many, will likely get slower performance in many locations.

Because CalSPEED samples all areas of California - urban (37%), rural (56%) and tribal (7%), analysis of its results explicitly measures the state's mobile digital divide.

Not Just Data but Voice and Video. CalSPEED measures not only the underlying basic Internet data transmission of datagrams and TCP connections, but also interactive voice (the Internet's replacement for POTS), streaming video and interactive video (video conferencing).

CalSPEED constructs an over-the-top interactive voice model, using the LTE voice digitization method, that gives an estimate of the Mean Opinion Score (MOS) of the voice service.

CalSPEED uses a derivative of the Googles' video quality metric[8] to construct a metric of Internet video quality. CalSPEED measures both downstream streaming video (such as YouTube or Netflix) as well as interactive video (such as Skype or FaceTime). Streaming video is measured using downstream performance from CalSPEED's West server - assuming that most such video is cached closer to the user. Interactive video is measured both to the West and East servers (to assess the affect of the Internet backbone) and uses both upstream and downstream performance measures.

Maps for decision-makers not just for information. We then take the measurement data and create geospatial kriging[9] maps interpolating CalSPEED measurements of (but not limited to) latency, downstream and upstream throughput, jitter and packet loss over the entire state.

These maps can be overlaid with other geostatistical data on population, income, ethnicity, education, and census areas to provide more informed choices for consumers, businesses and governments. The CPUC web site uses this data to suggest what mobile service is available and at what performance at locations of the consumer's choice.

7 Originally 1200, but later increased to improve predictive precision of the interpolation models.

8 https://www.google.com/get/videoqualityreport/#methodology

9 http://en.wikipedia.org/wiki/Kriging

Massive Dataset. CalSPEED has now had eleven rounds of sampling California (Spring 2012, Fall 2012, Spring 2013, Fall 2013, Spring 2014, Fall of 2014, Spring 2015, Fall 2015, Spring 2016, Fall 2016, and Spring 2017) and is shortly to finish a twelfth round (Fall 2017). In each sampling round, we have surveyed the entire state and all four of the major wireless carriers - AT&T Mobility, Sprint, T-Mobile and Verizon Wireless.

Appendix B: Terms

Term	Definition
Downstream	The Internet direction from a server to a client.
East Server	Test server located on the East Coast in the Northern Virginia Amazon AWS
Jitter	The variation in end to end packet latency between user and server.
Kriging	A geostatistical technique for interpolating data from a sample set.
Latency	The end to end round trip delay for a single packet to traverse the Internet from user to server and back.
MOS	Mean Opinion Score. A measurement of VoIP quality
Packet Loss	The rate of loss of packet delivery end to end.
TCP	Transmission Control Protocol. The essential end to end protocol for the Internet that creates a reliable, sequentially delivered byte stream via a sequence of individual IP datagrams.
TCP Connection Failure	Each TCP connection requires a bidirectional packet handshake to initialize data flow. If the handshake cannot occur within a timeout period, the connection fails. The rate of failure is one measurement of the quality of the Internet connection.
Throughput	The number of bytes per second of user data communicated end to end.
Upstream	The Internet direction from a client to a server.
VoIP	Voice over Internet Protocol. Generic name for a family of IP based protocols to replace legacy circuit switched voice with packet based voice.
West Server	Test server located on the West Coast in the San Francisco Bay Area in the Amazon AWS