LOON AND A TERRESTRIAL LTE NETWORK

HOW LOON COVERAGE IMPACTS AN EXISTING TERRESTRIAL LTE NETWORK, THE INTERACTIONS BETWEEN THE TWO NETWORKS, AND THE LOON USER EXPERIENCE

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Prepared by

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We conducted this benchmark study on behalf of Loon, LLC. We stand behind analysis and commentary provided in this report, which are supported by results from extensive testing done over a five-day period in a region just south of Tarapoto, Peru.

In addition to providing consulting services on wireless-related topics, including performance benchmark studies, Signals Research Group is the publisher of the *Signals Ahead* and *Signals Flash!* research reports (www.signalsresearch.com).

Key Highlights

Signals Research Group (SRG) conducted a comprehensive network performance benchmark study of Loon. We collected the data over a period of five days (September 23–27) in a region just south of Tarapoto, Peru. The results presented in this paper stem from a combination of drive testing and walk testing in a very rural part of the country where terrestrial LTE coverage wasn't always available. The results and our commentary are based on the capabilities of Loon and the configuration used in this network deployment when we tested it in 2019. We recognize that these performance results do not take into consideration pending and potential improvements to the Loon system, not to mention different deployment configurations that are currently available.

We used a Rohde & Schwarz scanner to capture fundamental network parameters, including signal strength (RSRP) and signal quality (SINR) from the nearby serving cell sites (PCIs), which could be terrestrial cell sites or Loon balloons overhead. We also used a mix of smartphones, connected to Accuver America's XCAL-M and XCAL-Solo drive test solutions, to log LTE chipset diagnostic messages. We used chipset messages to augment scanner data and to help us quantify the user experience with Loon.

Key observations, which we support with test results and analysis in this paper, include the following:

Loon only has a modest detrimental impact on the existing terrestrial LTE network while improving coverage in areas where terrestrial LTE coverage does not exist. Any time a new cell site gets deployed in an LTE network it will generate at least some interference with adjacent cells. Loon is no different. However, we only detected Loon's presence in poor terrestrial coverage areas since the Loon signal strength (RSRP) was almost always below -100 dBm. Further, self-interference between terrestrial LTE sites, which is typical in an LTE network, existed even in the absence of Loon while Loon's contribution to interference in the LTE network was comparable to the interference generated by other terrestrial cell sites. The self-interference in the terrestrial network was also present in high geometry scenarios (strong RSRP) while Loon's impact on the terrestrial network was frequently limited to a small region of the network – outside that region Loon provided coverage where the terrestrial network coverage wasn't adequate or the Loon signal strength was sufficiently below the terrestrial network that it had minimal impact on the terrestrial LTE network.

The performance of the Loon network is somewhat comparable to a terrestrial LTE network with similar attributes. The Loon network that we tested primarily used a 2x10 MHz channel in Band 28 (DL = 795.5 MHz) so comparisons with a terrestrial LTE network need to be made accordingly. We also briefly tested a Loon 2x5 MHz channel bandwidth, and we know Loon can operate in other frequency bands, plus support other channel bandwidths that we did not test. Although we observed sustained data speeds in the high teens (Mbps) and a peak physical layer throughput that was just over 40 Mbps (BLER = ~10%), we believe more typical data speeds with Loon are in the mid- to high- single digits. Latency was also only modestly higher (13%) than the terrestrial LTE network. Although we didn't analyze battery life, we noticed the transmit power of the smartphones connected to Loon was frequently 23 dBm – the highest transmit power level – even when downloading content. The Loon network we tested wasn't optimized for handovers with the terrestrial LTE network or between different Loon cells. Nonetheless, when moving between Loon cells or between Loon and the terrestrial network (and vice versa) the smartphone does an RRC detach/attach that was fast enough it should go unnoticed by consumers. Further integration of the Loon network and the terrestrial network is possible and it should improve handovers and cell reselection, but we have not yet tested this configuration.

The user experience with Loon is surprisingly good. Separate from data speeds and latency, we also evaluated how Loon performed with popular mobile data applications, such as web browsing, video chat, YouTube, and downloading applications from Google Play. Web page load times were very comparable with Wi-Fi and LTE – sometimes a bit faster and sometimes a bit slower. Our experience with streaming 360p and 720p videos was favorable with no buffering although the video start times took a bit longer than the terrestrial LTE network (2x20 MHz channel bandwidth) and Wi-Fi. Likewise, the download times with Google Play took a bit longer with Loon than the terrestrial LTE network, but it is an unfair comparison since the Google Play (and YouTube) tests took place in Tarapoto where the operator has LTE deployed in Band 4 (2x20 MHz channels) and the Loon testing occurred in a region where terrestrial LTE coverage did not exist. We also successfully placed a video chat call (Google Duo) back to the United States, and while the quality of the video wasn't as good as we experience when we use video chat applications at home, it was more than satisfactory without any observable video freezes or dropped audio.

We expand on our findings in the next chapter and then back them up with detailed analysis of multiple test scenarios in the subsequent chapters of this paper. We include additional test results without commentary in the appendix.

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1.0 Key Findings and Observations

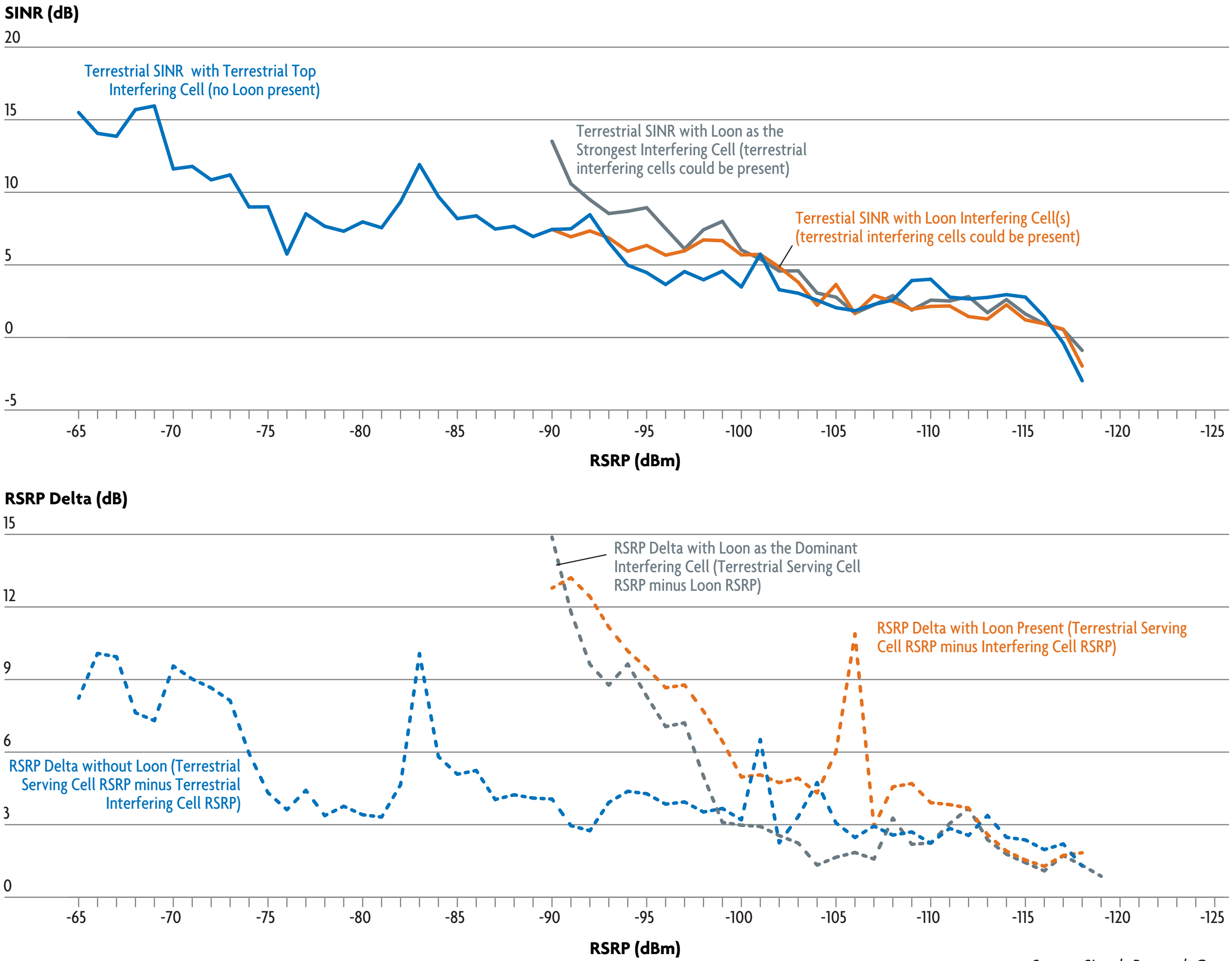
Much of our focus while testing in Peru and the analysis phase once we returned pertained to how Loon impacted the terrestrial LTE network. Specifically, we wanted to determine if Loon could be a "good neighbor" to the terrestrial network by providing adequate coverage in areas the terrestrial network did not cover and, most importantly, minimizing interference at the boundary between the two networks. Additionally, we wanted to determine how well Loon performed and the subsequent user experience. The two figures in this chapter summarize our overall findings.

To determine the impact on the terrestrial LTE network, we aggregated all relevant test results with scanner data (e.g., most of the tests provided in this paper and in the appendix). To ensure the results weren't influenced by an overweighting of data points in one location versus another location (e.g., due to differences in vehicular speed or the inclusion of stationary tests), we geo binned the data in 3-meter quadrants. We filtered this data (nearly 20,000 data points) into three buckets. Each bucket required the strongest cell, based on measured RSRP, to be a terrestrial cell site (PCI). The first bucket includes results where the scanner did not detect the presence of a Loon PCI in any of the top four interfering cells. We only included the top four interfering cells, plus the strongest cell, in this analysis since the relative signal strength of additional cells would be well below that of the strongest cell. The second bucket includes results where the scanner detected a Loon PCI as an interfering cell in the list of top four interfering cells. This bucket includes instances when there was a terrestrial cell with higher interference than the Loon cell, although the Loon cell was still present in the list of top four interfering cells. Finally, we looked at data points for those cases when Loon was the strongest interfering cell site. This bucket is a subset of the second bucket since it excludes data points when Loon was the second, third or fourth strongest interfering site with terrestrial cell(s) generating more interference.

The signal quality in the terrestrial network in the absence of Loon was no different than the signal quality with Loon.

Figure 1 summarizes the results of this analysis. The solid lines in the top figure show the relationship between the RSRP and SINR of the terrestrial cell site with the strongest signal. We calculated the median RSRP at each SINR value for the three previously described buckets. All three lines show an upward trend with increasing RSRP, but the *Terrestrial SINR with Loon as the Strongest Interfering Cell* line is higher in absolute terms and it increases more rapidly with higher RSRP, for reasons explained in a bit. Comparing the *Terrestrial SINR with Terrestrial Top Interfering Cell* and *Terrestrial SINR with Loon Interfering Cell(s)* lines, it is evident the SINR values are quite similar – the terrestrial signal quality was slightly better with Loon as the interfering source between -90 dBm and -105 dBm and the terrestrial signal quality was modestly better without Loon's presence when the RSRP was below -105 dBm. There were not enough data points to extend the plots below -118 dBm since frequently Loon was the dominant cell in this region of RSRP.

Figure 1. Terrestrial LTE Network Signal Quality with and without Loon



Source: Signals Research Group

The median RSRP of the strongest Loon cell was frequently below -105 dBm if not below -110 dBm.

In the detailed analysis in the next chapter we show the median and cumulative distribution of the Loon RSRP in the drive tests we conducted. The median RSRP of the strongest Loon cell was frequently below -105 dBm if not below -110 dBm and the strongest Loon signal rarely exceeded -100 dBm. For this reason, when Loon was the dominant source of interference, its impact on the terrestrial LTE network dropped off more rapidly with increasing RSRP in the terrestrial LTE network – hence the more rapid increase in the *Terrestrial SINR with Loon as the Strongest Interfering Cell* line. Likewise, when the LTE terrestrial network RSRP was higher than -90 dBm, there would almost always be a separation of at least 15 dB between the signal strength of the LTE network and the signal strength of Loon. In other words, Loon had no detrimental impact on the terrestrial LTE network in the higher RSRP regions of the network.

The second figure shows the delta between the RSRP of the terrestrial serving cell and the source of interference, which could be a Loon cell or another terrestrial cell. As expected, the scenario with Loon as the strongest interfering cell *(RSRP Delta with Loon as the Dominant Interfering Cell)* had the steepest increase in the RSRP delta. For example, when the terrestrial cell RSRP was -90 dBm, the median separation with the Loon cell site serving as the strongest source of interference was 14.9 dB. The *RSRP Delta without Loon* line shows a very gradual increase in the delta with increasing RSRP. This trend is due to the self-interference within the terrestrial LTE network that existed, even with very favorable RF conditions. We provide additional clarity on this point later in this paper.

In addition to analyzing the impact of Loon on a terrestrial network, we also evaluated Loon's ability to provide cellular coverage. Due to the length of time required to drive from Tarapoto to the start of the Loon coverage area, we couldn't test the breadth of Loon coverage in the region. However, we extended far enough into Loon-only coverage to evaluate its performance, plus we were able to evaluate how mobile devices perform when moving between the two networks as well as between different Loon cells.

Loon's performance was somewhat comparable to a terrestrial LTE network, especially when compared with a terrestrial LTE network utilizing a single 2x10 MHz channel. Measured physical layer data speeds were typically in the mid- to high- single digits (Mbps) although we did observe sustained data speeds in the mid-teens with a peak speed of just over 40 Mbps. Loon wasn't designed to provide in-building coverage, nor was it designed to provide in-vehicle coverage. However, we witnessed Loon sustain a video call for several kilometers without dropping the connection even though the smartphone was located within the test van. We also point out that in the region where we tested, open-air Moto taxis were the dominant form of transportation used by the locals.

Latency using Loon was only 13% higher than the terrestrial network, although the transmit power was frequently much higher with Loon than with the terrestrial network.

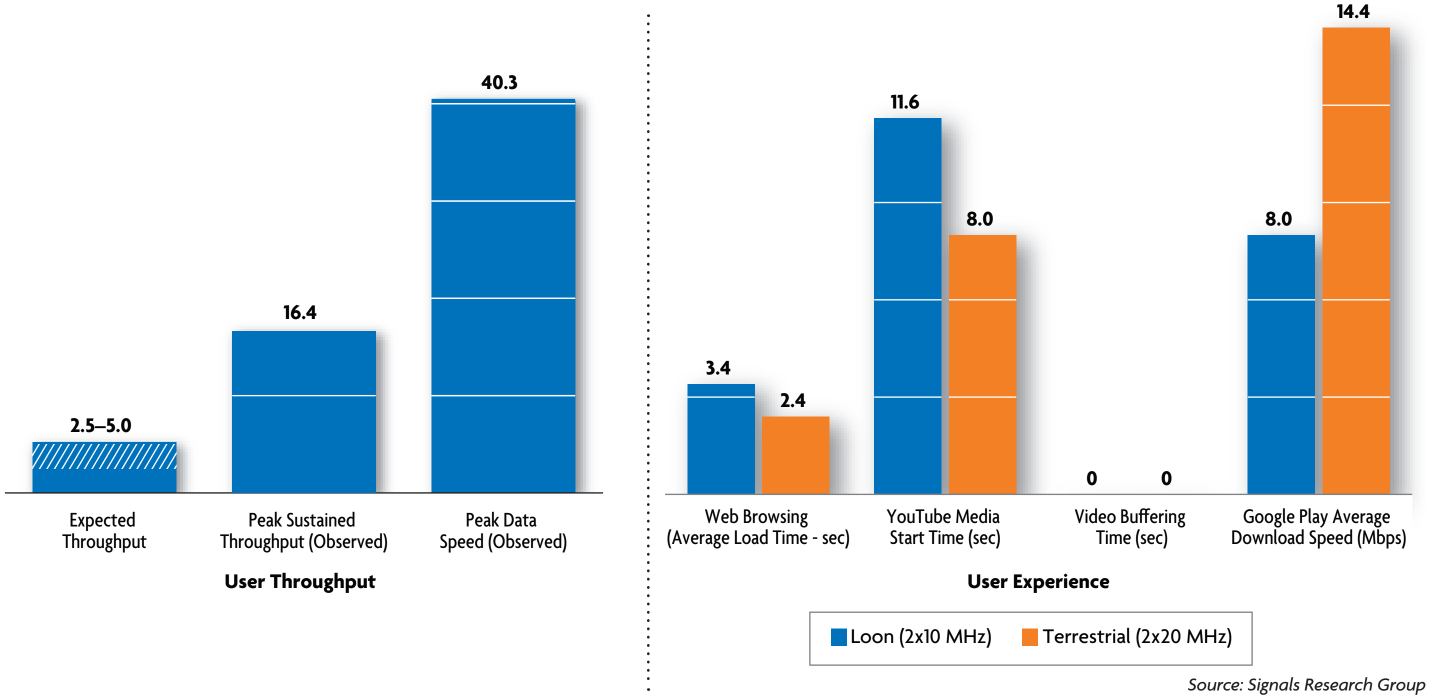
Latency was another area of interest. Our results found that latency using Loon was only 13% higher than the terrestrial network, based on round trip time (RTT) ping tests to a local server. The Block Error Rate (BLER) during FTP data transfer tests was also consistent with what we observe in terrestrial networks, or just under 10%. We did identify higher transmit power with Loon than with the terrestrial network. The PUSCH transmit power with Loon was 23 dBm, including while web browsing or streaming a YouTube video. These values were much higher than what we observed with the terrestrial network while web browsing (13.3 dBm) or streaming a YouTube video (9.69 dBm). The terrestrial results, in this case, stem from testing that we did in Tarapoto when the smartphone was connected to Band 4 and the serving cell site was likely nearby our location. In one of our tests in a Loon coverage area the mobile device did one FTP transfer over the terrestrial network before switching to Loon and doing a second FTP transfer. With this scenario, which represents a fairer comparison, the transmit power with Loon was only 4 dB higher than over the terrestrial network. The terrestrial cell site was likely far away from our location, hence the transmit power was higher than it was in the city.

It took the mobile device just under 2 seconds to move between networks and it took less than 20 ms to move between Loon cells.

A mobile device moving between the two networks does an RRC detach from the origin network and then an RRC attach to the destination network. In our tests it took the mobile device just under 2 seconds to move between the networks and it took less than 20 ms to move between Loon cells. A consumer wouldn't likely notice when the mobile device switched networks and it would seemingly be impossible to observe the mobile device moving between Loon cells without appropriate test equipment. In another test, also highlighted in this paper, we observed the Loon network can switch ground stations, which provide the S1 connection to the Loon balloons, without any meaningful disruption. We were performing a sustained FTP data transfer when the Loon engineers reconfigured the network for the new ground station, and we could barely detect the impact when analyzing the log file. Switching ground stations might be required due to poor weather conditions, which would cause impacts to the S1 connection as discussed. From the test results, this should not cause a noticeable impact to the user experience.

Figure 2 summarizes some results from the performance and user experience testing that we performed.

Figure 2. Loon Performance and the User Experience



Source: Signals Research Group

Loon delivered a good user experience with several applications that was largely on par with the terrestrial LTE network and Wi-Fi.

Although we observed a sustained data speed of 16.4 Mbps over a period of several minutes (peak = 40.3 Mbps), we believe an expected data speed of 2.5 to 5 Mbps is more realistic, especially when other people are accessing the Loon network. The user experience results also reflect good performance relative to the terrestrial LTE network, even though the comparison isn't fair since the terrestrial LTE network used a 2x20 MHz radio channel. The terrestrial LTE user experience testing also took place in Tarapoto where we would expect much better performance than in the rural areas where we tested Loon. For web browsing, the average web page load time for some of the most popular mobile websites in Peru was 3.4 seconds with Loon and 2.4 seconds with the terrestrial network. With YouTube, the video took 3.6 seconds longer to start playing, but there wasn't any video buffering once the video started to play. We used 360p and 720p video resolution, with the latter probably being the upper limit for typical Loon network conditions. Finally, we observed an average data speed of 8 Mbps while downloading an application from Google Play versus 14.4 Mbps with the terrestrial LTE network.

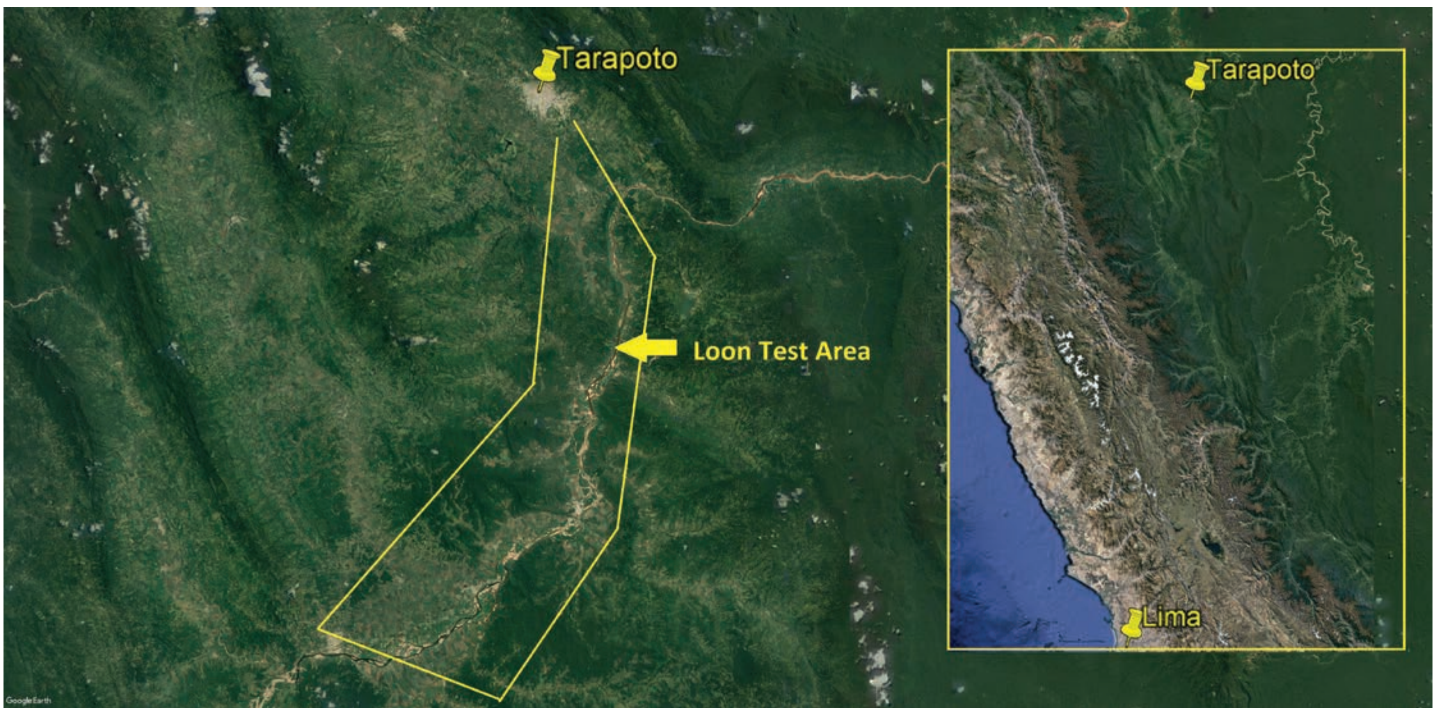
In the next three chapters we provide test results which support these observations. Chapter 3 addresses Loon's impact on the terrestrial LTE network. Chapter 4 deals with Loon coverage and the interactions between the two networks. Finally, Chapter 5 provides the results and analysis from the user experience tests.

2.0 The Impact of Loon on an Existing Terrestrial LTE Network

In this section, we include results and analysis for three sets of drive test results, which occurred on two different days in an area that started 8 kilometers south of Tarapoto and extended for an additional 52 kilometers further south, not to mention along tangential roads. We also include results from two stationary tests where we turned Loon coverage on and off. Collecting data on different days meant the Loon balloons in the vicinity were at different positions relative to their terrestrial cell sites. We've selected these tests, because we could detect the presence of the Loon serving cells, even if the terrestrial network had the dominant serving cell (e.g., the strongest signal strength). In other words, these test results are ideal for determining how Loon impacted the terrestrial LTE network when the terrestrial network was providing primary coverage. In the appendix, we include some additional test results.

Figure 3 provides a geo plot of the Loon test area.

Figure 3. Loon Test Area

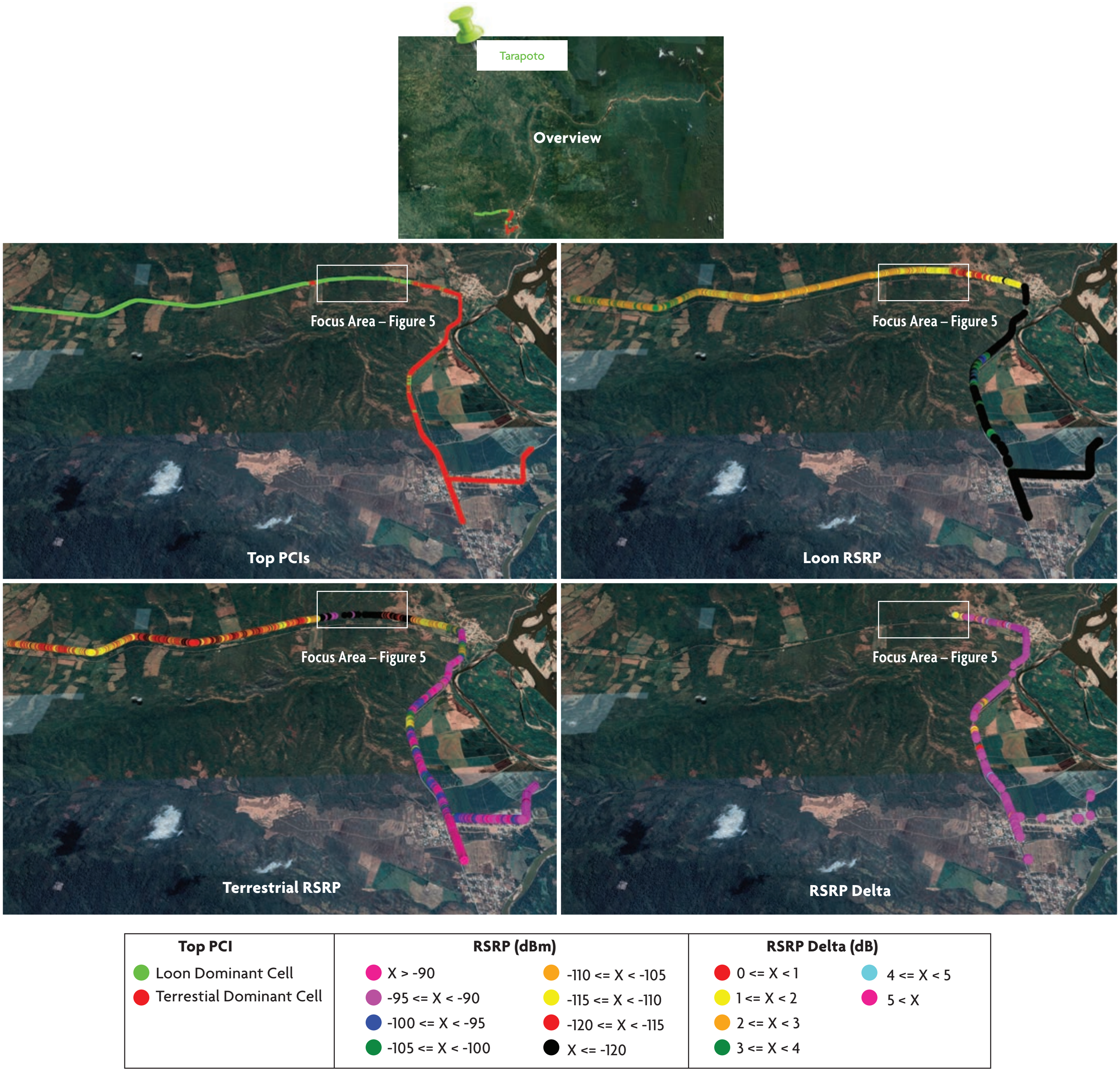


Source: Signals Research Group

2.1 Tests 61 Through Test 71

We combined these tests into a single study for analysis purposes, since each individual test was merely a continuation of the preceding test without any other meaningful differentiation. Figure 4 provides four key metrics in a geo plot of the 18-kilometer test. The Green-Red line identifies if the terrestrial network (Red) or Loon (Green) was providing cellular coverage, as determined by the

Figure 4. Test 61-71 Key Metrics – geo plot



Source: Signals Research Group

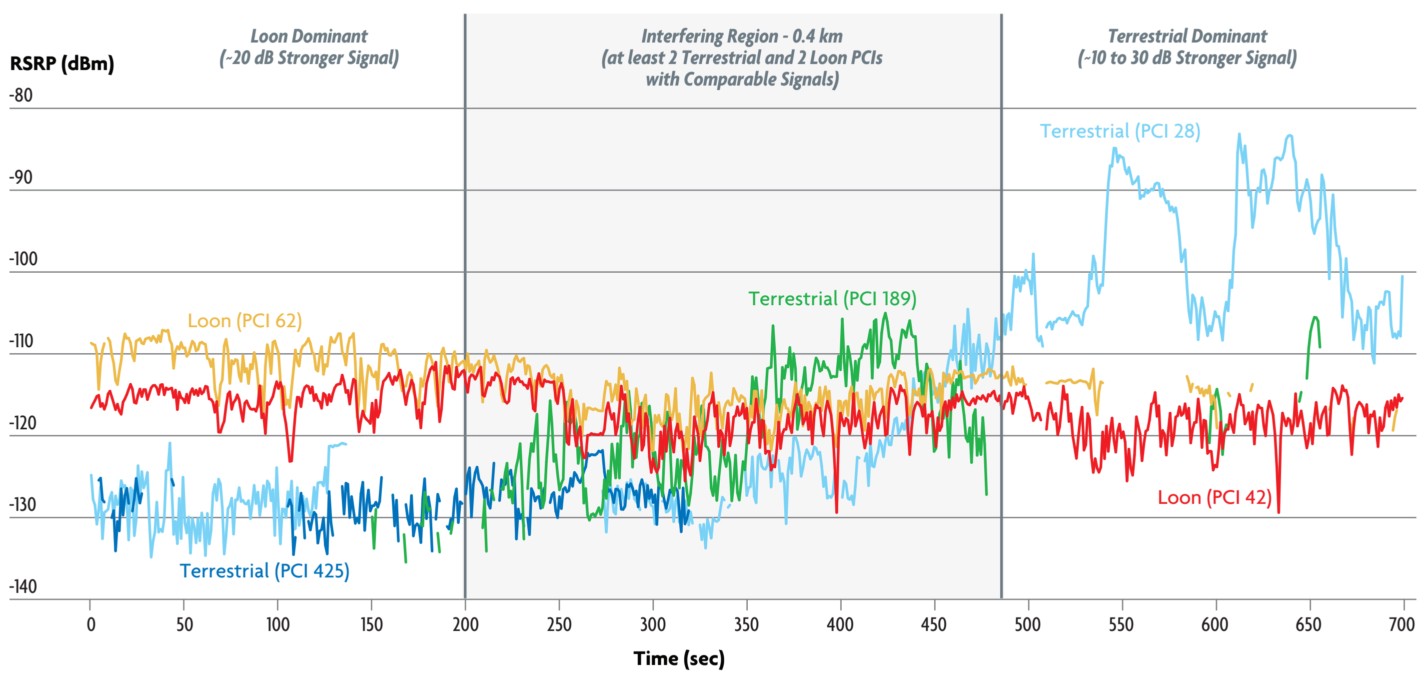
serving cell PCI with the strongest signal (RSRP). We used the R&S scanner to make this determination. The figure also shows the signal strength of the strongest Loon and the strongest terrestrial PCI at each point along the route. Black indicates the scanner could not detect the presence of the pertinent network. Finally, the RSRP Delta plot shows the difference in signal strength between the serving terrestrial cell site and the strongest Loon PCI. In the event Loon was the dominant cell, no colored circle is shown. This attribute explains why much of this plotted line is "missing."

There was a strong delineation between the area covered by the terrestrial network and the area covered by Loon.

Looking at the four bottom images in the figure, there are a few observations worth making. First, there was a strong delineation between the area covered by the terrestrial network and the area covered by Loon. Additionally, in terrestrial-covered areas the Loon signal was generally weak. or it went undetected (black circles). Likewise, in areas where Loon was the dominant cell, the terrestrial signal strength was generally very weak and frequently below -115 dBm. It is worth noting the Loon signal rarely exceeded -105 dBm, based on scanner measurements. Lastly, the RSRP delta image shows the differences between the strongest terrestrial cell and the strongest Loon cell were frequently more than 5 dB (magenta) with some limited regions where the differences in signal strength were more modest, indicating an area where Loon was creating some interference with the terrestrial network.

Figure 5 shows the signal strength for the scanner-detected terrestrial and Loon cells in the highlighted region shown in Figure 4. For the first 200 seconds of the plot, Loon had two PCIs (42 and 62) which were approximately 20 dB higher than the two terrestrial cells, which had very low signals. In this region of the network, Loon provided coverage with inconsequential interference from the terrestrial network. From 500 seconds onward, the terrestrial network (PCI 28) had a much stronger signal than Loon (10-20 dB), indicating the terrestrial network provided coverage with Loon causing inconsequential interference to the network. Finally, between 200 and 500 seconds there was interference between the terrestrial network and Loon, as well as interference between three terrestrial cell sites (PCI 425, 189 and 28). The self-interference in the terrestrial network would exist with or without Loon. This region of the drive route was approximately 0.4 kilometers, compared with the

Figure 5. Terrestrial and Loon RSRP Time Series



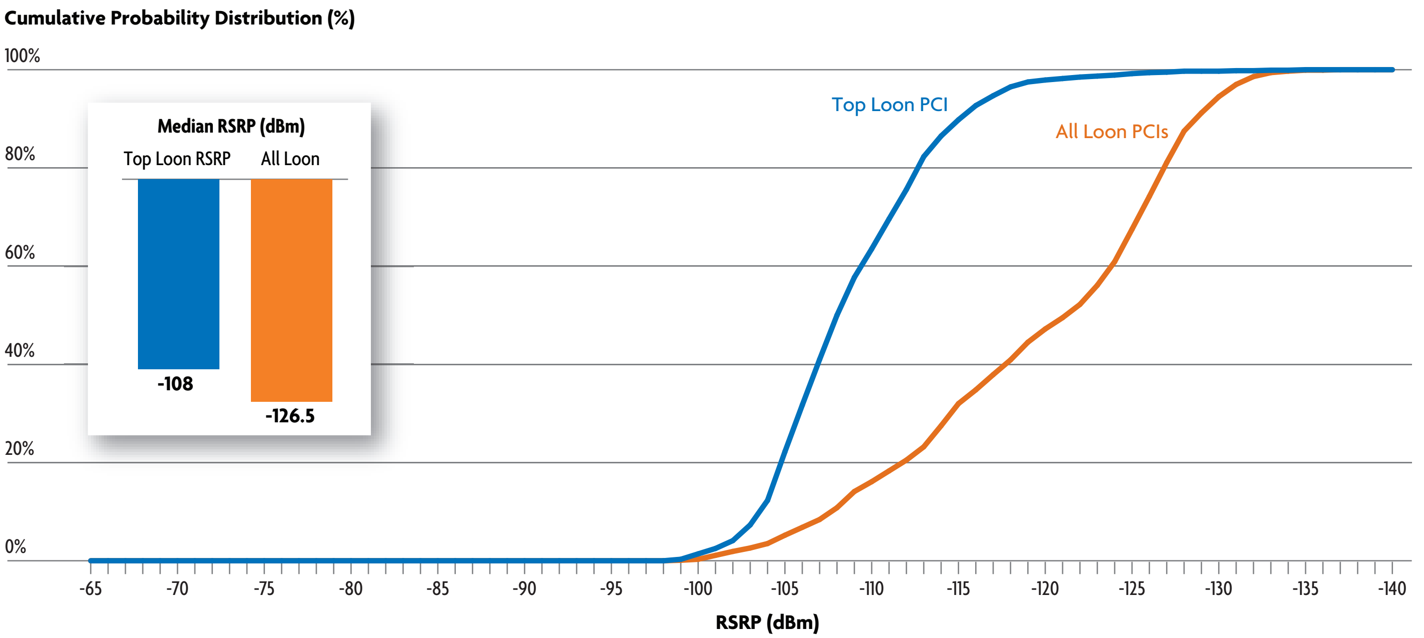
Source: Signals Research Group

8 kilometer stretch where Loon provided the only reliable signal. We didn't continue further down the road so we don't know where (or even if) the terrestrial network would have resumed providing coverage.

The Loon signal strength was rarely higher than -100 dBm and frequently below -110 dBm.

Figure 6 shows the cumulative distribution for the Loon signal strength (RSRP). The Top Loon plot and median value (-108 dBm) reflects the distribution of the strongest detected Loon signal along the route. The All Loon plot and median value (-126.5 dBm) includes all Loon signals, including the strongest Loon signal as well as all the weaker Loon signals detected by the scanner. Including both sets of values demonstrates that while the strongest Loon signal – the one likely used by a mobile device – was more than adequate for providing coverage without unnecessarily high signal levels, Loon can also extend to much lower signal levels. The latter point indicates that the potential Loon coverage area was much greater than we document in this paper.

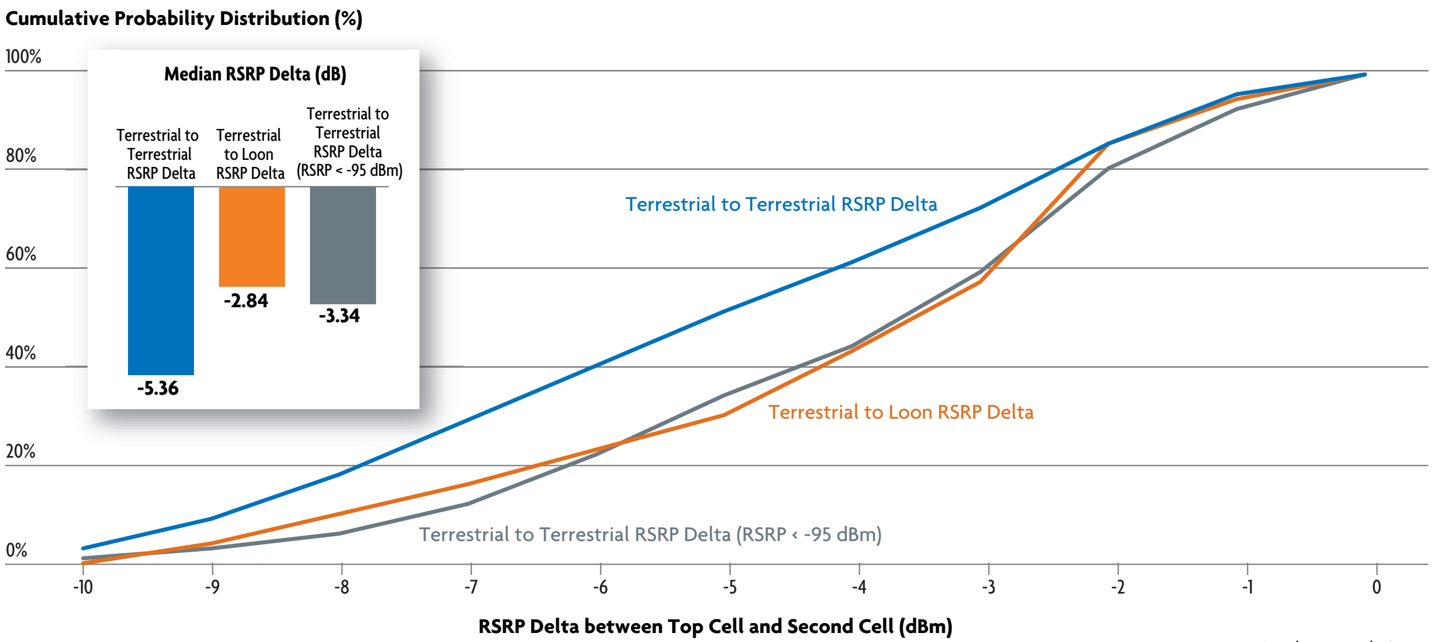
Figure 6. Cumulative Distribution of Loon Signal Strength



Source: Signals Research Group

Finally, Figure 7 shows the cumulative distribution of the differences in signal strength between the top terrestrial cell and the strongest interfering cell. We excluded all instances when Loon was the strongest cell since the focus of this analysis is to evaluate Loon's impact on the terrestrial network and not to highlight Loon's ability to extend coverage (something we do in the next two chapters).

Figure 7. Cumulative Distribution of the Differences in Signal Strength between the Top Terrestrial Cell and the Strongest Interfering Cell



Source: Signals Research Group

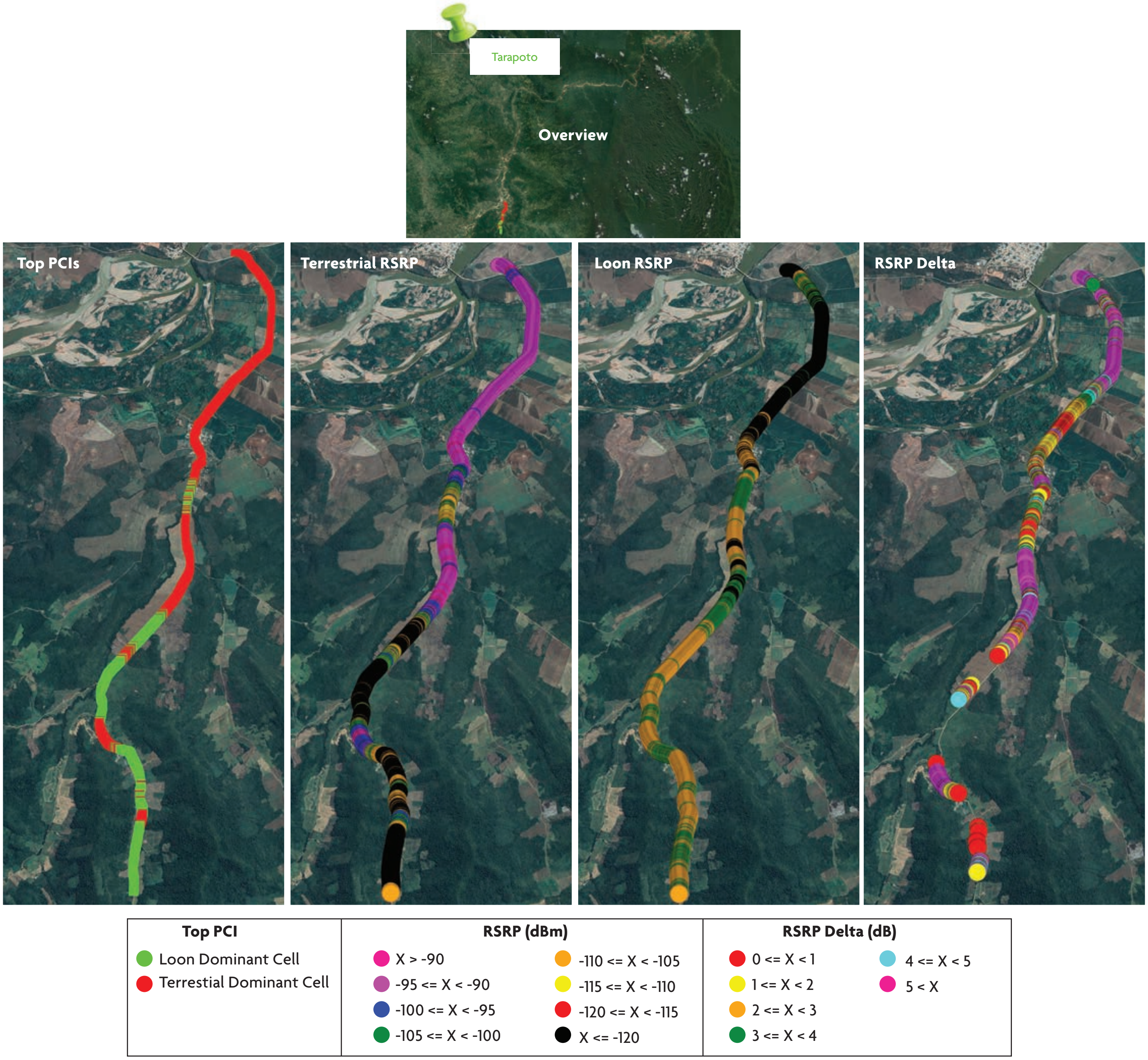
For this analysis, we looked at three scenarios. First, we looked at the differences in signal strength between the top terrestrial cell and the strongest interfering cell, which had to be a terrestrial cell. This relationship, labeled Terrestrial to Terrestrial RSRP Delta, serves as one benchmark we can use to evaluate Loon. With more favorable RSRP, the differences in signal strength between the strongest cell and the top interfering cell should be much higher than when the signal strength from the strongest cell is low, since the latter suggests an edge-of-cell location where there will be detected signals with largely comparable signal strength from multiple cell sites. High RSRP values suggest a location near the serving cell site where interference from adjacent cells should be less pronounced. Since Loon operates in a region with low signal strength from the terrestrial network, we then filtered the terrestrial-terrestrial scenario to only include those data points when the top terrestrial cell had an RSRP below -95 dBm (labeled Terrestrial to Terrestrial RSRP Delta (RSRP < -95 dBm). This comparison is more appropriate for evaluating Loon's impact on the terrestrial network, but we also include the Terrestrial to Terrestrial RSRP Delta scenario with all RSRP values for full transparency. Finally, we included those instances when Loon was the strongest interfering cell with the terrestrial network (labeled Terrestrial to Loon RSRP Delta).

The information in Figure 7 indicates the Loon signal was -2.84 dB lower [median] than the top terrestrial cells' signal strength, or largely comparable to the scenario when the top terrestrial cell's signal strength was below -95 dBm and the strongest interfering cell was another terrestrial cell site. As expected, if we include all RSRP values, the difference in signal strength between the top cell and the interfering terrestrial cell increases to 5.36 dB, since this analysis includes regions of the network where the interference was inherently lower. Looking at the distribution plot, the Terrestrial to Terrestrial RSRP Delta scenario with all RSRP values shows this scenario had the highest probability of having the biggest differences in signal strength [lowest interference]. The plot also shows the Terrestrial to Loon RSRP Delta scenario had a slightly lower probability of having a signal strength that was within 3 dB of the strongest terrestrial cell, compared with the Terrestrial to Terrestrial (RSRP < -95) interference scenario. This observation is important because comparable signal strengths indicate higher interference and a lower signal quality (SINR).

2.2 Test 87

Test 87 took place along an 11.5-kilometer drive route which began 10.5 kilometers southeast of the Test 61-71 drive route, which we analyzed in the previous section. Additionally, we conducted this test on a different day so the locations of the Loon balloons would have been different than with the Test 61-71 study. Figure 8 identifies the location of the drive route and it provides a geo plot of several relevant network metrics. The figure shows that Loon had the strongest cell in the southern portion

Figure 8. Test 87 Key Metrics – geo plot

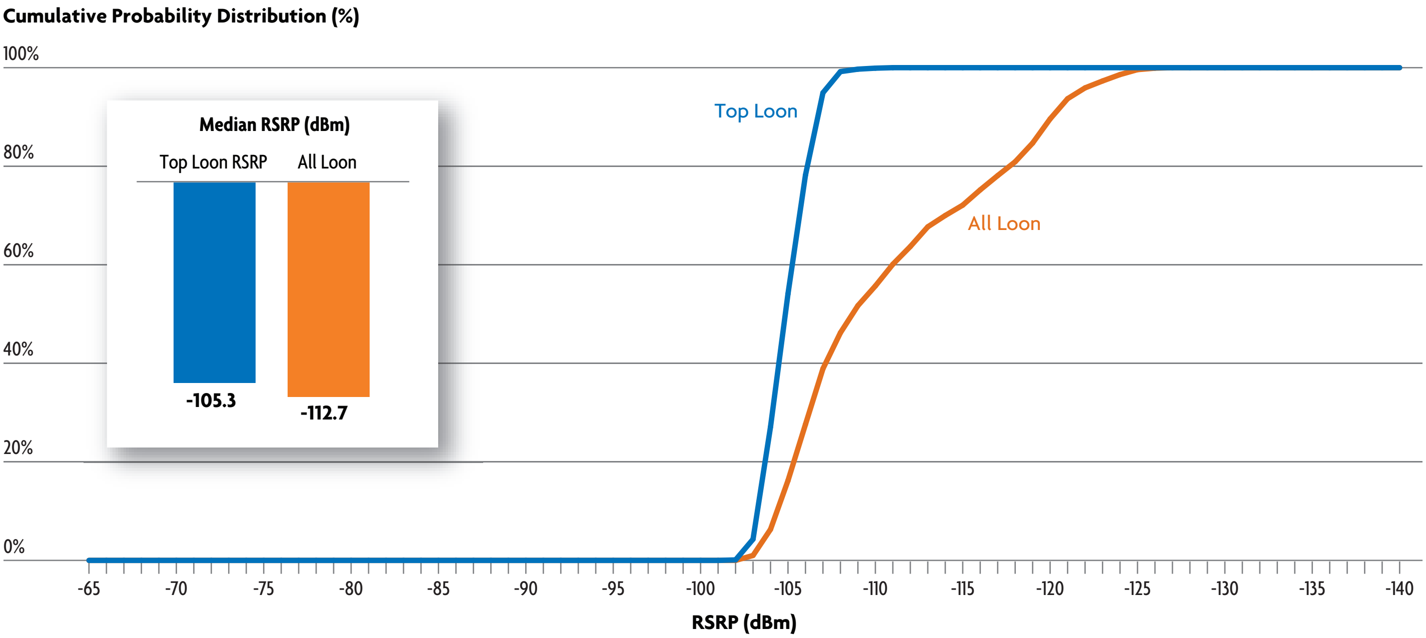


Source: Signals Research Group

of the test where the terrestrial coverage was generally poor with RSRP frequently below -120 dBm. As we continued further north the terrestrial network coverage improved while the signal strength from the Loon cells dropped. The RSRP delta figure shows the relative changes in the terrestrial and Loon signal strengths.

Figure 9 provides the median values and distribution plots for the strongest Loon cell as well for all Loon cells (PCI values), regardless of whether these cells were providing the strongest Loon signal. We detected four unique Loon PCI values during this drive, but one Loon PCI was generally 3-4 dB stronger than two PCIs while the scanner only detected the fourth Loon PCI for a short period of time.

Figure 9. Cumulative Distribution of Loon Signal Strength

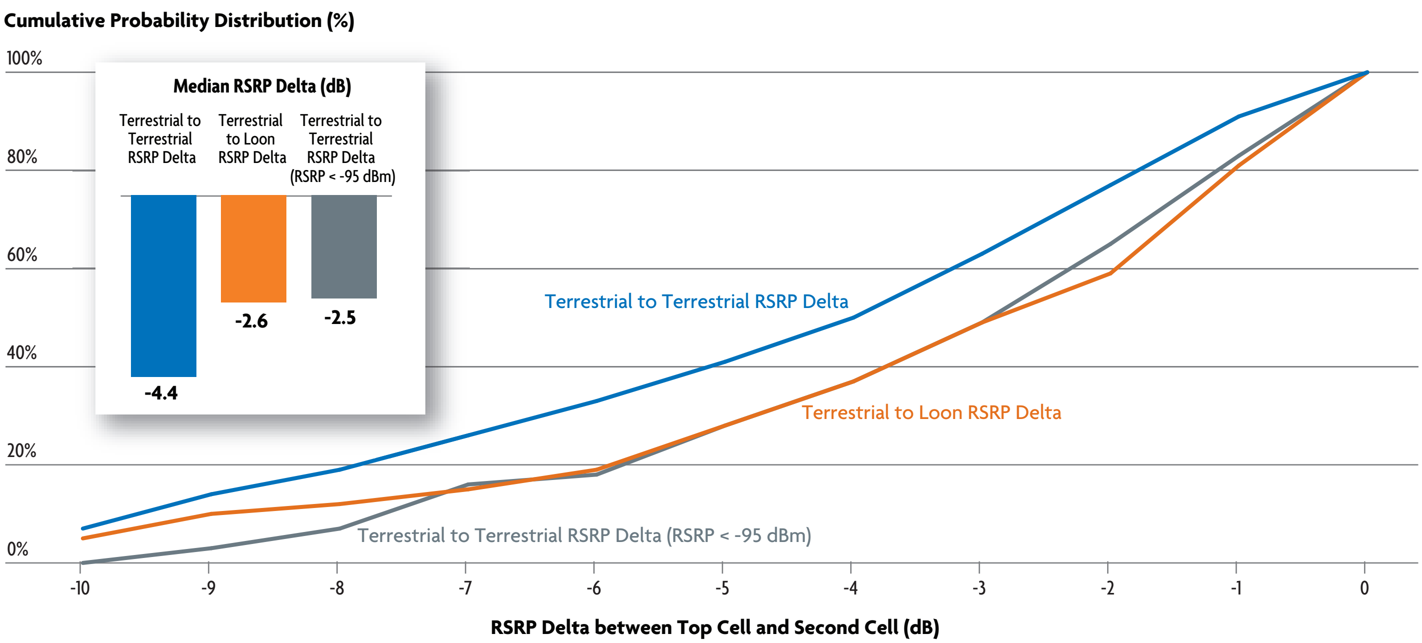


Source: Signals Research Group

Figure 10 shows the cumulative distribution of the differences in signal strength between the top terrestrial cell and the strongest interfering cell. Our approach to this analysis is consistent with what we did in the previous section. For this test, the *Terrestrial to Terrestrial Interference* scenario was higher than in Test 61-71 by nearly 1 dB (5.36 versus 4.4 dB) while the *Terrestrial to Loon Interference* scenario was comparable. More importantly, the results indicate Loon's potential contribution to interference with the terrestrial network was nearly identical to the self-interference that already existed within the terrestrial LTE network when the RSRP was below -95 dBm *(Terrestrial to Terrestrial RSRP Delta (RSRP < -95 dBm)*.

Since there was a good mix of areas along this drive route where Loon was present as well as areas where we couldn't detect Loon (or it was inconsequential), we were able to look at the measured SINR versus RSRP for the two scenarios. To ensure a meaningful set of data to analyze, we included data points in the Terrestrial SINR with Terrestrial Top Interfering Cell scenario if Loon was present, as long as the RSRP was at least 8 dB lower than the top terrestrial cell site and it wasn't the strongest interfering site.

Figure 10. Cumulative Distribution of the Differences in Signal Strength between the Top Terrestrial Cell and the Strongest Interfering Cell

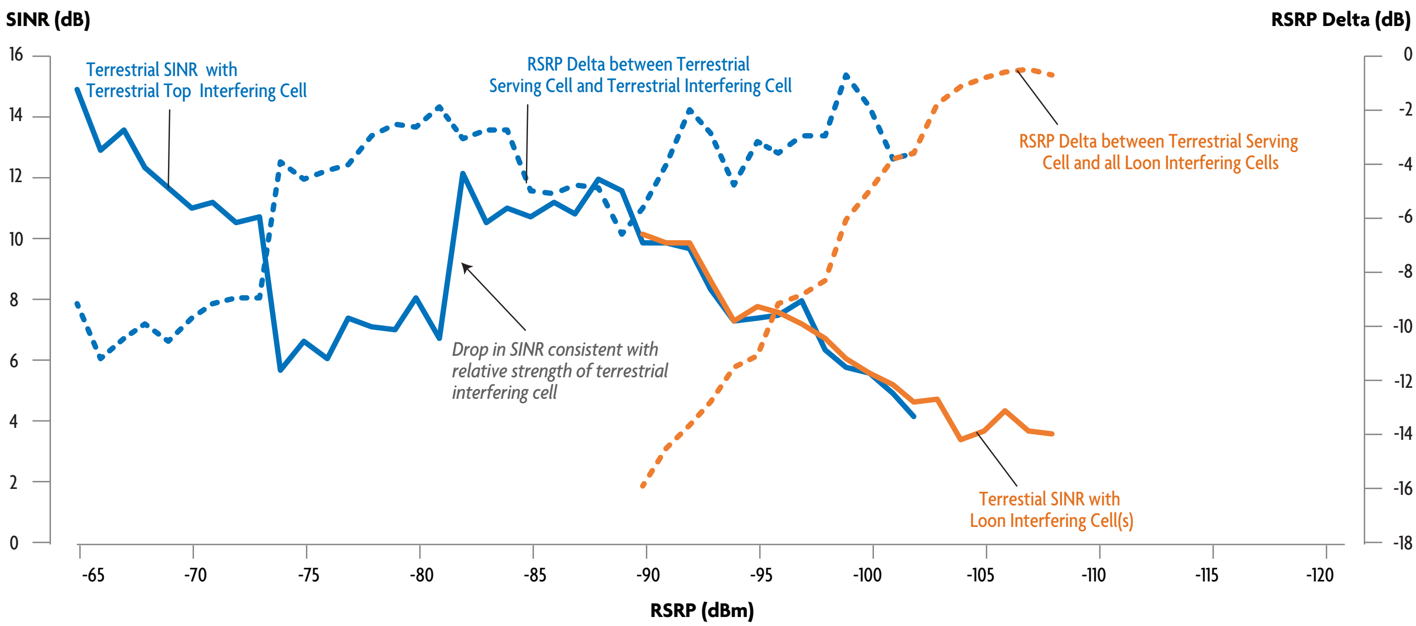


Source: Signals Research Group

As evident in Figure 11, when the measured RSRP from the strongest terrestrial cell was in the range of -90 to -105 dBm, the impact of Loon as an interfering cell site was very comparable to the impact of another terrestrial cell site creating interference. With higher RSRP, the scanner didn't detect Loon's presence or the RSRP delta was so significant (> 20 dB) that Loon would have no impact on the terrestrial LTE signal quality. With RSRP below -105 dBm, Loon was frequently the dominant cell over the terrestrial cells so providing interference-related information for the terrestrial LTE network is not meaningful. The figure also shows that the differences in RSRP between the top terrestrial cell and Loon dropped significantly, and much faster than the Terrestrial SINR with Terrestrial Top Interfering Cell scenario, as the dominant terrestrial cell's RSRP increased.

Figure 11 also shows an interesting phenomenon between RSRP -75 and -85 dBm, which falls outside the range where Loon was detected. Specifically, the differences in RSRP between the top terrestrial cell and the strongest interfering terrestrial cell were much lower and the top terrestrial cell's SINR declined. This information suggests there were two cell sites providing excellent coverage to the same physical location in the network, but the strong signals from both sites negated the benefit due to the increased interference.

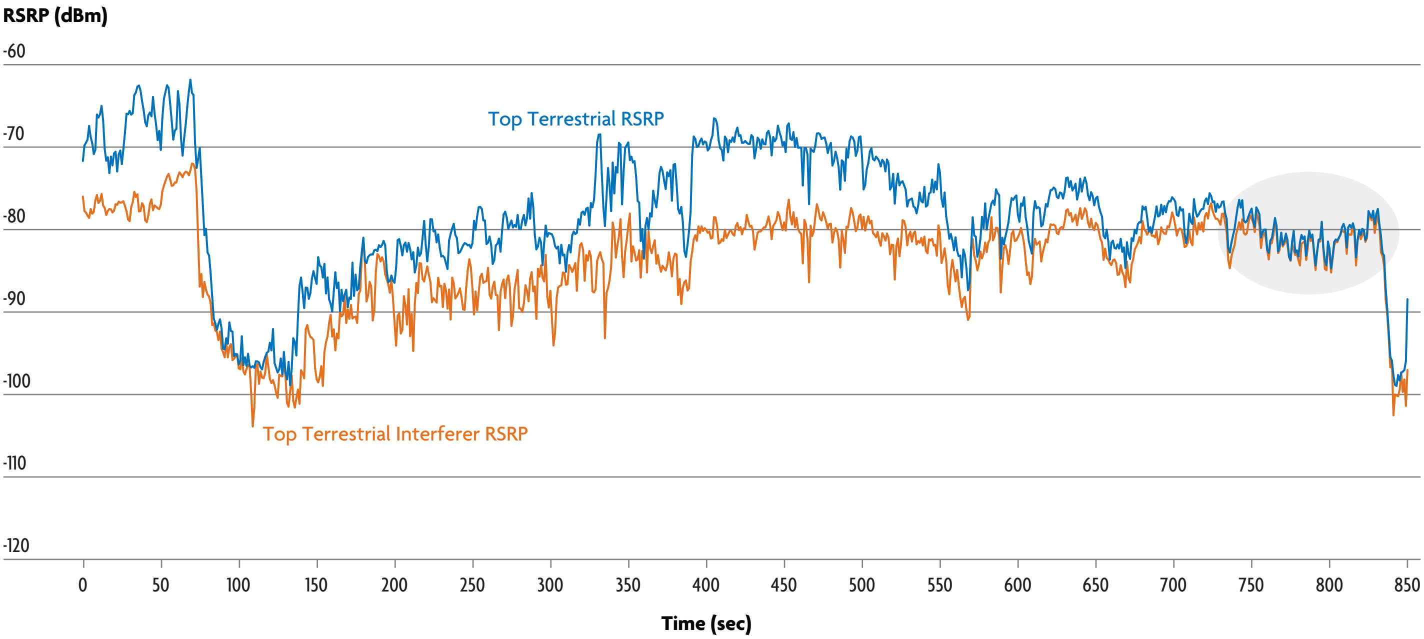
Figure 11. SINR and RSRP Delta as a Function of RSRP



Source: Signals Research Group

Figure 12 provides a time series plot of the scanner measured RSRP for the top terrestrial cell site and the strongest interfering cell site, which was also a terrestrial cell site. Generally, there is a good separation between the two lines, especially with higher absolute RSRP values. However, starting at 700 seconds, both cells had similar RSRP values in an area of the network where the measured RSRP was very favorable. This phenomenon, along with other occurrences along the route, explains the peculiar trends shown in Figure 11.

Figure 12. Time Series Plot of RSRP for Two Terrestrial Cell Sites

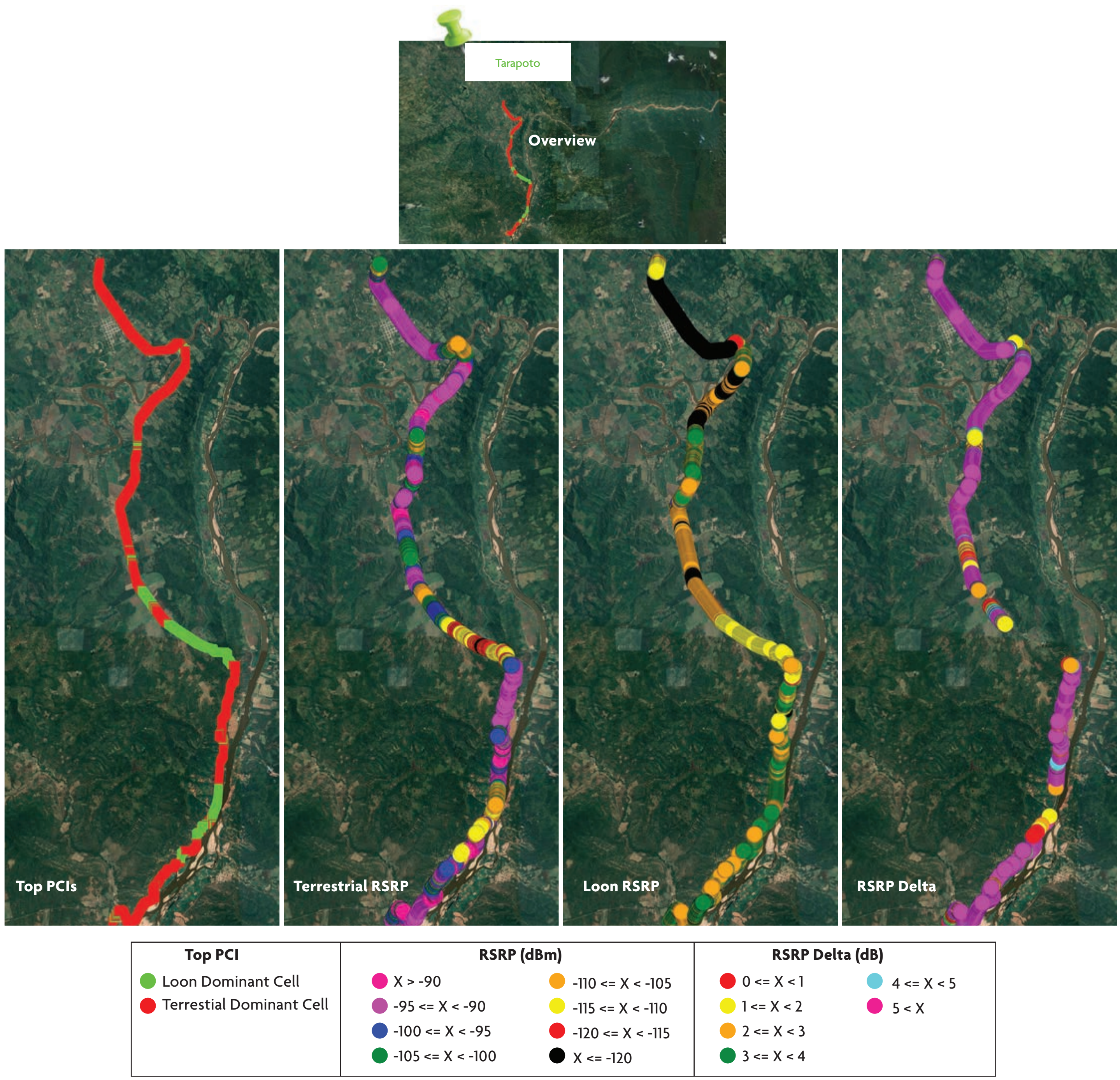


Source: Signals Research Group

2.3 Test 53

The Test 53 drive route started 7 kilometers outside of Tarapoto, winding down 35 kilometers along the major highway until the test ended 32.5 kilometers south of Tarapoto. Figure 13 shows the drive route as well as geo plots of some key performance metrics. Compared with other tests shown in this section, Loon was less frequently the dominant cell site – it provided coverage in the southern

Figure 13. Test 53 Key Metrics – geo plot



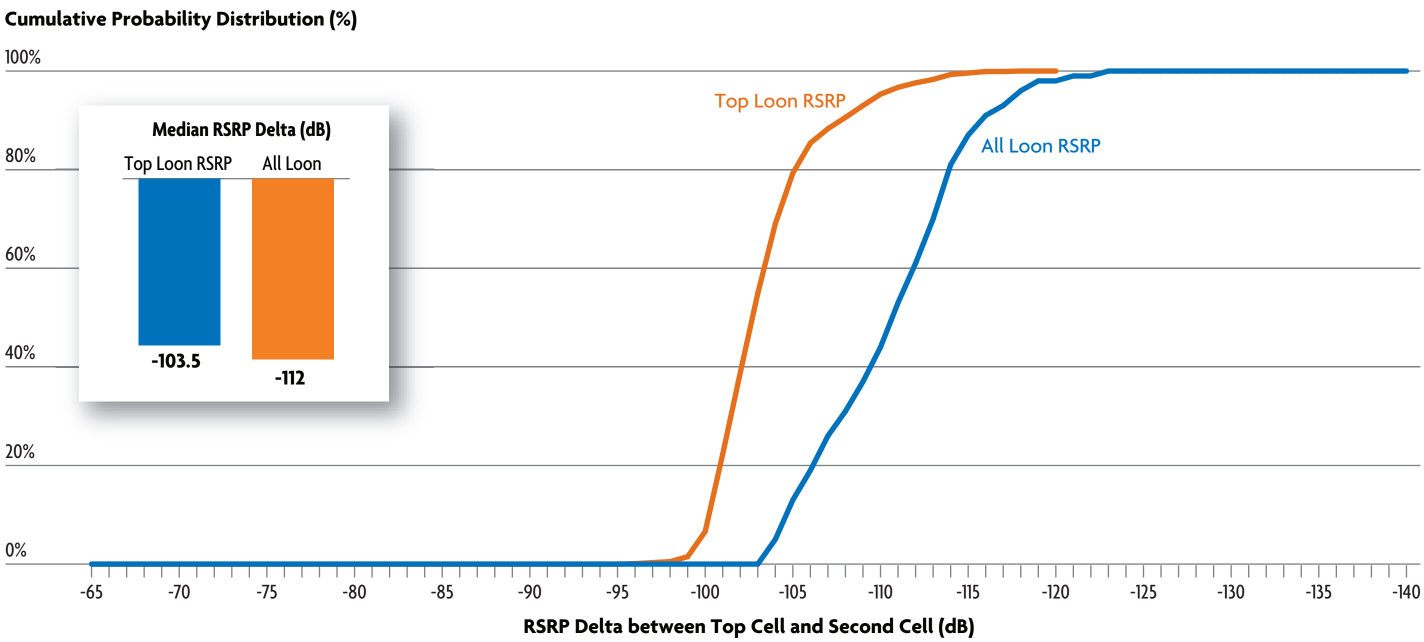
Source: Signals Research Group

portion of the drive route where there was poorer terrestrial coverage. However, Loon was present as a potential source of the interference with the terrestrial network for a good portion of the route.

Loon's impact on the terrestrial network was negligible.

Figure 14 shows the median and cumulative distribution plots for the strongest Loon cell as well as for all detected Loon cells. During this drive, we identified nine different Loon PCI values. Given the relative differences in the signal strength between the Loon cells and the terrestrial network, which was quite good along this route, Loon's impact on the terrestrial network was negligible, meaning that pre-existing self-interference in the terrestrial LTE was largely responsible for the interference that we observed. This statement is supported by the information in Figure 15, which shows the median delta between the terrestrial network and Loon was 9.63 dB, compared with only 5.21 dB with Terrestrial to Terrestrial interference scenario and 4.58 dB for the Terrestrial to Terrestrial (RSRP < -95 dBm) scenario.

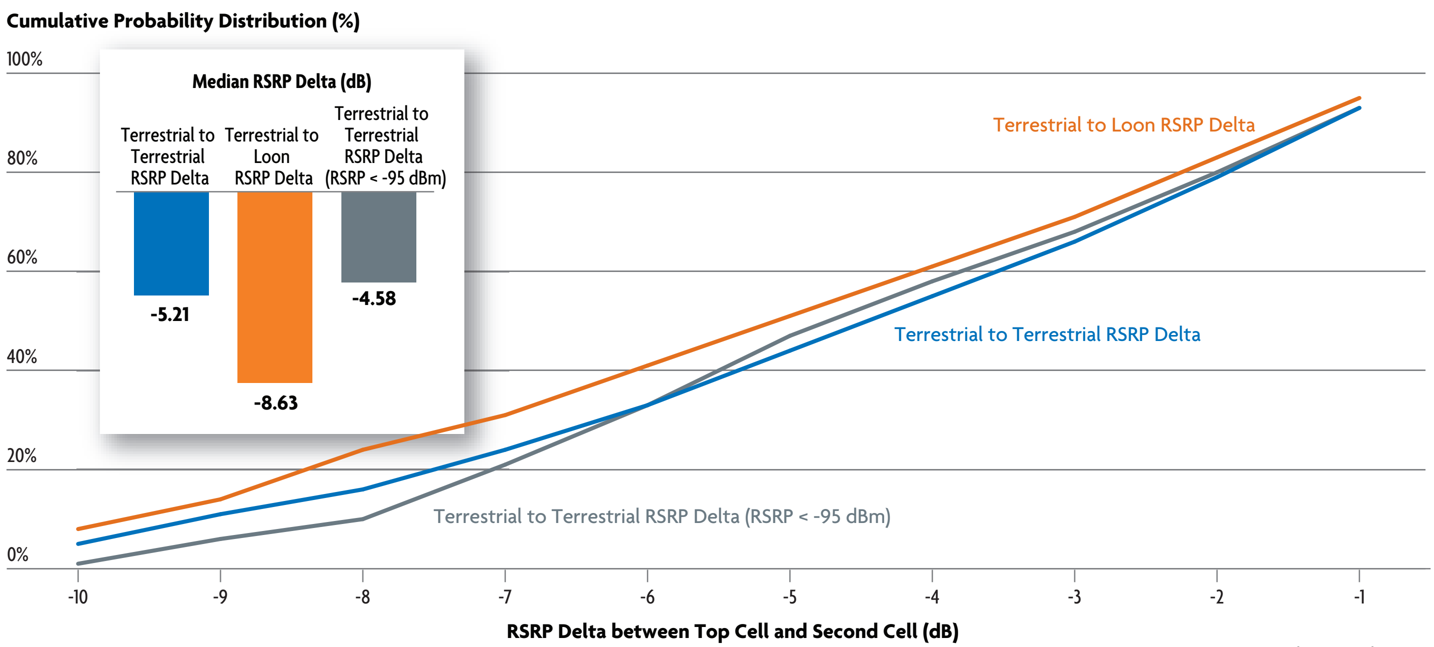
Figure 14. Cumulative Distribution of Loon Signal Strength



Source: Signals Research Group

The relationships between the terrestrial SINR and the terrestrial RSRP, as well as the differences in the RSRP between the top cell and the strongest interfering cell also show that Loon had minimal impact on network quality when the terrestrial network had the dominant cell. As shown in Figure 16, the terrestrial network's SINR was higher when there was interference from Loon (e.g., the Loon Interfering Cell(s) scenario) than in areas along the drive route where Loon didn't generate any interference (e.g., the Terrestrial Top Interfering Cell scenario) And as expected, the differences in RSRP between the terrestrial cell and the strongest Loon cell dropped off more rapidly than the Terrestrial Top Interfering Cell scenario when the terrestrial's network RSRP increased. There weren't enough data points to extend the Terrestrial Top Interfering Cell SINR plot below -102 dBm.

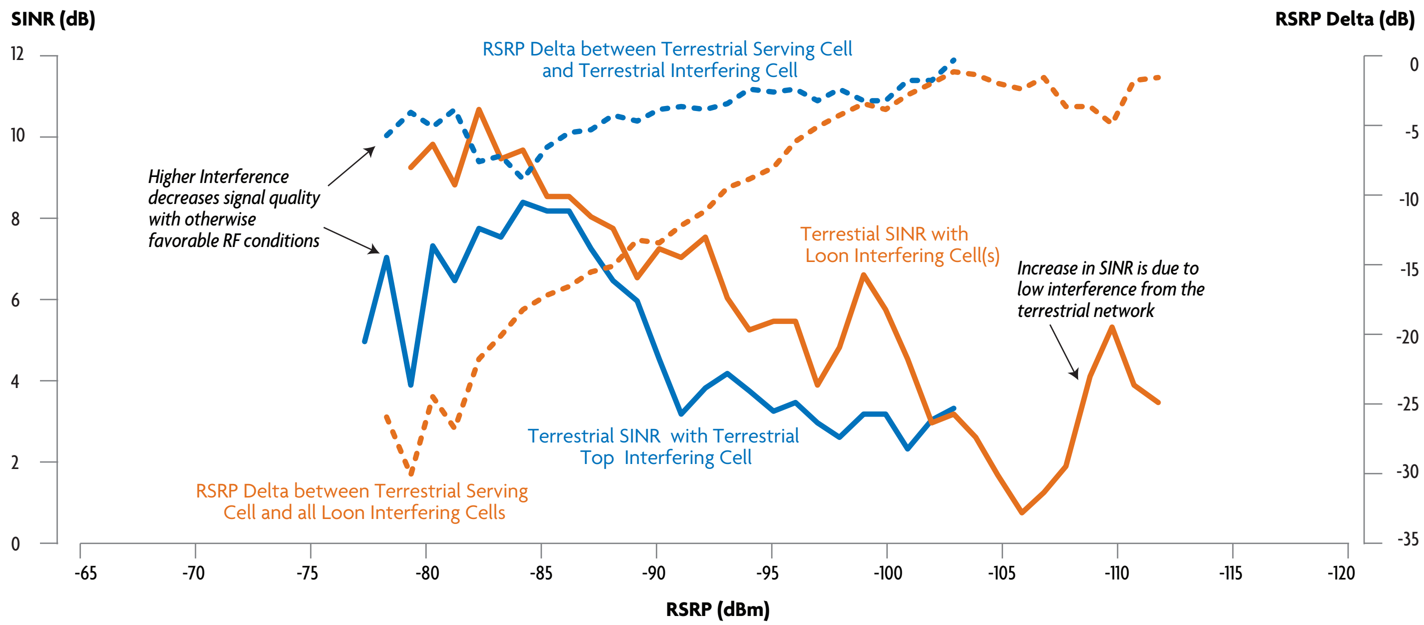
Figure 15. Cumulative Distribution of the Differences in Signal Strength between the Top Terrestrial Cell and the Strongest Interfering Cell



Source: Signals Research Group

The figure also shows two other interesting trends. First, with improving terrestrial RSRP the signal quality declined due to terrestrial to terrestrial interference. This trend is evident with RSRP higher than -85 dBm. The other interesting trend occurs with the Loon Interfering Cell(s) scenario with RSRP lower than -105 dBm. This counterintuitive trend is due to the absence of meaningful interference from the terrestrial cells when Loon was the dominant interfering source. Worth reiterating, with lower RSRP values there weren't enough data points when Loon wasn't present for this test, so we can't show comparative results for the Terrestrial Top Interfering Cell scenario.

Figure 16. SINR and RSRP Delta as a Function of RSRP



Source: Signals Research Group

2.4 Stationary Tests with and without Loon

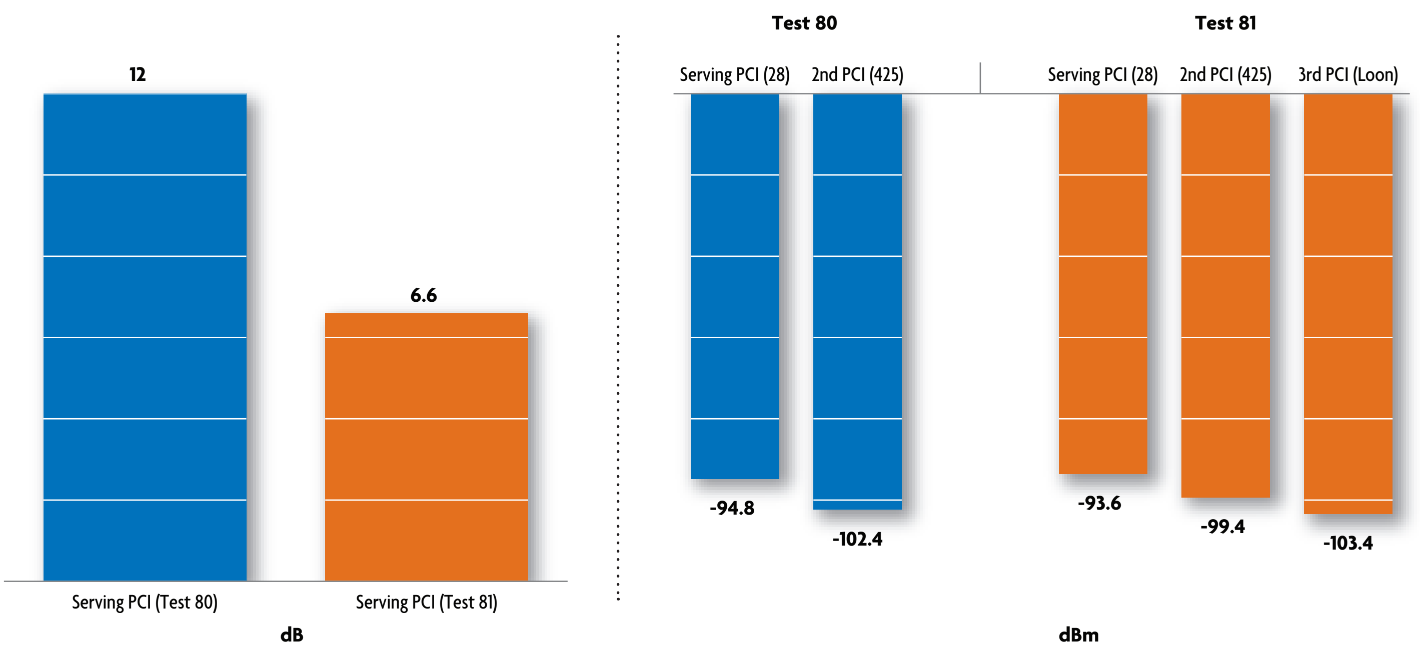
In this section we include the results from two pairs of stationary tests in which we collected network performance metrics with Loon present as an interfering cell and with Loon turned off. Figure 17 shows the locations where the tests took place.

Figure 17. Test Locations

Source: Signals Research Group

Figure 18 shows the SINR and the RSRP values for the serving cell and the interfering cells for Test 80 (No Loon) and Test 81 (Loon). This test occurred at the same location with approximately ten minutes separating the completion of Test 80 and the start of Test 81. We needed this time to bring up the Loon cell sites. In both cases the serving cell, based on scanner metrics, was in the terrestrial network, as was the strongest interfering cell. Loon was the second strongest interfering cell (labeled 3rd PCI (Loon) in the figure. Although the serving cell SINR dropped by 5.4 dB with Loon present in Test 81, the results also show the signal strength from the strongest interfering cell (terrestrial) increased by 3 dB for reasons that are not entirely clear. Additionally, the Loon RSRP was 9.8 dB lower than the serving cell and 4 dB lower than the terrestrial interfering cell. Therefore, although the presence of Loon likely had a negative impact on the serving cell SINR, much of the drop in SINR for the serving cell was due to changes in the terrestrial network that had nothing to do with Loon.

Figure 18. Network Performance Parameters with and without Loon

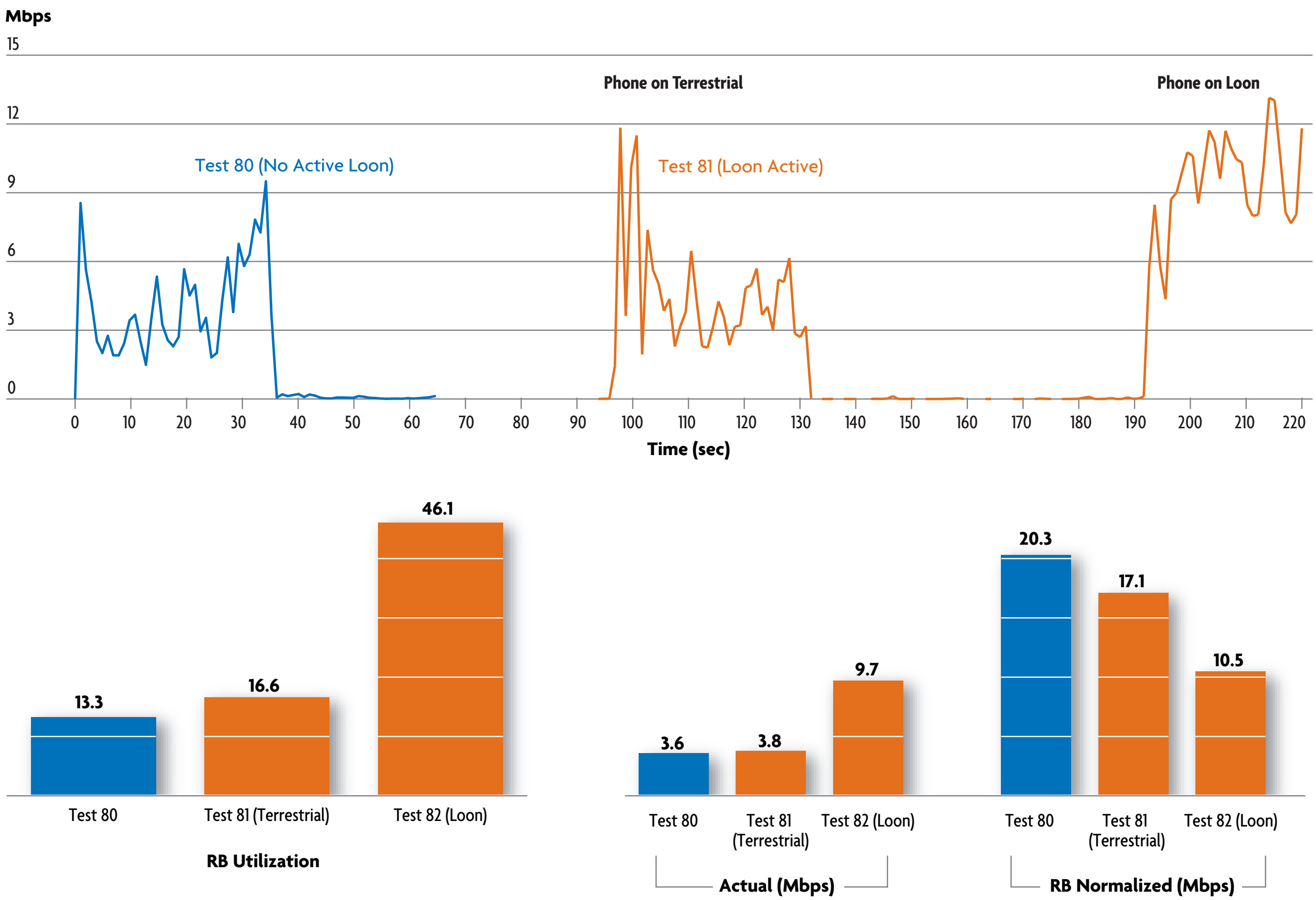


Source: Signals Research Group

Figure 19 shows the observed physical layer (PDSCH) data speeds recorded on a smartphone using a high-bandwidth Umetrix FTP server, located in Virginia. The figure shows we did one data speed test without Loon and two data speed tests with Loon present. In the first test the mobile device was obviously using the terrestrial network since Loon wasn't present. In the second test, the smartphone used the terrestrial network for the first data transfer but then it switched to Loon (PCI 52) for the second data transfer.

Figure 19 also shows the median actual and RB-normalized data speeds for the three tests. The information indicates Loon delivered higher data speeds than the terrestrial network (9.7 Mbps versus 3.6 Mbps and 3.8 Mbps). However, the RB-normalized data speeds, which take into consideration network loading and channel bandwidth favor the terrestrial results, especially the Test 80 results when Loon wasn't present. One critical piece of information, which helps explain the RB-normalized results is that the Loon channel bandwidth was 2x10 MHz (50 RBs), compared with the terrestrial channel bandwidth, which was 2x15 MHz (75 RBs). Given the disparity in channel bandwidth between the two networks, we would expect the Loon RB-normalized throughput to be lower than the terrestrial results and the comparison isn't fair. However, we are including the information to show that the terrestrial network had lots of data traffic from other mobile devices in the area while at the time we did this test the Loon network was lightly loaded.

Figure 19. Mobile Device Performance with and without Loon

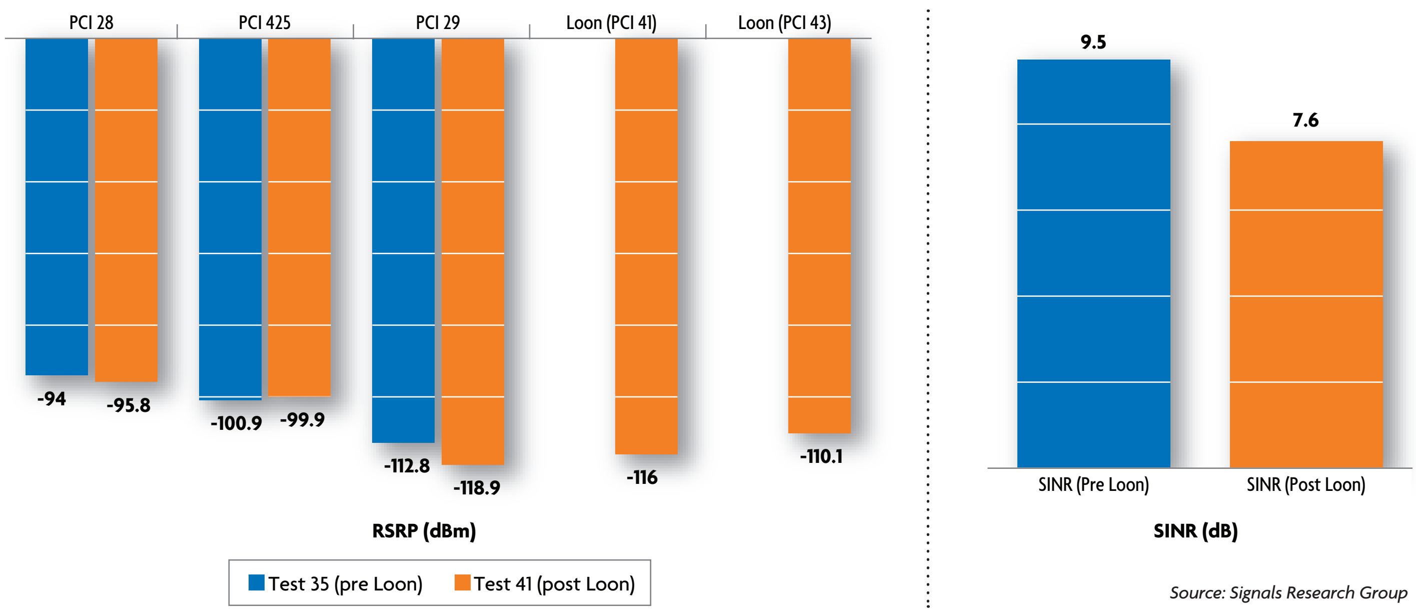


Source: Signals Research Group

We did another stationary test on a different day in the general location of the previous test. The Loon cell sites had an RSRP nearly 15 dB lower than the strongest terrestrial cell at this location. There was a 1.9 dB drop in the measured SINR with Loon present but given the huge difference in signal strength between Loon and the terrestrial network, it isn't clear how much of this drop was due to Loon versus other factors involving the terrestrial network. We also point out that Loon's intended coverage area was not at this location, but further outside the village. Test 42 and Test 46, in the next Chapter, show the impact of this Loon balloon on improving terrestrial coverage.

In the appendix we include results from other drive tests. These test results, along with the test results provided in this section, are included in the analysis used to create the two summary figures in Chapter 2.

Figure 20. Network Performance Parameters with and without Loon



Source: Signals Research Group

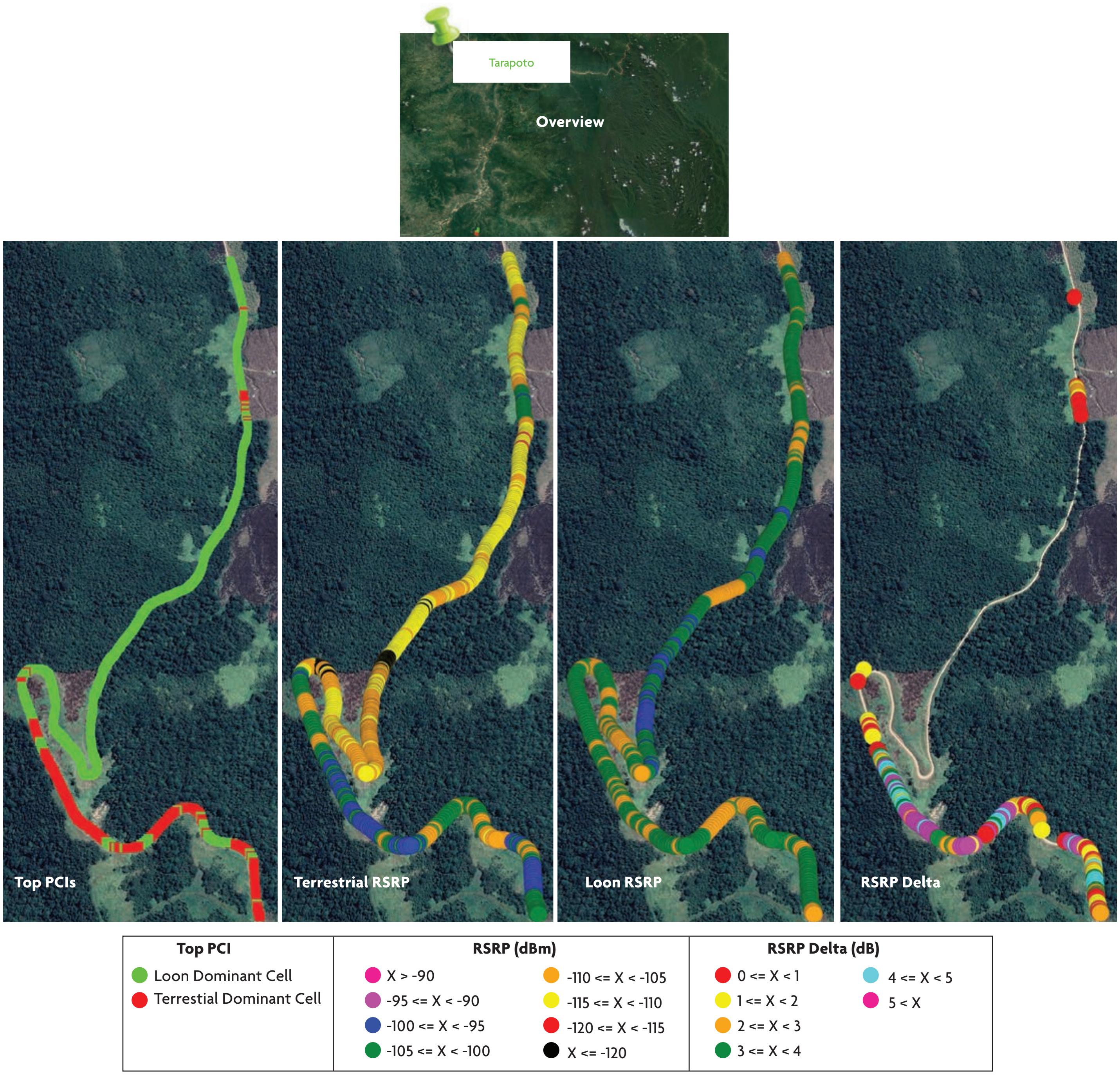
3.0 Extending Terrestrial Coverage with Loon and the Interactions between the Two Networks

In this chapter we show results where Loon coverage was more extensive along the drive route and we show how our mobile devices interacted with the two networks when moving between them or between different Loon cells (PCIs). Given the distance between Tarapoto and the outer boundary where Loon coverage was primarily targeted, it wasn't logistically possible to navigate much further into the Loon coverage area in a day. However, we went far enough into the Loon coverage area to quantify Loon performance attributes and, most importantly, we were able to evaluate Loon's impact on the terrestrial network (previous chapter) and the interactions between Loon and the terrestrial network (this chapter).

3.1 Test 91

The Test 91 drive route began just south of the end point for Test 87 (55 kilometers south of Tarapoto) and extended for an additional 2.9 kilometers. Figure 21 shows the drive route as well as geo plots of some key performance metrics. Along this route, there were three Loon PCIs (two different balloons) that had a stronger signal than the terrestrial network at various sections along the route. In total, Loon had the dominant signal over 78% of the drive route.

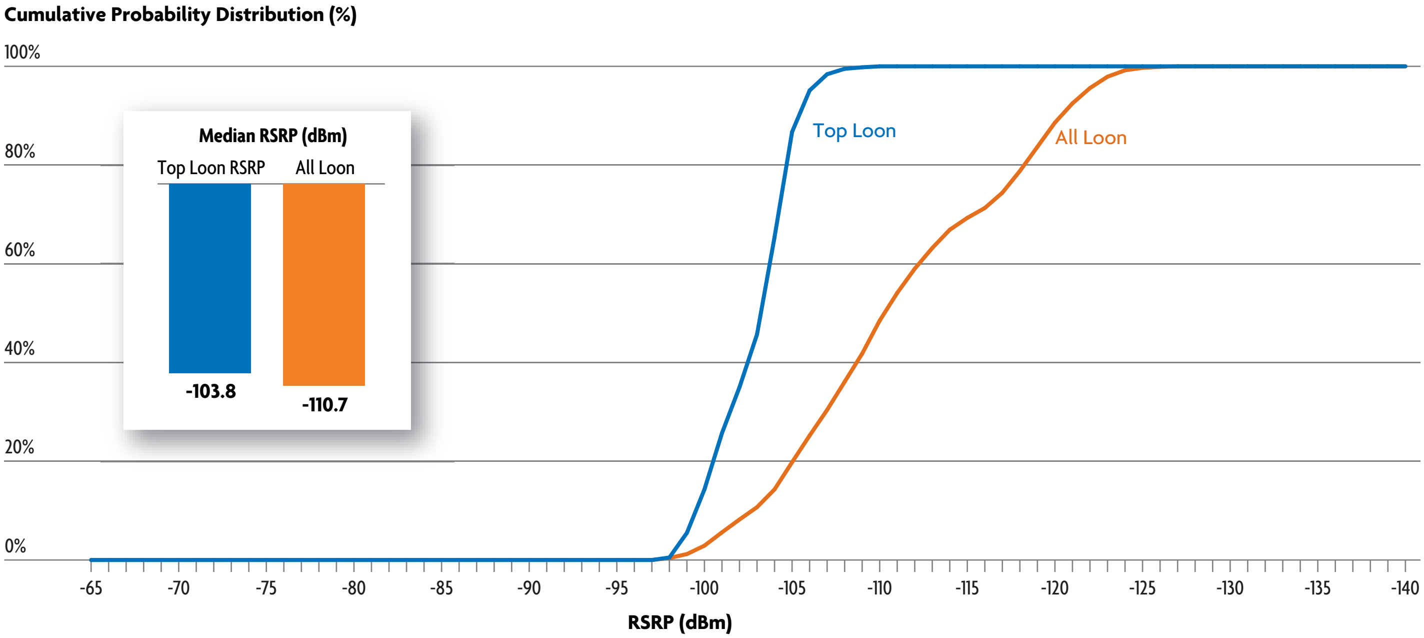
Figure 21. Test 91 Key Metrics – geo plot



Source: Signals Research Group

Although three Loon PCIs shared responsibility for the top PCI, based on measured signal strength, we identified nine unique Loon PCIs along the drive route, coming from three different Loon balloons. Figure 22 provides the median values and cumulative distribution plots for the top Loon RSRP as well as the RSRP values, based on including all Loon measurement values.

Figure 22. Cumulative Distribution of Loon Signal Strength



Source: Signals Research Group

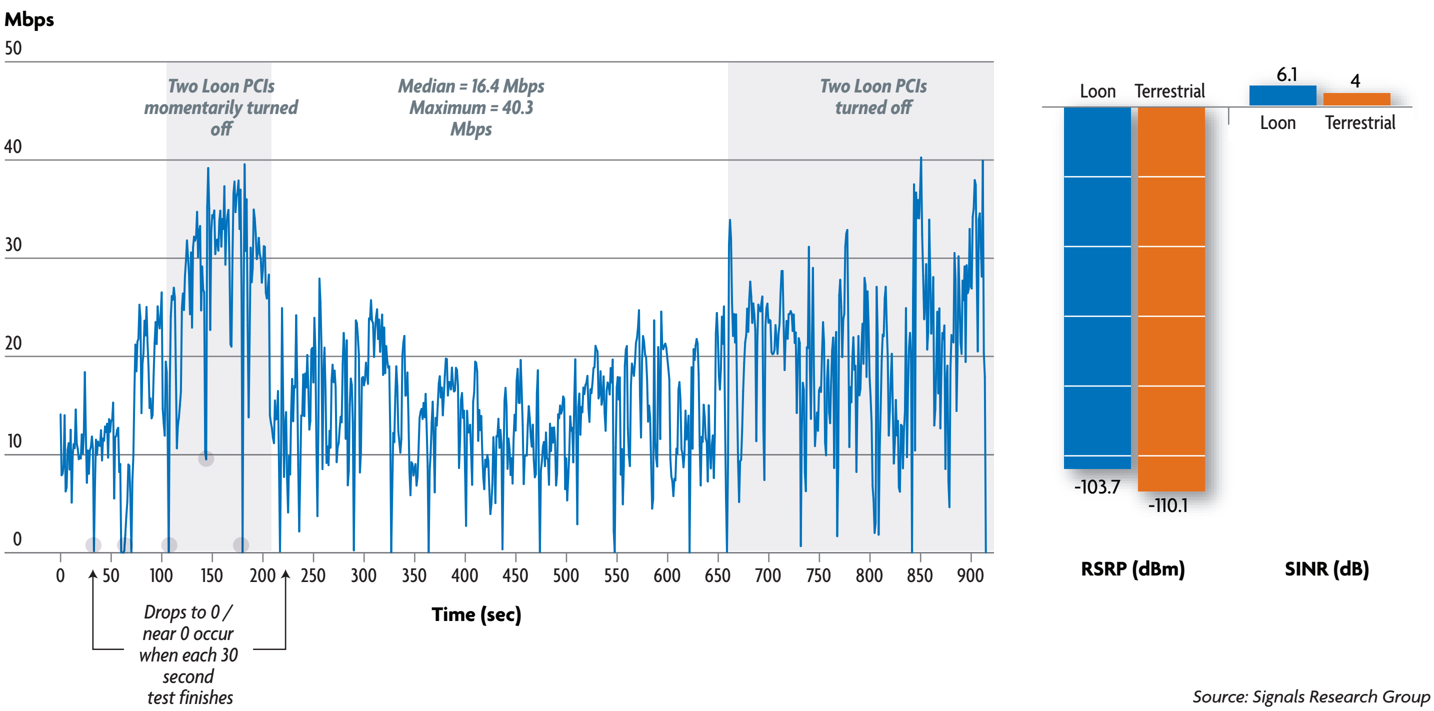
Given the limited data set when the terrestrial network had the strongest serving cell, there isn't enough data to show how Loon impacted the terrestrial network. This information is also less meaningful since in most cases Loon was providing coverage. However, at the conclusion of this test (not captured in the first two figures in this section), we did an additional test with the mobile device + scanner during which time Loon engineers made two changes to the Loon network configuration at our request. Since we knew that the S1 interface in Loon's network transits across a stratospheric mesh network, comprised of point-to-point millimeter wave links that change over time, , we wanted to see the impact of changing the active ground station on Loon's performance. Switching ground stations could be required for technical reasons or to accommodate unfavorable weather conditions.

Prior to changing the active Loon ground station, we started capturing data with the R&S scanner and a Galaxy Note 9 smartphone. We used the Umetrix data platform from Spirent Communications to generate high bandwidth throughput using the FTP protocol to the mobile device. The Umetrix server was in Virginia. Loon engineers then switched the active ground station from Yurimaguas to Iquitos. As part of this activity, Loon engineers also switched off two Loon cells (PCI 81 and PCI 83) which were on the same Loon balloon as the serving cell (PCI 82) being used by the mobile device.

We observed a median sustained data speed of 16.4 Mbps (peak = 40.3 Mbps) using Loon with a BLER of 9.7%.

Figure 23 shows the physical layer (PDSCH) throughput for the mobile device while changing the ground station and turning off two Loon cells. The RSRP and SINR metrics come from the scanner data. We've highlighted a section of the plot where the two neighboring Loon cells were momentarily turned off – they disappeared in the scanner data and on the mobile device – and the moment when they permanently disappeared. The periodic dips in the throughput were due to the Umetrix test scenario. We used a 30-second FTP data transfer which ran in a repetitive loop, albeit with very brief periods when no data was being sent. Although it isn't shown in the figure, the median BLER (Block Error Rate) was 9.7%, or comparable with what we would expect with a terrestrial network. Surprisingly [at least to us], it isn't evident in the figure when the Loon engineers changed the active ground station. Loon developed a "Temporospatial SDN" that orchestrates the backhaul network radio resource management, link handoffs, and routing table updates around each other to automate such events based on the forecast motion and weather, which minimizes packet loss during such events. In any event, it is very unlikely a consumer would notice the switch.

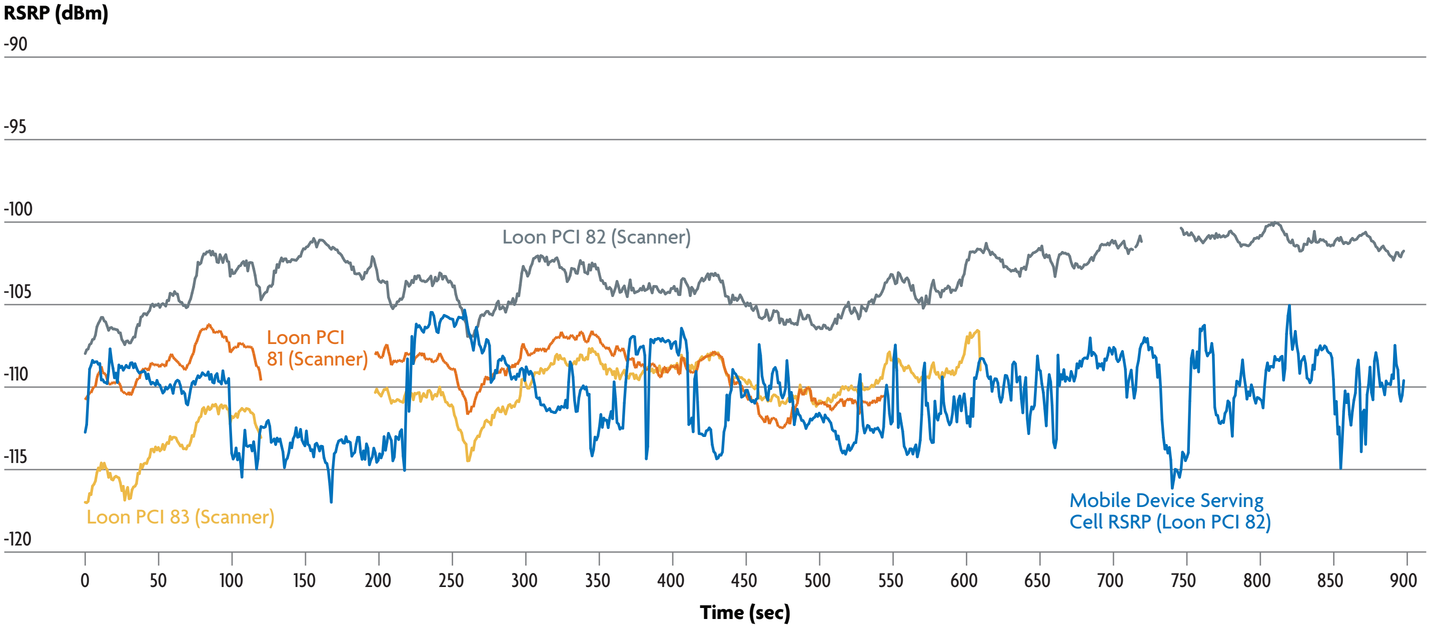
Figure 23. Mobile Device Throughput While Changing the Loon Ground Station



Source: Signals Research Group

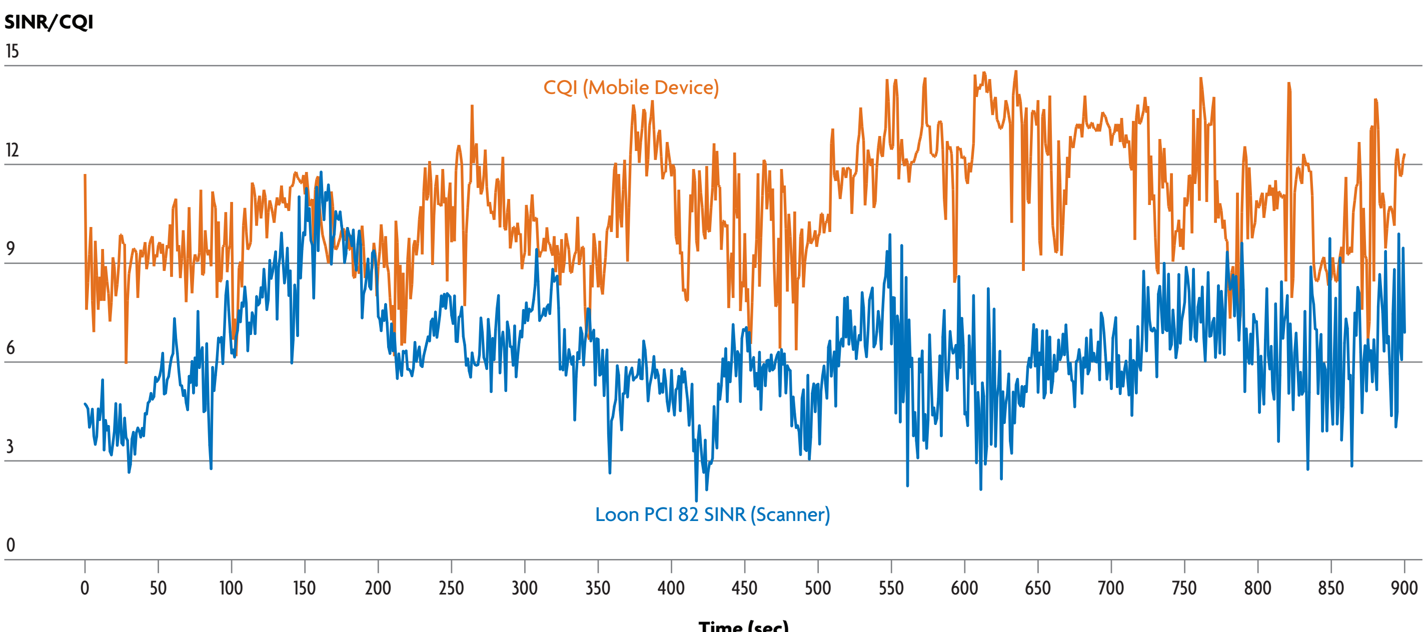
Figure 24 and Figure 25 provide additional information about the radio conditions during this stationary test. The first figure shows when PCI 81 and PCI 83 were not radiating as well as the RSRP for PCI 82 (the serving cell), as measured by the mobile device and the scanner. Interestingly, the mobile device observed a meaningful drop in the PCI 82 RSRP when PCI 81 and PCI 83 were momentarily turned off. In the second figure, there is a noticeable improvement in the mobile device CQI, starting at 120 seconds when PCI 81 and PCI 83 were not active. Toward the end of the test when both Loon PCIs were turned off the second time there was a modest improvement in the CQI. Throughout this test the data speeds were excellent. Although turning off two Loon cells helped improve radio conditions, we believe switching to the new ground station was a bigger factor in the favorable data speeds since we believe there was high packet-loss in the wired connection from the original ground station (external to the Loon network). This observation isn't evident in the figure and it is based on additional information that we obtained while testing in Peru.

Figure 24. Mobile Device and Scanner RSRP Measurement Reports



Source: Signals Research Group

Figure 25. Mobile Device CQI and Scanner RSRP Measurement Reports

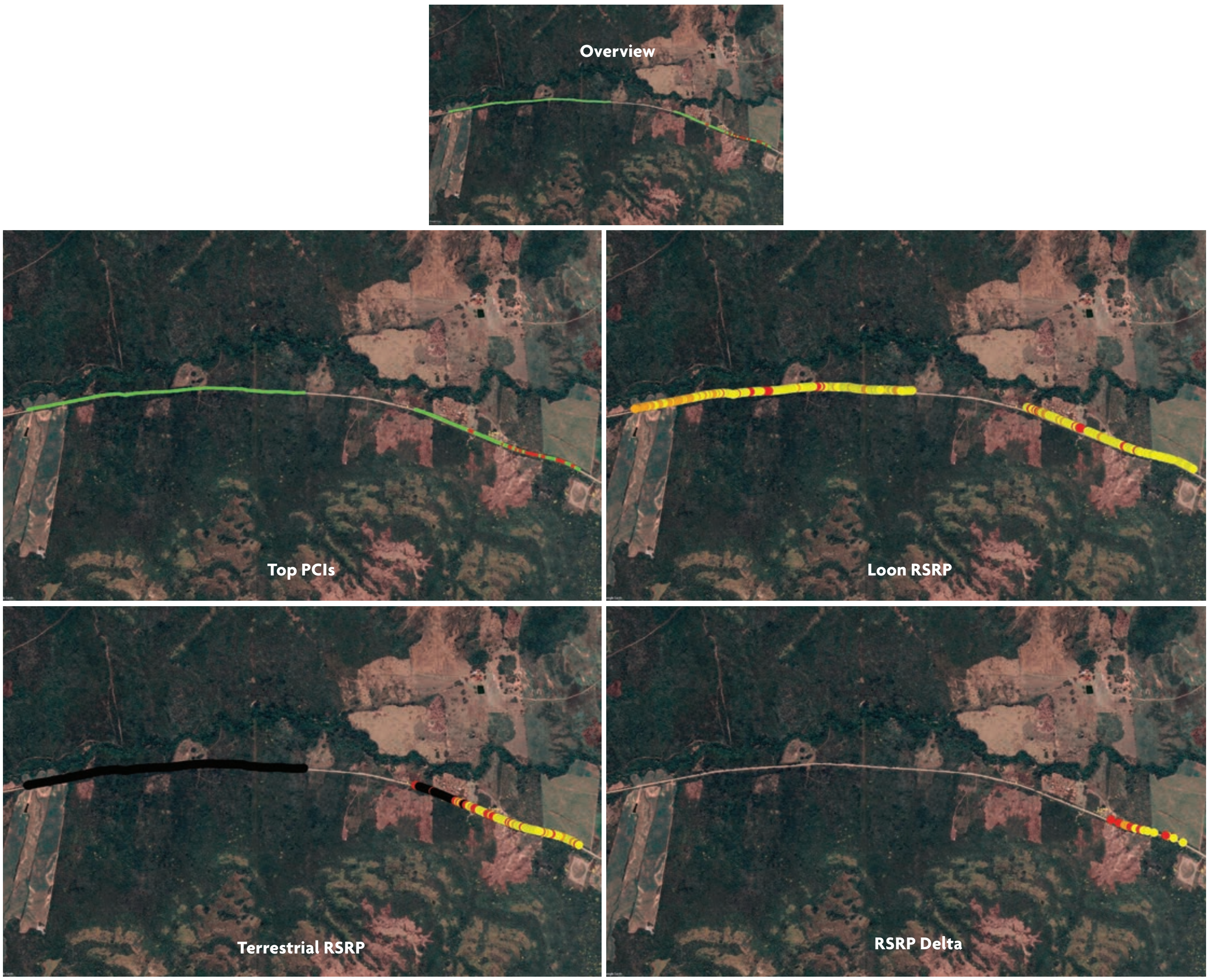


Source: Signals Research Group

3.2 Test 42 and Test 46

These two tests occurred 30 kilometers south of Tarapoto along a rural secondary road. Test 42 (0.7 kilometers) included a mix of terrestrial and Loon cells serving as the dominant cell (primarily Loon). The start of Test 46 was another 0.5 kilometers past the end point for Test 42 and extended for another 1.2 kilometers. Figure 26 shows the location for these two tests as well as other information about the RF environment.

Figure 26. Test 42 and Test 46 Key Metrics – geo plot

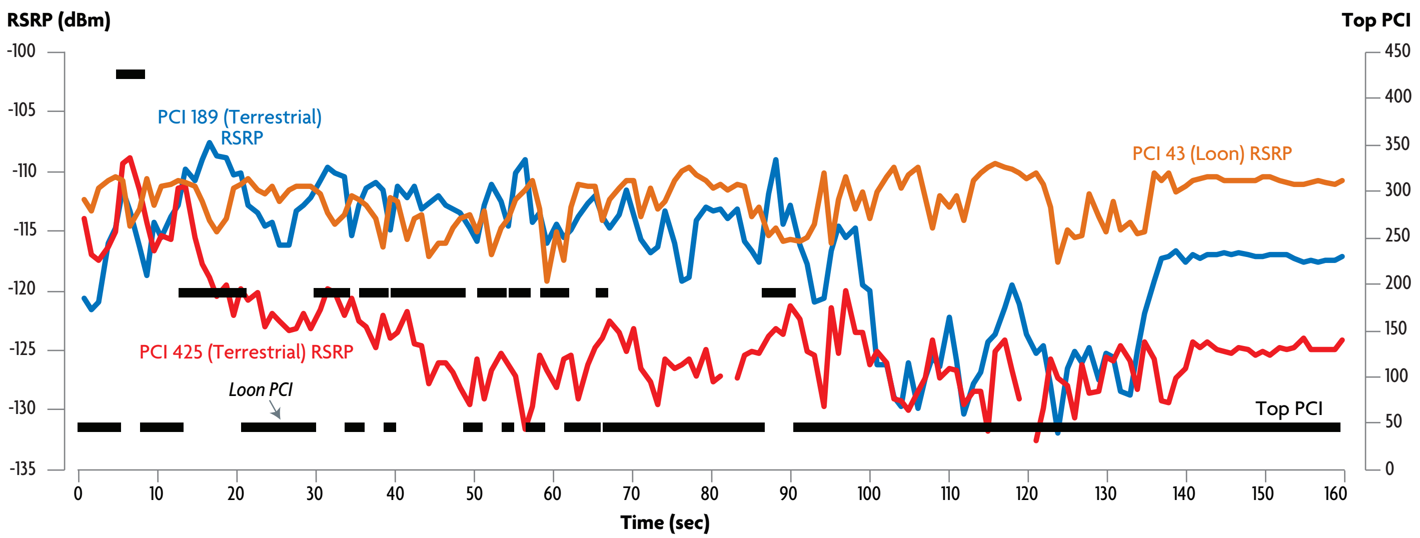


Top PCI	RSRP (dBm)		RSRP Delta (dB)	
Loon Dominant Cell	X > -90	-110 <= X < -105	0 <= X < 1	4 <= X < 5
Terrestial Dominant Cell	-95 <= X < -90	-115 <= X < -110	1 <= X < 2	5 < X
	-100 <= X < -95	-120 <= X < -115	2 <= X < 3	
	-105 <= X < -100	X <= -120	3 <= X < 4	

Source: Signals Research Group

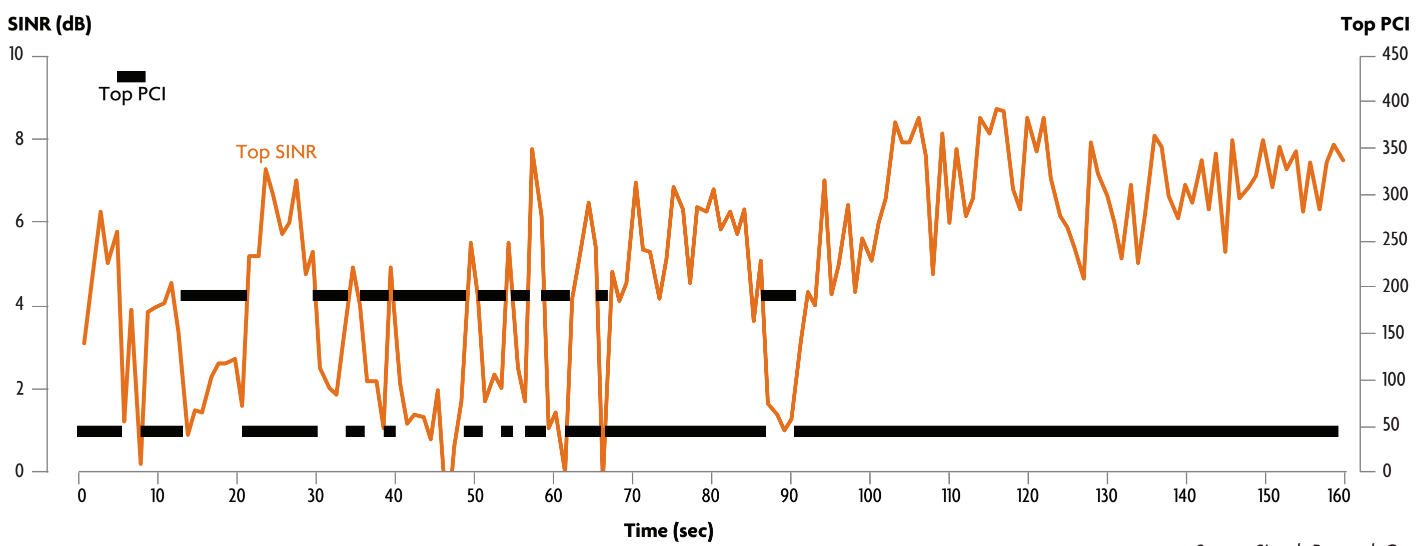
It is clear in the geo plot that by the end point of Test 42 the terrestrial coverage was very poor. At the start point for Test 46, the terrestrial coverage was virtually nonexistent. Figure 27 shows how the RSRP for the Loon cell (PCI 43) and the two terrestrial cells changed throughout the test. Figure 28, which covers the same period, shows the SINR for the serving cell (the PCI with the strongest RSRP). The serving cell in this figure alternates between PCI 189 (terrestrial) and PCI 43 (Loon) at the beginning before remaining entirely on PCI 43. Comparing the two figures, it is also evident that PCI 425 was only a factor for the first twenty seconds of the test before its RSRP dropped below -120 dBm for the remainder of the test. The improving SINR starting at ninety seconds was due to the drop in the PCI 189 RSRP shown in Figure 27.

Figure 27. Test 42 RSRP for Loon and Terrestrial Cells



Source: Signals Research Group

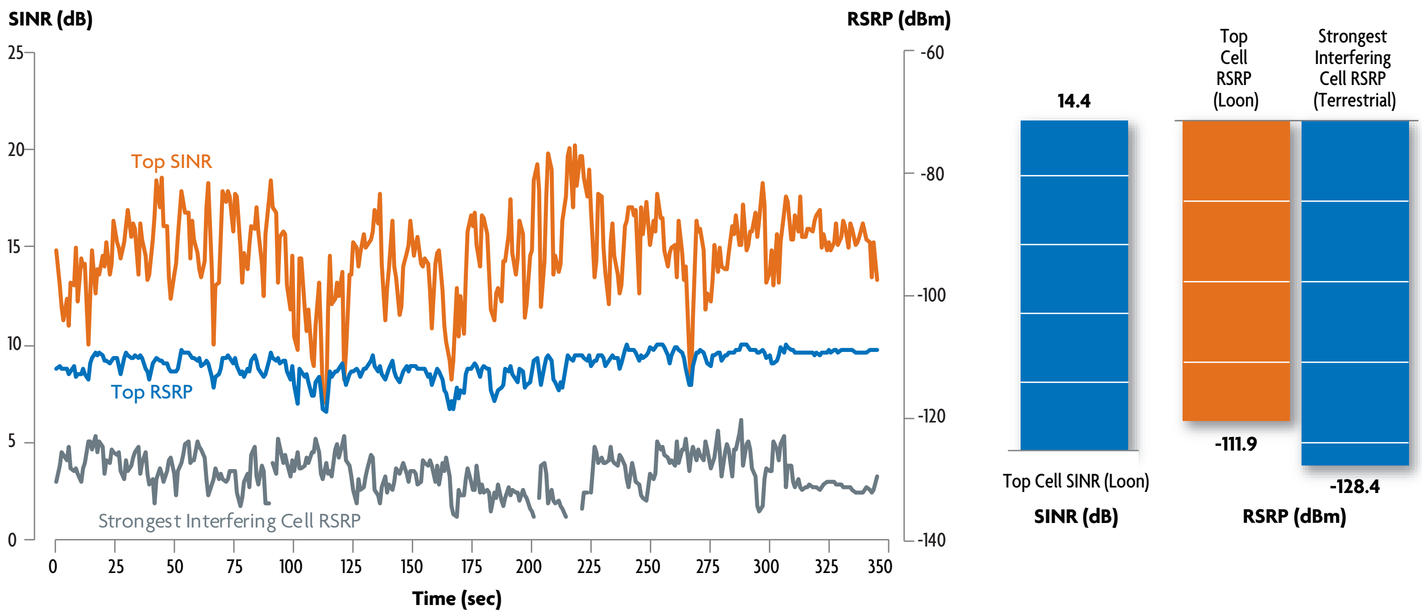
Figure 28. Test 42 Serving Cell SINR



Source: Signals Research Group

Finally, we observe in Figure 29 that by the time we reached the start point of Test 46 the terrestrial network was barely present. The strongest interfering cell, which happened to be a terrestrial cell, had a signal strength that was 16.5 dB below the serving Loon cell. This situation explains why the serving cell SINR was a very favorable 14.4 dB. All results based on scanner measurements.

Figure 29. Test 46 Serving Cell SINR and RSRP

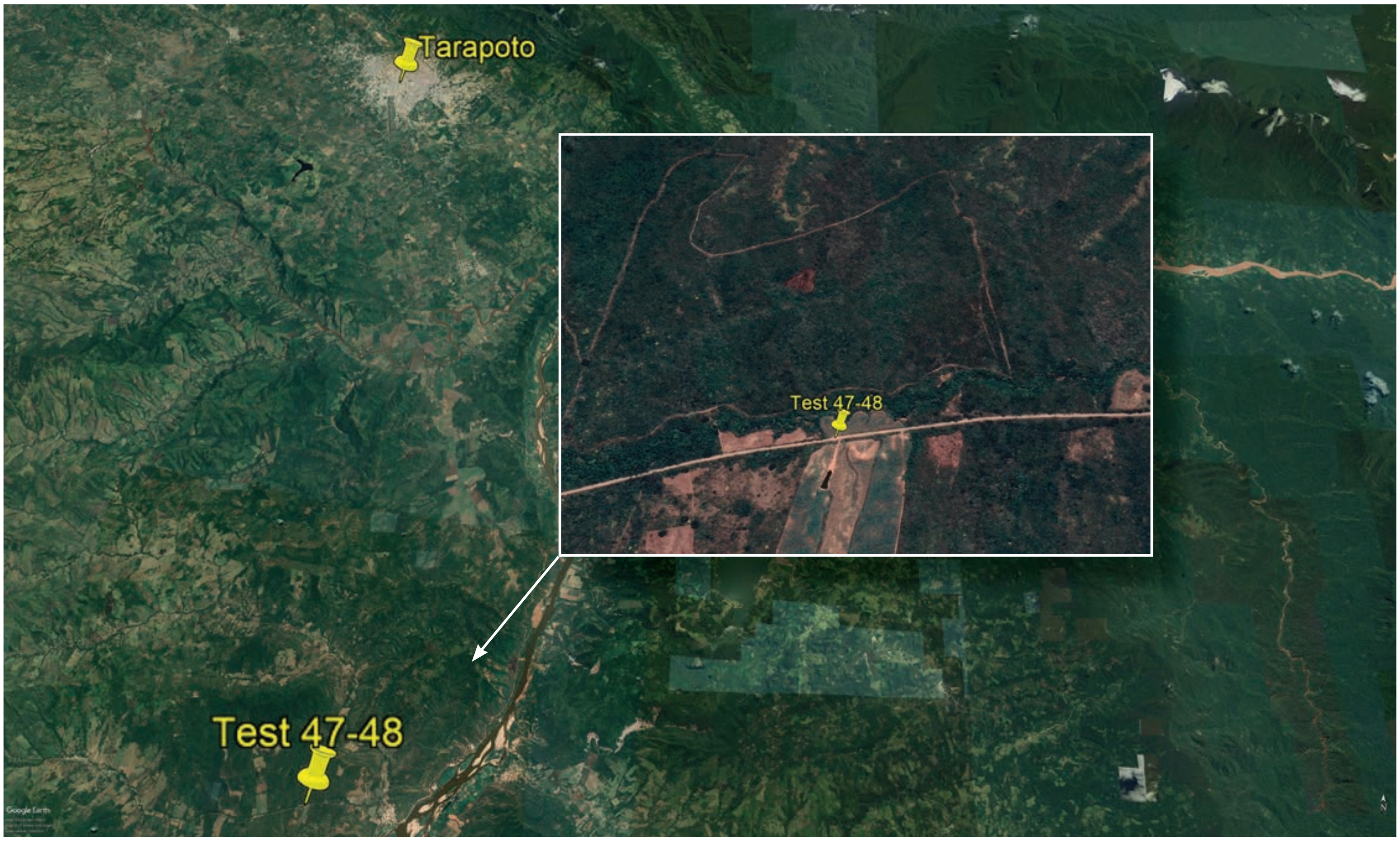


Source: Signals Research Group

3.3 5 MHz and 10 MHz Loon Sensitivity

In this section we include the results from three different network configurations: Terrestrial Only, Loon 2x10 MHz and Loon 2x5 MHz. This test occurred near the conclusion of the drive test in the previous section (Figure 30). It isn't clear if an operator would use Loon with a 2x5 MHz channel bandwidth but since we found these results interesting, we are including them for informational purposes.

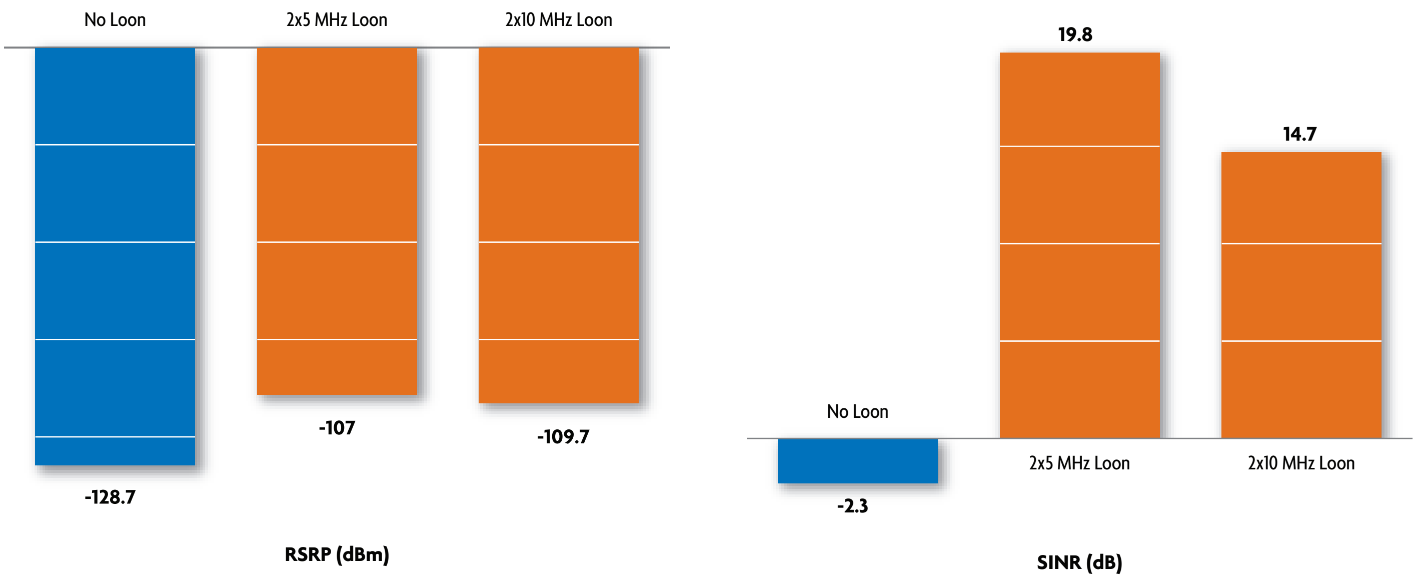
Figure 30. Stationary Test Locations



Source: Signals Research Group

With the introduction of a Loon 2x10 MHz radio channel the RSRP improved by 19 dB and the SINR improved by 17 dB, compared to the terrestrial LTE network. Switching to a 2x5 MHz radio channel with Loon improved the RSRP by an additional 2.7 dB and it improved the SINR by 5.1 dB. Figure 31 shows this information.

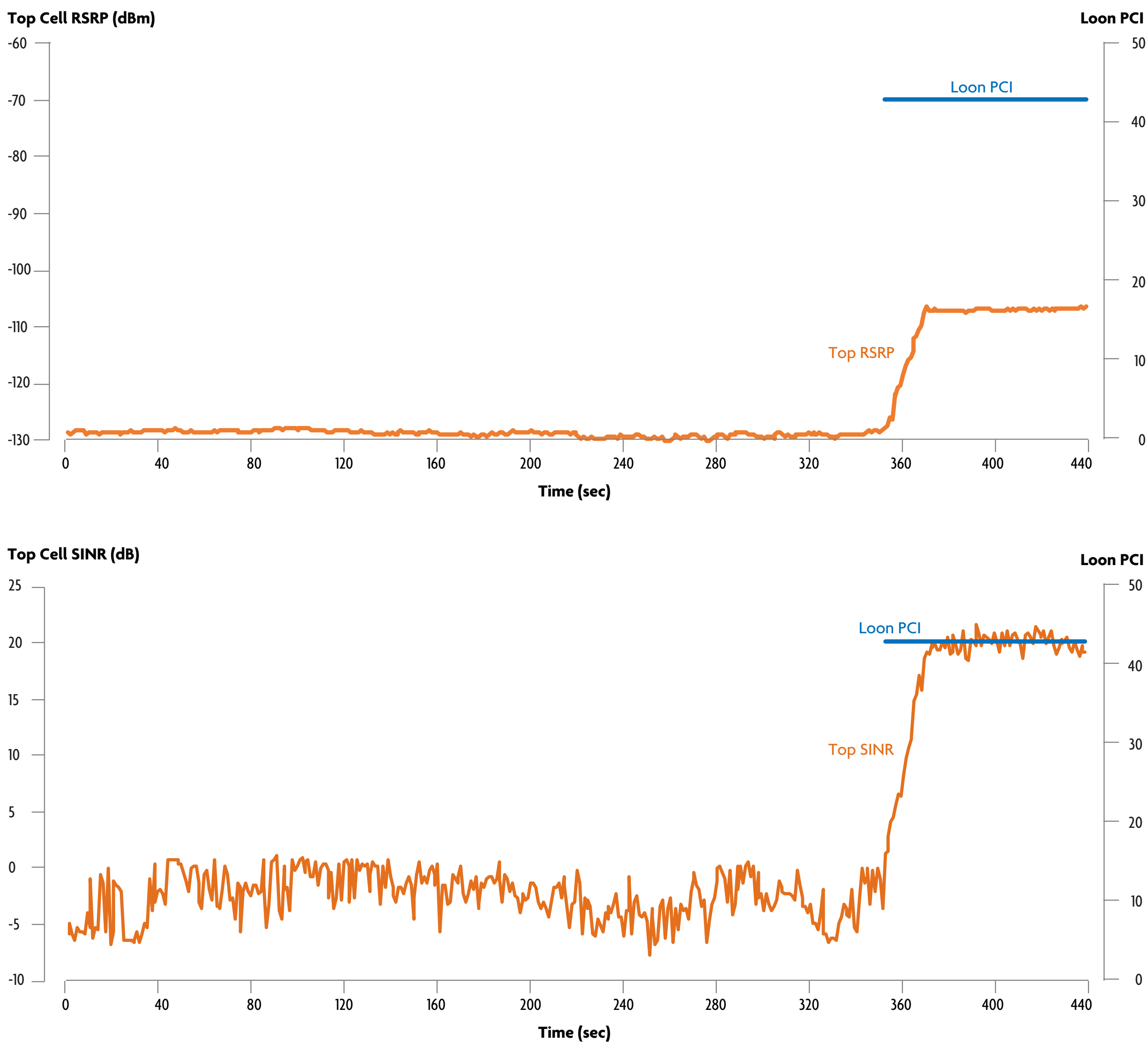
Figure 31. RSRP and SINR for Loon and Terrestrial Cells



Source: Signals Research Group

Finally, Figure 32 shows a time series plot of the RSRP and SINR, as measured by the scanner for the period prior to Loon (terrestrial only), followed by the Loon cell turning on and radiating a 5 MHz channel. Although it isn't evident in the figure, the strongest terrestrial serving cell jumped frequently between three difference PCI values for that portion of the figure when Loon wasn't present.

Figure 32. Serving Cell RSRP and SINR with the Introduction of a Loon 5 MHz Channel

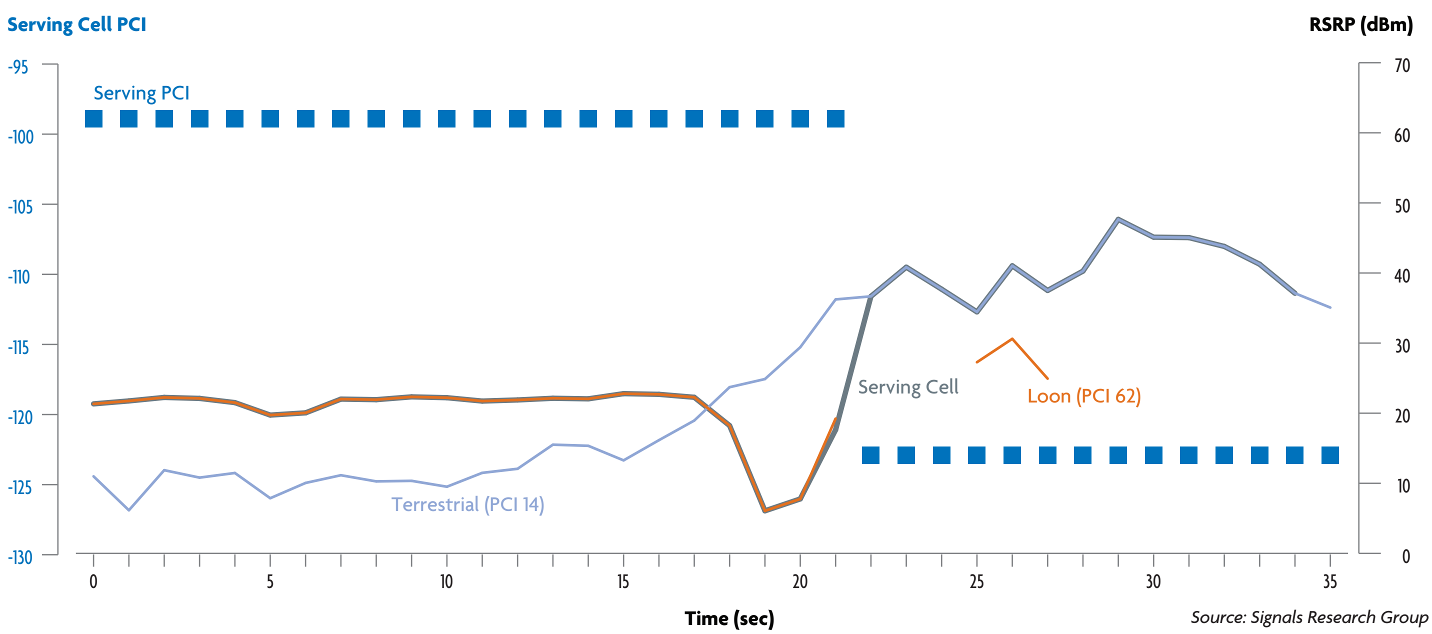


Source: Signals Research Group

3.4 Moving between Loon and Terrestrial Cells with a Mobile Device

Although it is possible to integrate the terrestrial network and Loon, the configuration we tested in Peru did not support this capability. Therefore, when a mobile device moved from Loon coverage to the terrestrial network (or vice versa) it didn't do a traditional handover, that occurs when moving between different terrestrial cell sites. Instead, since the two networks were distinct entities, the mobile device did an RRC detach from a Loon/Terrestrial cell, followed by an RRC attach to a Terrestrial/Loon cell. Figure 33 shows a time series plot of the RSRP for the top terrestrial and the top Loon cells as well as the strongest RSRP at each point, as captured by the mobile device. The serving cell is Loon (PCI 62) at the start of the figure when Loon had the strongest signal and then it switches to a terrestrial cell (PCI 14) when the terrestrial network had the stronger signal. When Loon was the serving PCI, its RSRP was approximately 5 dB higher than the terrestrial cell. Starting at X=18 seconds PCI 14 had the stronger signal and by X=22 seconds the mobile device switched to the terrestrial network. Shortly thereafter, the mobile device couldn't even detect the Loon PCI. Although not shown in this figure, scanner data from this test also shows the scanner stopped detecting the Loon PCIs shortly after the mobile device moved to the terrestrial network.

Figure 33. Mobile RRC Reconnect when Moving from Loon to the Terrestrial Network



Source: Signals Research Group

Table 1 shows the relevant RRC signaling messages when the mobile device moved from Loon to the terrestrial network. The table shows the transition took 1.8 seconds, which for most data applications would go unnoticed by the consumer.

Table 1. RRC Signaling Messages When the Mobile Device Moved from Loon to the Terrestrial Network

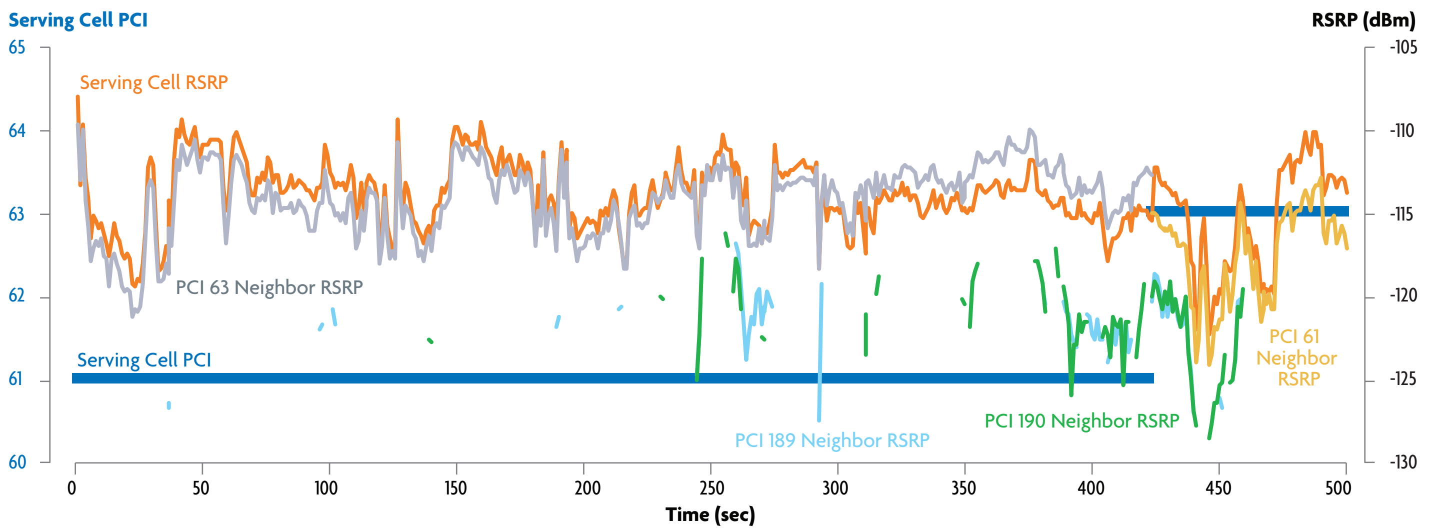
TIME_STAMP	Serving PCI	TAU Request	NAS Attach Request	NAS Attach Accept	NAS Attach	EPS Bearer Setup Time	RRC Setup	RRC Setup	RRC Connect Attempt	RRC Connect Success	RRC Connect Release
2019-09-24 18:06:53.000	62										
2019-09-24 18:06:54.000	62										
2019-09-24 18:06:55.000	62										
2019-09-24 18:06:56.000	62										
2019-09-24 18:06:57.000	62										
2019-09-24 18:06:58.000	62										
2019-09-24 18:06:59.000	62										
2019-09-24 18:07:00.000	62										
2019-09-24 18:07:01.000	62										
2019-09-24 18:07:02.000	62										
2019-09-24 18:07:03.000	62										
2019-09-24 18:07:03.518		TA/LA updating									
2019-09-24 18:07:03.518									RRC Attempt		
2019-09-24 18:07:03.717							RRC Connect Setup				
2019-09-24 18:07:03.725										RRC Success	
2019-09-24 18:07:03.791											other
2019-09-24 18:07:03.853			EPS/IMSI attach								
2019-09-24 18:07:03.854									RRC Attempt		
2019-09-24 18:07:04.000	14										
2019-09-24 18:07:04.030							RRC Connect Setup				
2019-09-24 18:07:04.031										RRC Success	
2019-09-24 18:07:05.000	14										
2019-09-24 18:07:05.294				EPS/IMSI attach							
2019-09-24 18:07:05.295					Attach Complete	0.007					
2019-09-24 18:07:06.000	14										
2019-09-24 18:07:07.000	14										
2019-09-24 18:07:08.000	14										

Source: Signals Research Group

3.5 Moving between Loon Cells with a Mobile Device

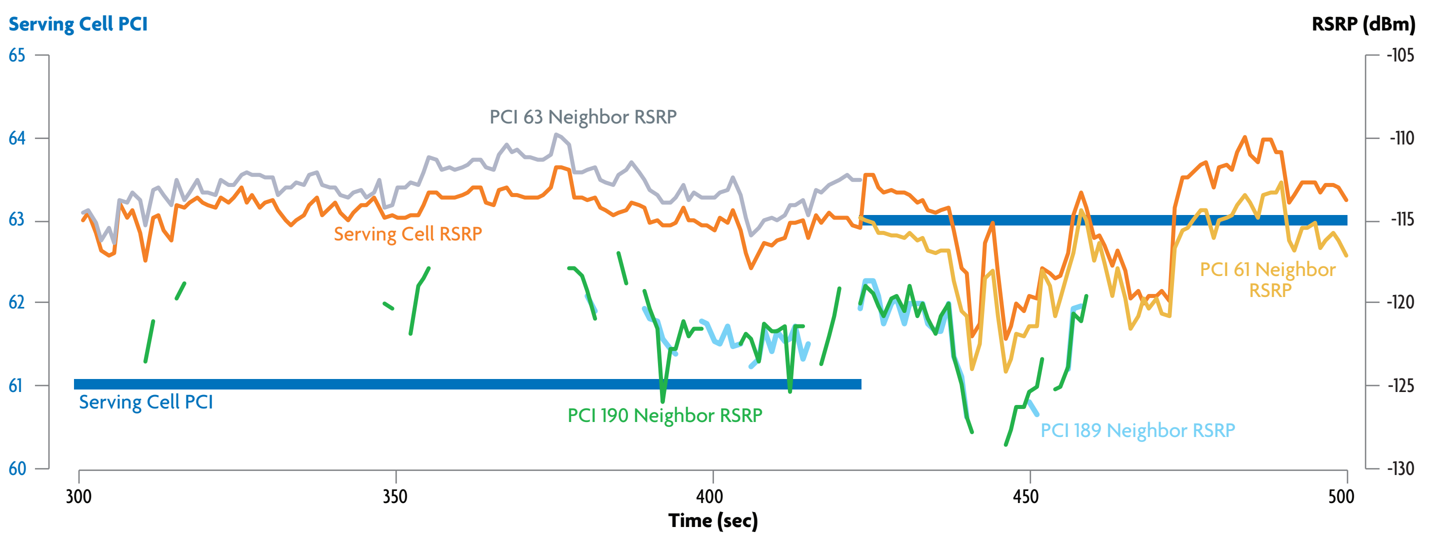
We also captured data which shows a mobile device moving between two Loon PCIs. Figure 34 provides a time series plot of the serving cell PCI, its RSRP and the RSRP of neighboring cells. We captured this information with the mobile device. The neighboring cells include other Loon PCIs and two terrestrial PCIs. Figure 35 shows the same information but it focuses on a 200-second interval to provide additional visibility. Both figures show the mobile device barely detected the terrestrial network and when it did detect the network, the RSRP was frequently below -120 dBm. The figures also show Loon PCI 61 and PCI 63 had comparable signal levels. From 0 to 300 seconds, PCI 61 had a slightly stronger signal and it was the serving cell. Starting at 300 seconds PCI 63 had a slightly stronger signal over PCI 61, although until ~425 seconds PCI 61 was the serving cell. Then, at X = 425 seconds, the mobile device moved from PCI 61 to PCI 63.

Figure 34. Serving Cell PCI and RSRP, including RSRP from Neighboring Cells



Source: Signals Research Group

Figure 35. Serving Cell PCI and RSRP, including RSRP from Neighboring Cells – Enhanced View



Source: Signals Research Group

Table 2 shows the RRC signaling messages that took place during this transition (19 ms) between Loon PCIs.

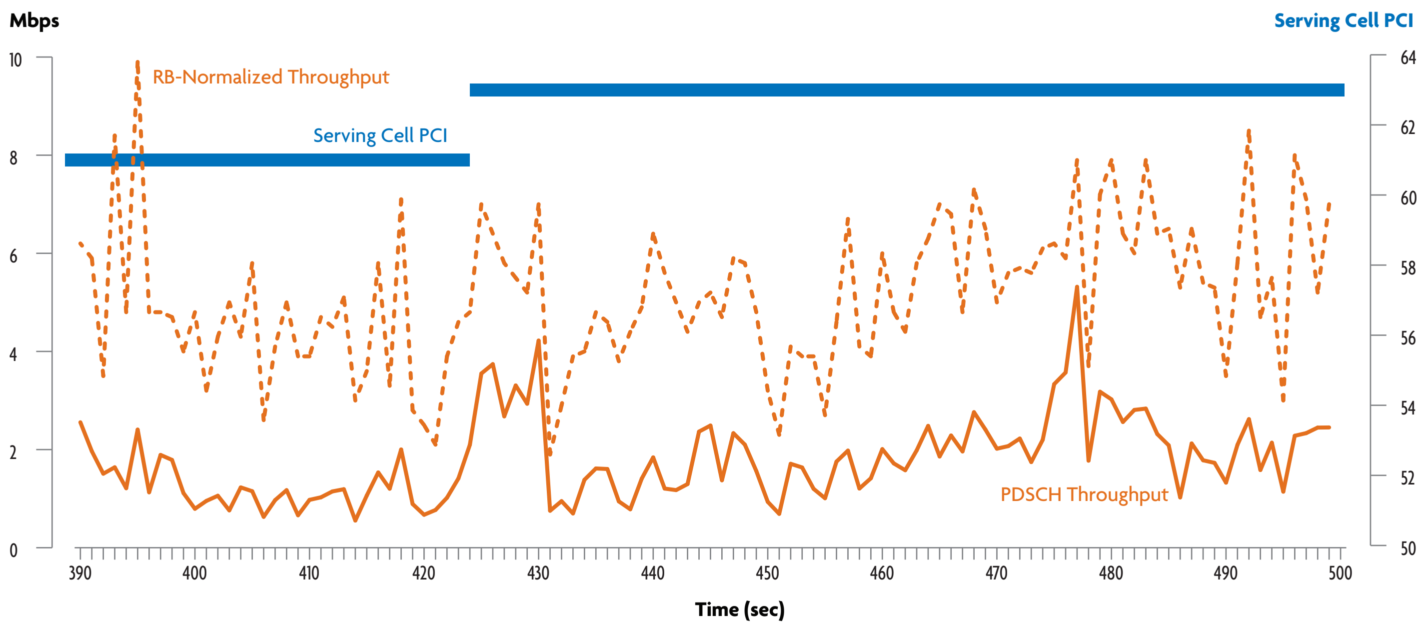
Table 2. RRC Signaling Messages When the Mobile Device Moved from Loon to the Terrestrial Network

TIME_STAMP	Serving Cell PCI	RSRP	SINR	NAS Attach Complete	RRC Success	Handover Duration
2019-09-24 16:30:10.000	61	-116.08	1.13			
2019-09-24 16:30:11.000	61	-114.63	0.77			
2019-09-24 16:30:12.000	61	-115.07	-0.09			
2019-09-24 16:30:13.000	61	-114.54	2.39			
2019-09-24 16:30:14.000	61	-114.76	-1.88			
2019-09-24 16:30:15.000	61	-114.85	-2.72			
2019-09-24 16:30:16.000	61	-114.85	-3.45			
2019-09-24 16:30:17.000	61	-115.23	-2.88			
2019-09-24 16:30:18.000	61	-115.37	0.04			
2019-09-24 16:30:19.000				RRC Attempt		
2019-09-24 16:30:18.781					RRC Success	0.019
2019-09-24 16:30:19.000	63	-112.23	0.67			
2019-09-24 16:30:20.000	63	-112.24	1.47			
2019-09-24 16:30:21.000	63	-112.95	0.61			
2019-09-24 16:30:22.000	63	-113.28	0.55			
2019-09-24 16:30:23.000	63	-113.09	0.18			
2019-09-24 16:30:24.000	63	-113.25	-0.45			

Source: Signals Research Group

During this test, we had the mobile device mounted to the roof of the drive test vehicle. We also used Google Drive to generate data transfers. Since we couldn't reach the mobile device during this test, we didn't have good visibility of the Drive application and what it was or wasn't doing. Additionally, we later determined that Drive wasn't a good application to generate maximum speed data transfers. Therefore, the absolute data speeds shown in Figure 36 likely understate the capabilities of the network. Additionally, during this test we believe that there was at least one other mobile device in our test van connected to the Loon network and consuming network resources. For this reason, we are including RB-normalized throughput in the figure. Both plots show inconsequential impact to the throughput when the mobile device moved between two Loon PCIs. In fact, the observed data speed improved.

Figure 36. Mobile Device Throughput



Source: Signals Research Group

4.0 Loon and the User Experience

In earlier results we showed data speeds obtained with a smartphone attached to the Loon network. Those results, combined with other data we collected during the week of testing, indicate typical data speeds for a mobile device attached to the Loon network were frequently in the mid- to high-single digits (Mbps), although with good conditions they could reach into the mid-teens. We even observed a peak data speed of 40.3 Mbps with ideal conditions in a commercial network, but this speed is the exception and not the norm.

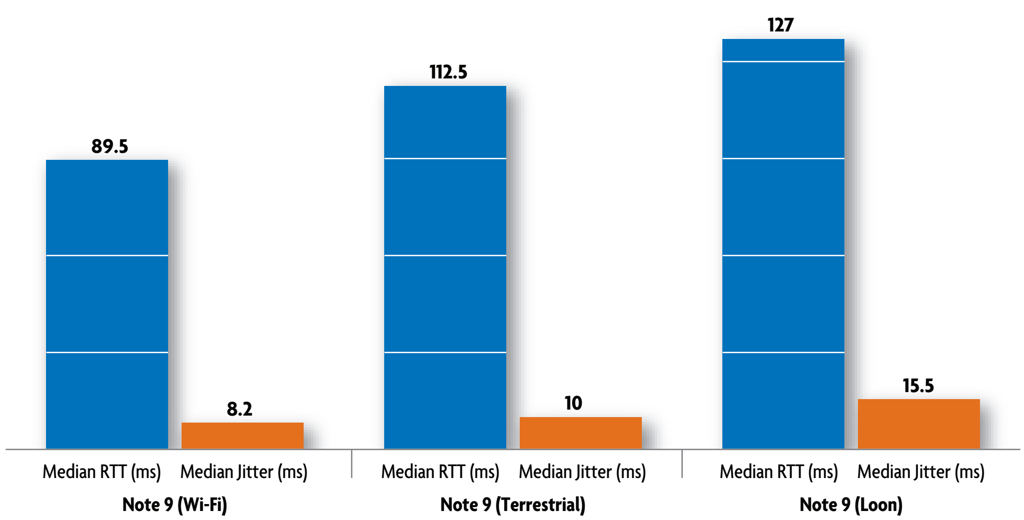
Loon delivers a comparable user experience to a terrestrial LTE network with many applications

In this chapter, we analyze the user experience with Loon, realizing that the user experience isn't just impacted by data speeds and that fast data speeds do not always improve the user experience. To summarize our findings, Loon delivers a comparable user experience to a terrestrial LTE network with many applications, especially an LTE network that is limited to a single 2x10 MHz channel. Comparing Loon to an LTE-Advanced network with 5-carrier carrier aggregation and 80 MHz of FDD spectrum isn't meaningful since networks with these advanced capabilities do not exist in the regions that Loon serves. Clearly, downloading a Gigabyte file over an LTE-Advanced network would take far less time than over Loon, but this isn't a fair comparison, nor does it represent a likely usage scenario for a mobile subscriber living in an area served by Loon.

The latency with Loon was 13% higher than the terrestrial LTE network.

Figure 37 shows the round-trip transfer (RTT) delay time and jitter, based on pinging a local server (Google) for 60 seconds. We did the Wi-Fi and terrestrial testing at our hotel in Tarapoto. The Loon testing occurred well outside of Tarapoto where terrestrial coverage did not exist. The latency for all three scenarios was higher than we are accustomed to seeing in the US, Western Europe, and developed Asia, however, on a relative basis Loon's performance was only modestly worse than the terrestrial network. Specifically, the latency with Loon was 13% higher than the terrestrial LTE network.

Figure 37. Latency and Jitter

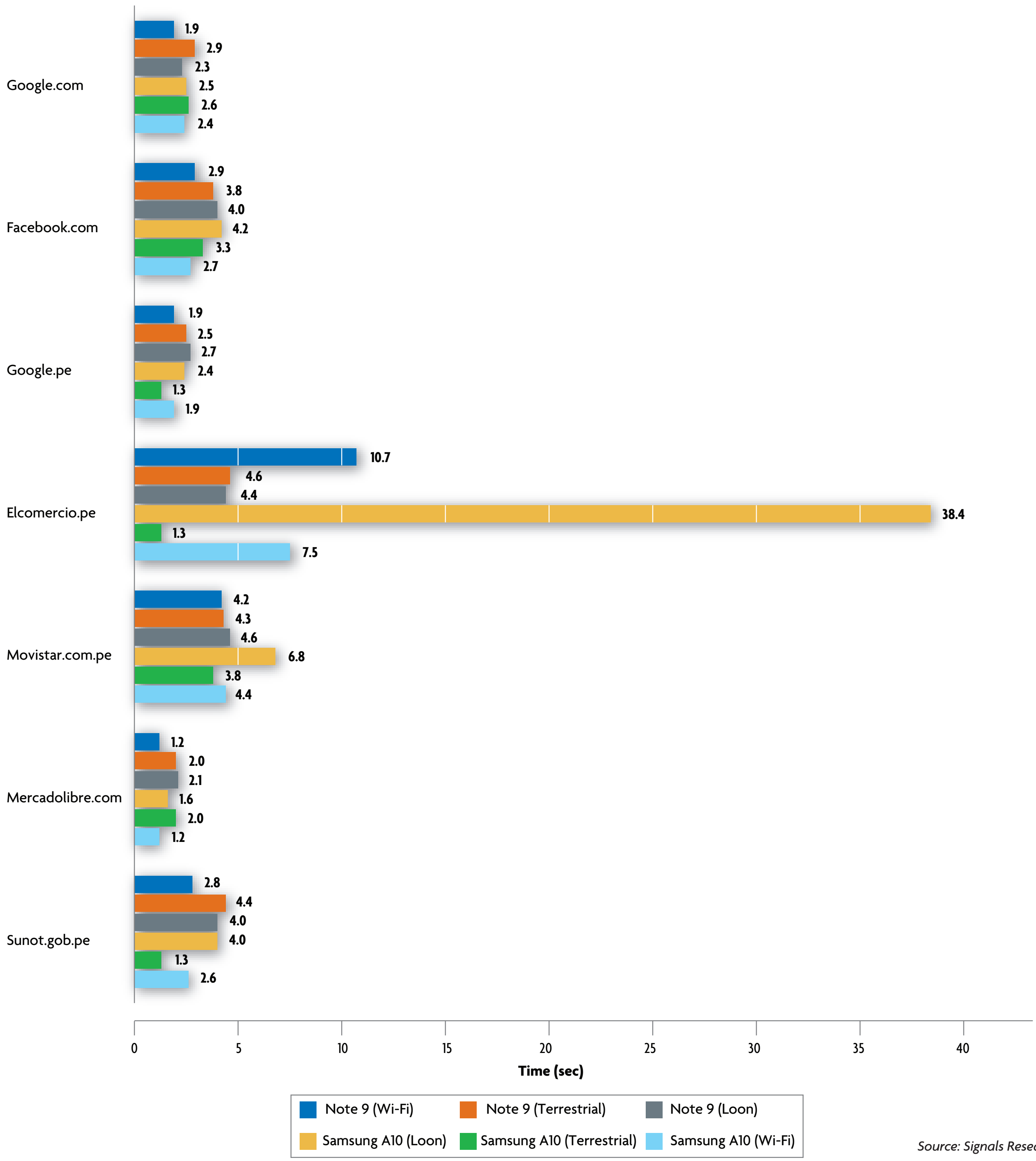


Source: Signals Research Group

Applications, such as web browsing, do not require high data speeds to provide a good user experience but they do benefit from low latency due to the back-and-forth transfers of data packets and TCP acknowledgement (ACK) messages. We performed web browsing tests with a Galaxy Note 9 and a Samsung A10 smartphone. The Loon testing occurred outside of Tarapoto in an area where terrestrial coverage did not exist. The Wi-Fi and terrestrial network tests occurred at our hotel in Tarapoto. We point out the Note 9 used Band 4 (2x20 MHz) for these tests. The Galaxy A10 used Band 28 for the terrestrial web browsing tests, although we note the channel bandwidth in the terrestrial Band 28 LTE network was 2x15 MHz, compared with 2x10 MHz in the Loon network. Figure 38 on the following page provides the results from these sets of tests.

We selected seven mobile websites that were popular in Peru. The test script, which we ran through the XCAL-Solo platform, loaded each website sequentially while capturing pertinent time stamps to determine how long it took to load each web page. We repeated each test 10 times, meaning there were 70 web pages loaded for each test scenario. Excluding the A10 results with www.elcomercio.pe, a local news media portal, the differences in webpage load times were inconsequential. In fact, in some cases, the results with Loon were slightly better than the terrestrial and/or Wi-Fi results. We have no reason to believe the A10 load time with this website is incorrect, but the result is an outlier. We also point out that during this test, the web page loaded in just a few seconds for the first few times (comparable to the other results), but for the remaining tests the load times were substantially longer. The A10 results with the other web pages during this test remained comparable so it is quite possible the long load times had less to do with Loon and more to do with the website. For completeness and full transparency, we are including the results in this paper.

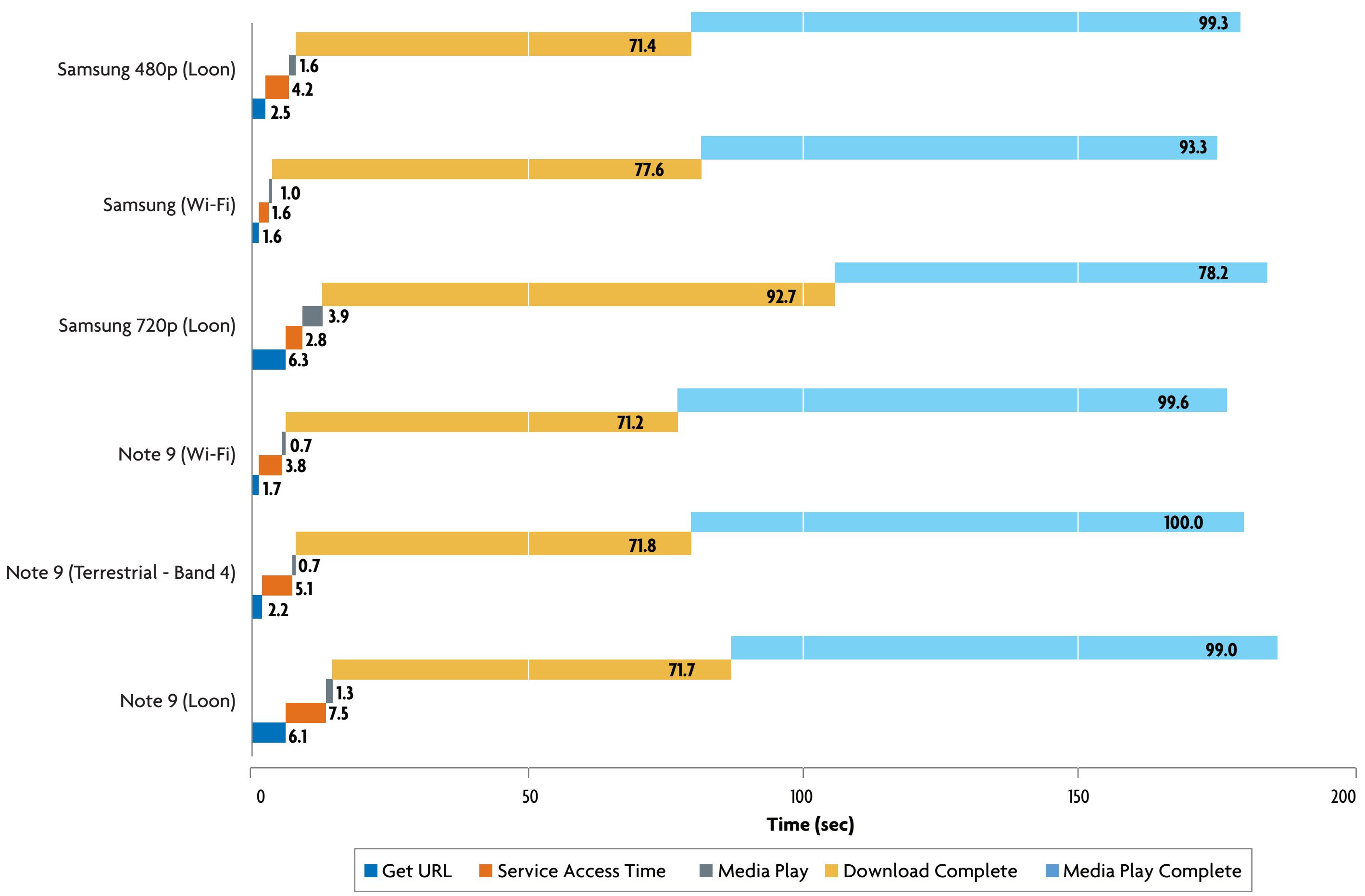
Figure 38. Web Browsing



Source: Signals Research Group

Figure 39 and Figure 40 show results from testing the user experience with YouTube. For this study, we used the same video (a 2:51 video entitled "Ben Fogle and Hugh Dennis – Peruvian Andes – Worlds Most Dangerous Roads – BBC"), although we did try both 360p and 720p resolutions. Figure 39 shows the timeline of events for the entire video playback and Figure 40 isolates the timeline to focus on the period prior to the video starting to play on the phone. Looking at the first figure, it is evident the phones had downloaded the video in its entirety long before the video finished playing on the phone. The 720p video took longer to download due to the file size. Additionally, YouTube uses buffer management to control how much video is downloaded to the phone's buffer during the playback. This mechanism means that the longer download time was due to the YouTube application and not to limitations with the network.

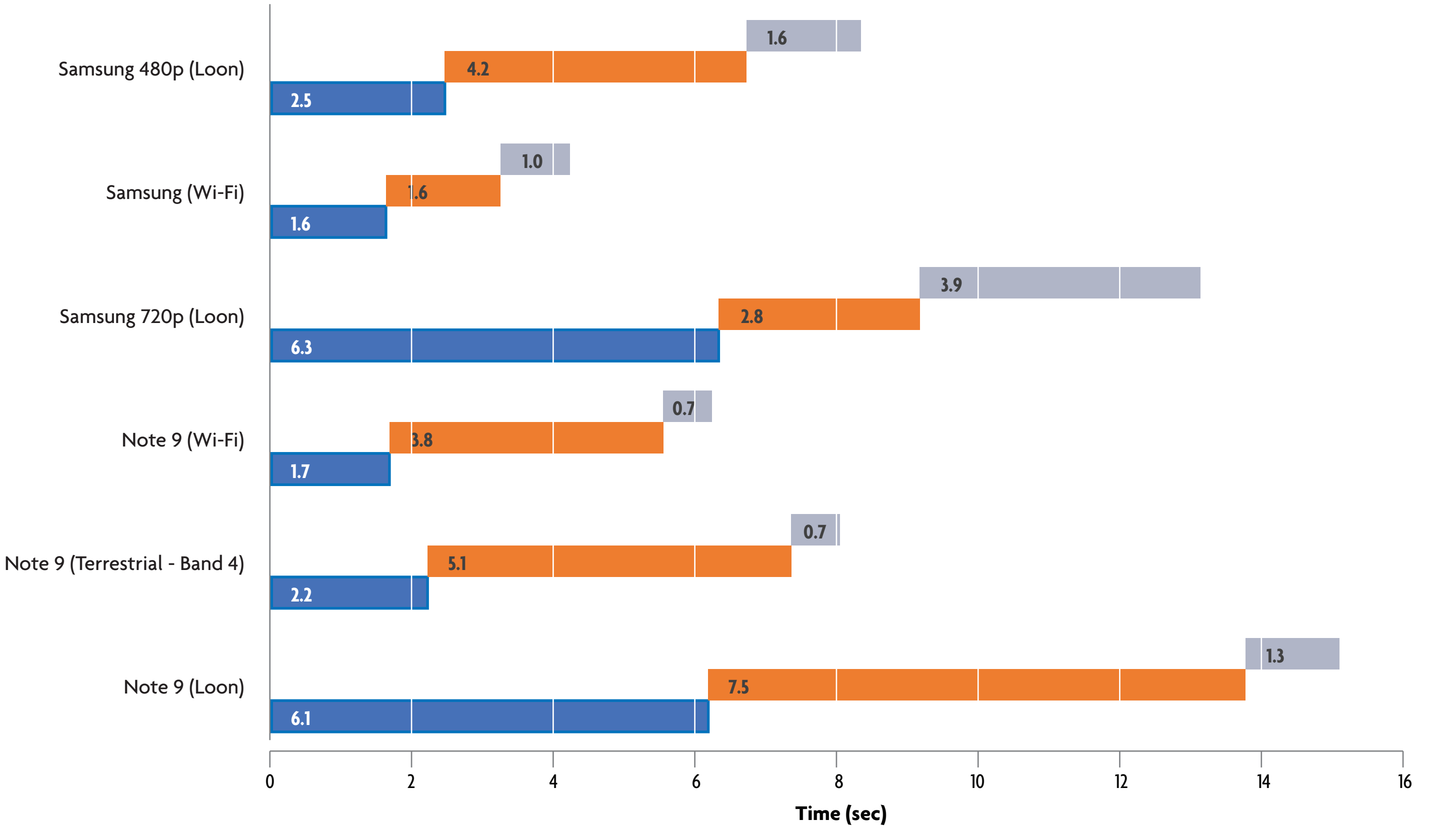
Figure 39. YouTube



Source: Signals Research Group

As shown in Figure 40, the video playback starting times ranged from 4.2 seconds (A10 smartphone with Wi-Fi) to 15 seconds (Note 9 smartphone with Loon). Within this range, Wi-Fi faired the best, followed by the terrestrial network and Loon, but the differences between the terrestrial network and Loon weren't substantial. The A10, for example, took 8.3 seconds for video playback to start with Loon, compared with 8 seconds with the Note 9 over the terrestrial network (Band 4).

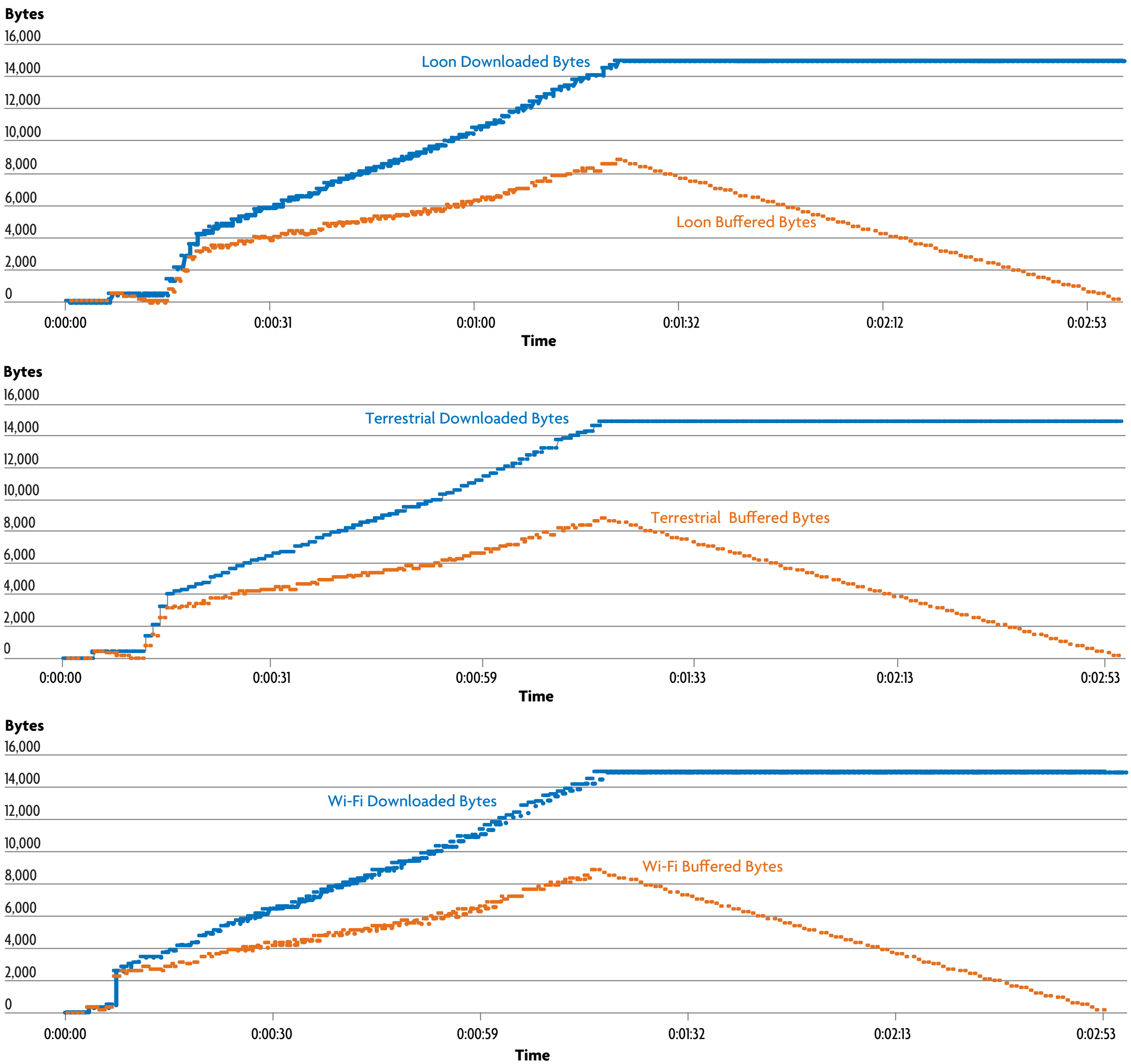
Figure 40. YouTube – enhanced view



Source: Signals Research Group

Once the videos started to play, we generally didn't experience any problems with video buffering. This statement is supported by the results in Figure 41. The figure shows three sets of results involving the Note 9 playing the video over Loon, the terrestrial LTE network, and Wi-Fi. The figure shows the cumulative number of downloaded bytes during the video playback as well as the amount of data in the buffer. The gradual ramp of the downloaded bytes for all three networks illustrates the buffer management technique used by YouTube. If the buffered bytes remain positive the video will continue to play.

Figure 41. YouTube Buffer Management



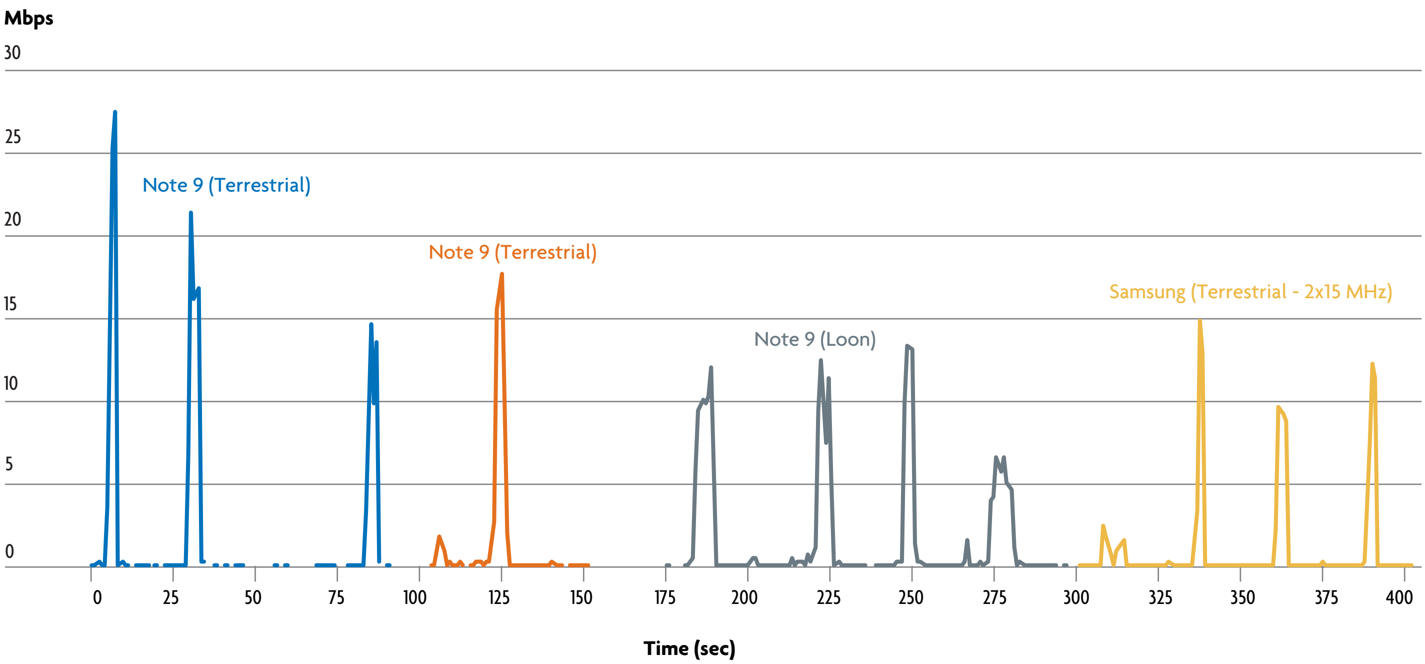
Source: Signals Research Group

We also took the opportunity to do a video chat (Google Duo) back to the United States while testing well outside of Tarapoto in an area only served by Loon. The video quality wasn't as good as it would be in a high bandwidth LTE network or over W-Fi, but it was more than acceptable. The video was a bit fuzzy, suggesting a low resolution, but there wasn't any freezing on either side and the audio quality was fine.

Downloads from Google Play were modestly slower with Loon than Wi-Fi and the terrestrial network, but differences in channel bandwidth were also a factor.

The last set of results pertain to downloading an application from Google Play. Figure 42 shows the physical layer throughput. We don't have Wi-Fi results because it isn't possible to capture physical layer throughput with the drive test tool. The figure plots each download sequentially – each spike represents a separate download of the ~5 MB application. The implied download times with the Note 9 smartphone using the terrestrial LTE network were the fastest, but it is important to note the phone was using Band 4 with 2x20 MHz of spectrum. Likewise, the Samsung A10 results over the terrestrial LTE network used a 2x15 MHz channel, compared with the Loon results, which stem from using a 2x10 MHz channel. The conclusion is that while the download times with Loon were modestly slower than the other networks, the differences were inconsequential and largely due to the narrower channel bandwidth used by Loon.

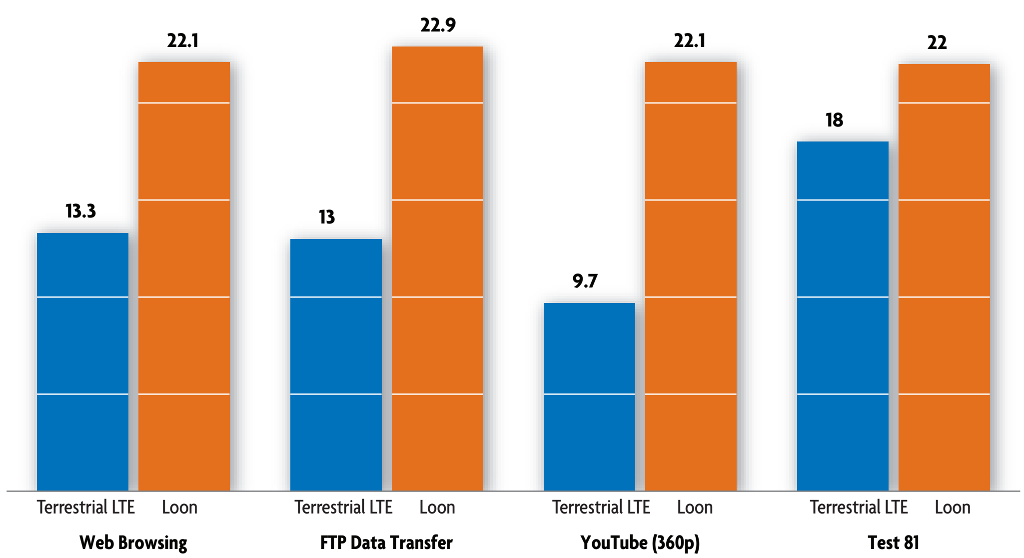
Figure 42. Physical Layer Throughput While Downloading an Application from Google Play



Source: Signals Research Group

We also looked at mobile device transmit power during some of these tests to determine if there were differences between the mobile device using Loon and the terrestrial network. As shown in Figure 43, the mobile device transmit power when attached to Loon was frequently 22 dBm. The median values for each scenario only include data points when the mobile device was transmitting. For example, the mobile device only transmits when it is downloading the YouTube video and not when the video is playing from the phone's buffer. When connected to the terrestrial LTE network the transmit power levels were much lower. The first three scenarios with the terrestrial network occurred in Tarapoto on Band 4. The last scenario (Test 81, which we discussed previously in the last chapter) is a very direct comparison since the Loon and terrestrial network transmit power levels occurred at the same location. Although we didn't quantify the impact on the user experience, we know a higher transmit power can have a negative impact on battery life. However, we know from other studies that we have done that display brightness combined with non-communications activities which trigger the display turning on, have a very meaningful impact on battery life, thereby minimizing the impact of the higher transmit power.

Figure 43. PUSCH Transmit Power



Source: Signals Research Group

5.0 Test Methodology

SRG conducted the Loon benchmark study during the week of September 23, 2019. The testing occurred in a region south of Tarapoto, Peru in the San Martin region in northern Peru. All testing occurred during daylight hours, starting around 9 AM and finishing around 5:30 PM to ensure we made it back to Tarapoto before it got dark. Given the travel time to the area where Loon was deployed to provide coverage, we couldn't extend deep into the Loon coverage area. However, we traveled far enough into the Loon coverage area to collect sufficient network performance data. Further, one key focus of this study was to evaluate Loon's impact on the terrestrial network and for this objective we needed to test at the boundary between Loon and the terrestrial LTE network. If anything, we are not showing the breadth of Loon coverage throughout Peru.

Loon engineers provided critical technical support, including guiding our drive test vehicle to locations where Loon coverage existed. Additionally, Loon engineers were able to turn on/off the Loon cells and identify the PCI values associated with their network. SRG collected all the performance data provided in this report and we take full responsibility for the analysis of the data.

We used the TSMA scanner from Rohde & Schwarz to log network parameters in the Band 28 LTE network. The scanner was in our test van with the antennas magnetically attached to the roof of the van. In addition to the scanner, we used a combination of XCAL-M and XCAL-Solo from Accuver Americas to log chipset diagnostic messages from the LTE modems in the smartphones that we used in the study. We used the Pixel 3 (Qualcomm chipset), Samsung Galaxy Note 9 (Qualcomm chipset) and a Samsung A10 (Samsung chipset) smartphones. Depending on the test, the smartphone(s) were placed inside the vehicle, mounted to the roof/side of the van, or we were holding the phone outside of the vehicle. Finally, we leveraged the Umetrix data platform from Spirent Communications to generate high bandwidth data transfers. Although the server that we used was located in Virginia, we were still able to generate very high data speeds to the mobile devices attached to Loon, suggesting the remote location of the server didn't have a big impact on performance. We work with all three companies in our benchmark studies of LTE and 5G networks.

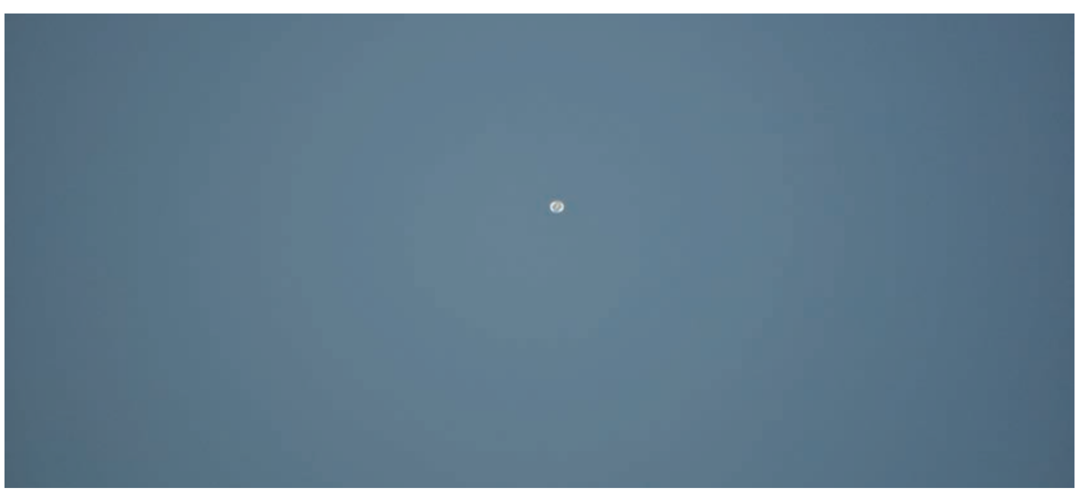
Since XCAL-M interfaces with the R&S scanner we were able to analyze the scanner and mobile device results with the Accuver Americas XCAP post-processing software. The results presented in this paper are based on geo binning the data in three-meter quadrants. For tests involving time sensitive information or tests where geo binning doesn't make sense (e.g., user experience tests and stationary tests), we binned the data in one-second time increments. RRC signaling messages are not time binned so we were able to extract precise time stamps for pertinent events, including web page load times and cell attach/detach times.

We are including a few pictures in this chapter to highlight the areas where we tested. Additionally, one evening we were able to view Loon balloons overhead. From the same location alongside a road we spotted three Loon balloons at different points in the sky.

Figure 44. Scenes from the Loon Coverage Area

Source: Signals Research Group

Figure 45. A Loon Balloon Overhead

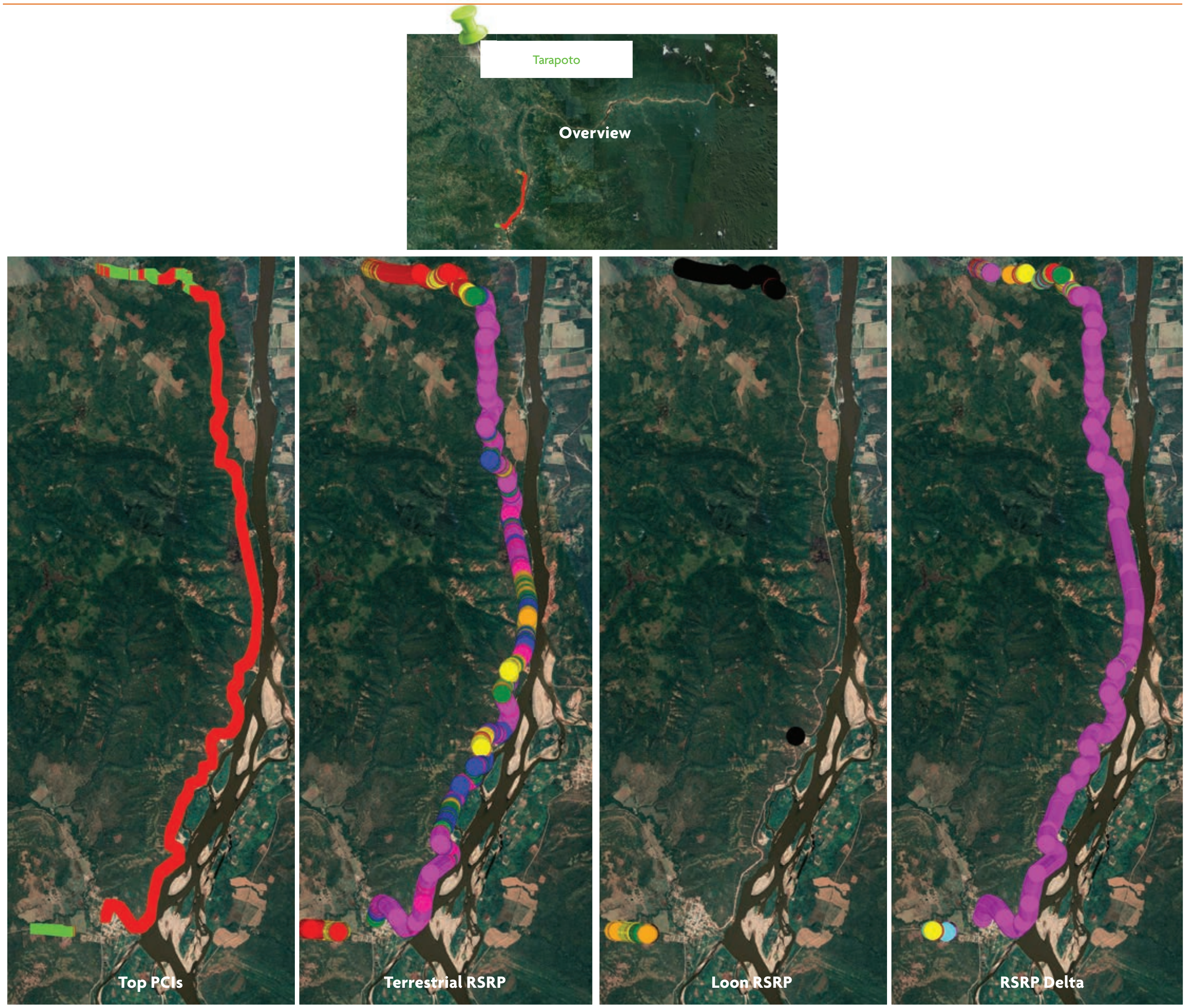


Source: Signals Research Group

6.0 Appendix

We include some additional test results in the appendix. Since we explained the analysis behind each figure in the previous chapter, we are not providing any additional commentary for these results. We included these results in the two summary figures in Chapter 1. However, we felt other test results provided better insight into Loon's performance and/or its impact on the terrestrial network, so we moved these results to the appendix. In these tests, Loon was barely present in the results, making them less interesting, or the drive route largely overlapped with another test shown in a previous chapter.

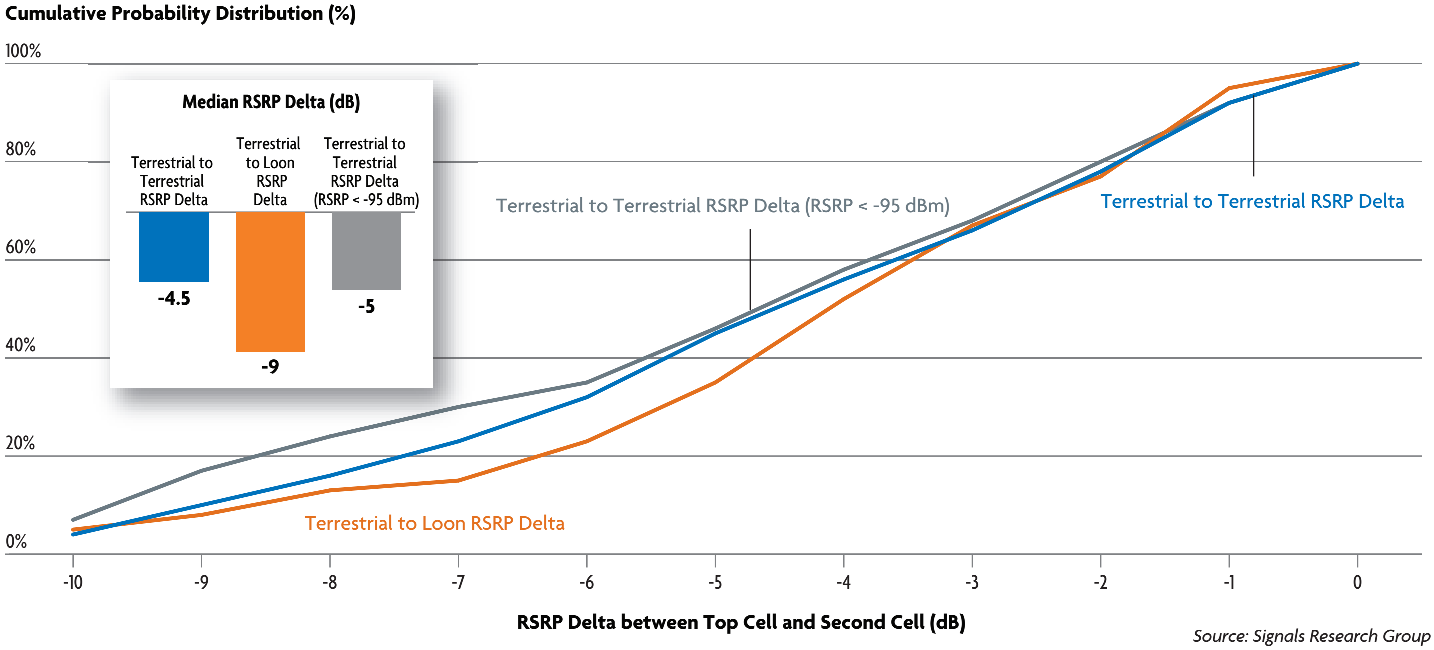
Figure 46. Test 25, 26 and 30 Key Metrics – geo plot



Top PCI	RSRP (dBm)		RSRP Delta (dB)	
Loon Dominant Cell	X > -90	-110 <= X < -105	0 <= X < 1	4 <= X < 5
Terrestial Dominant Cell	-95 <= X < -90	-115 <= X < -110	1 <= X < 2	5 < X
	-100 <= X < -95	-120 <= X < -115	2 <= X < 3	
	-105 <= X < -100	X <= -120	3 <= X < 4	

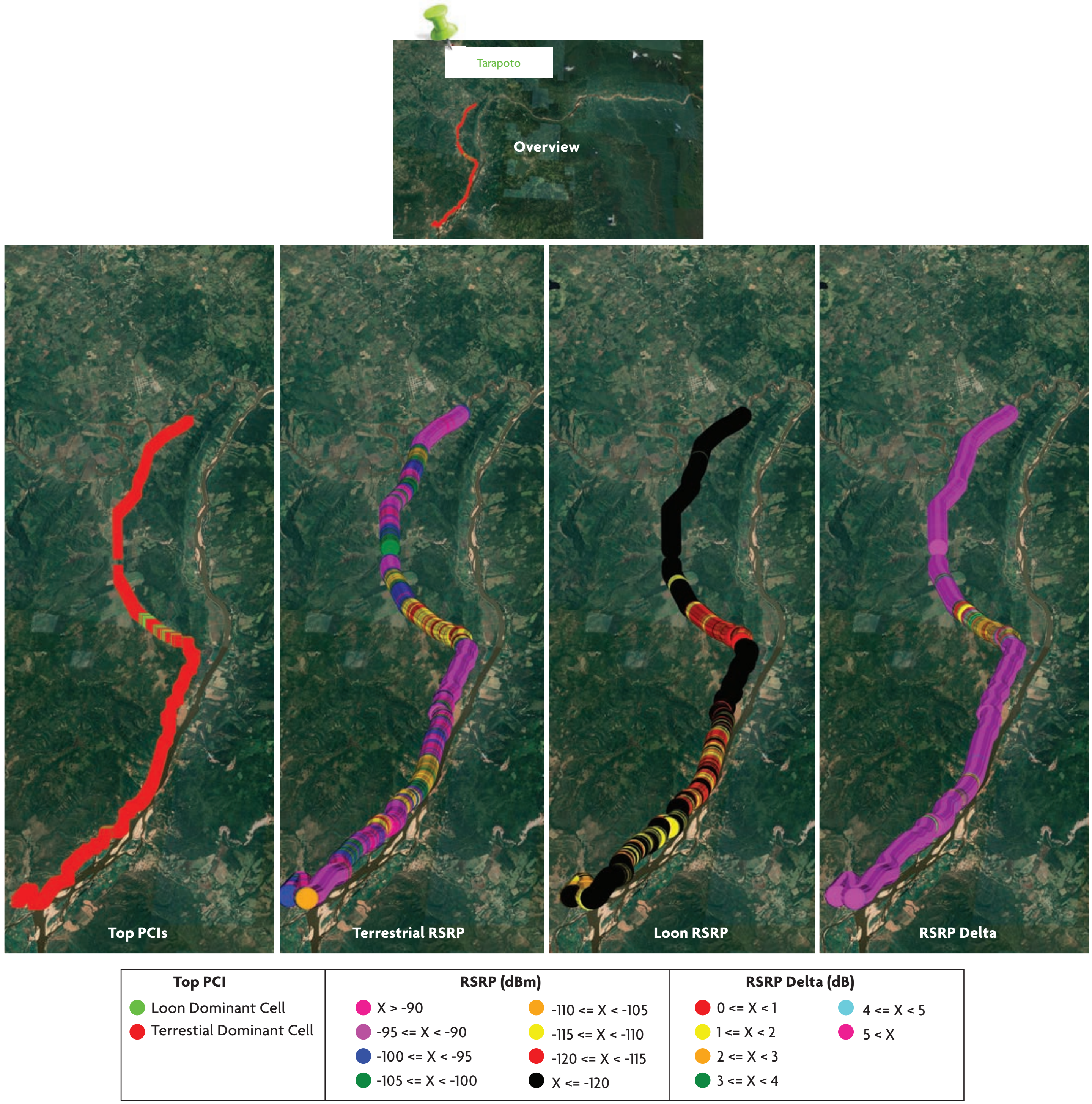
Source: Signals Research Group

Figure 47. Cumulative Distribution of the Differences in Signal Strength between the Top Terrestrial Cell and the Strongest Interfering Cell – Test 25, 26 and 30



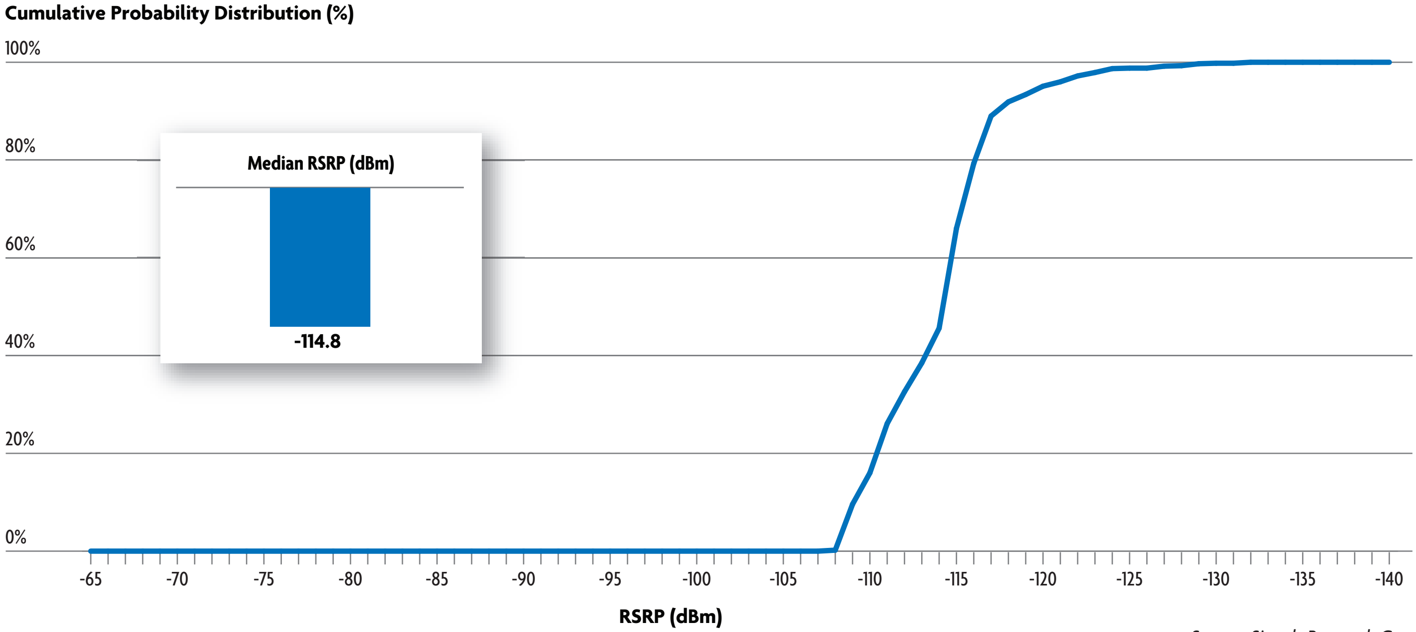
Source: Signals Research Group

Figure 48. Test 34-35 Key Metrics - geo plot



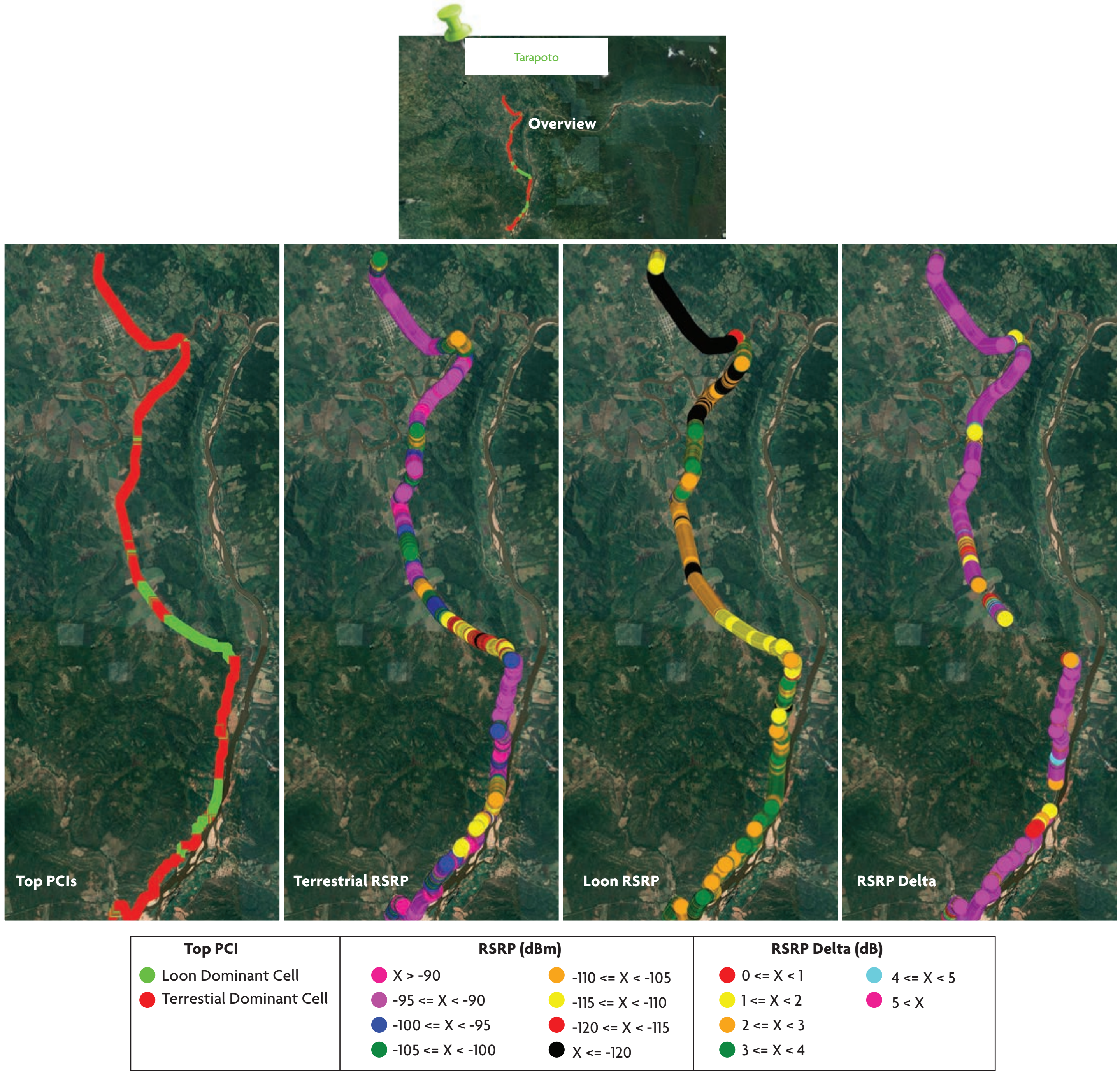
Source: Signals Research Group

Figure 49. Cumulative Distribution of Loon Signal Strength – Test 34 and 35



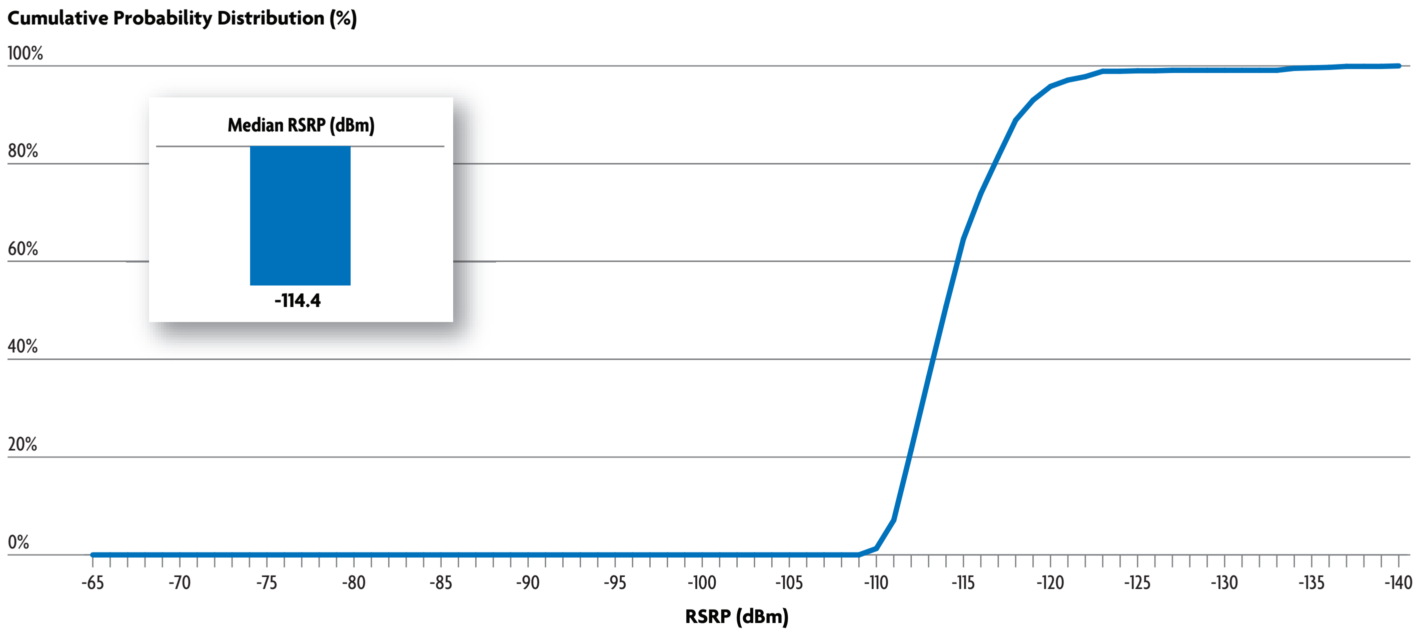
Source: Signals Research Group

Figure 50. Test 52 Key Metrics – geo plot



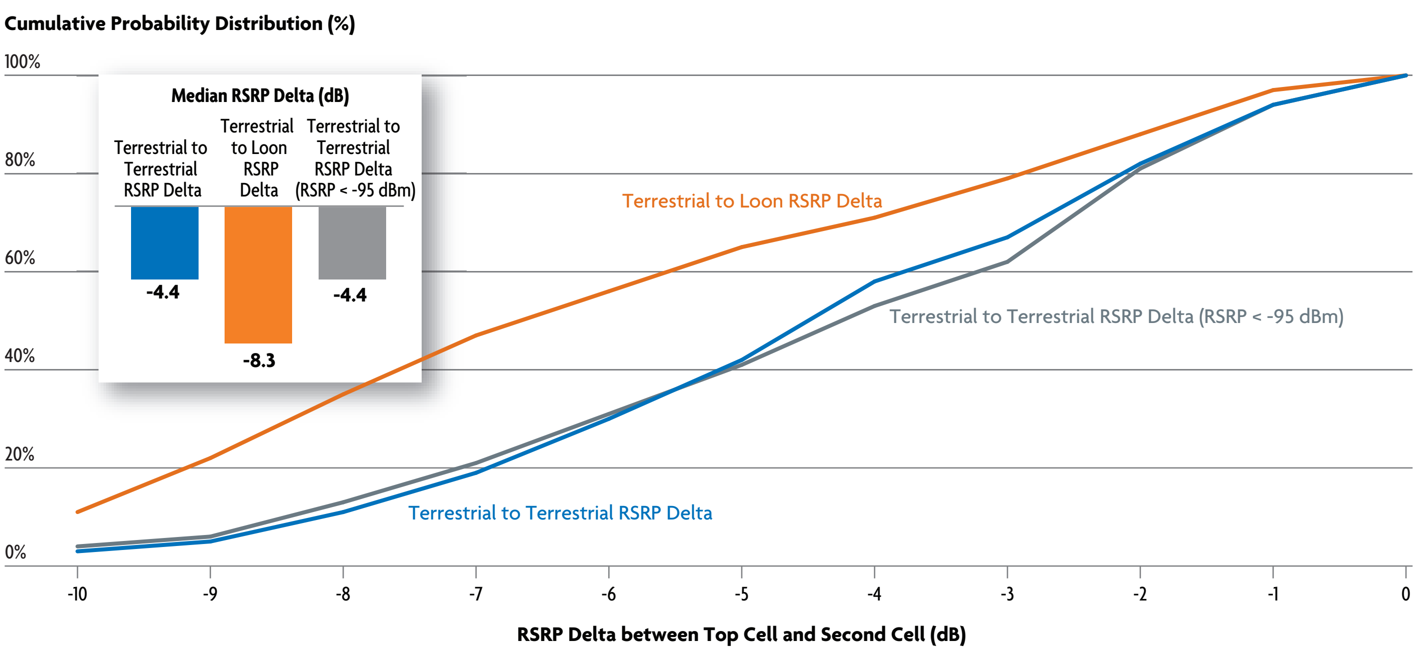
Source: Signals Research Group

Figure 51. Cumulative Distribution of Loon Signal Strength – Test 52



Source: Signals Research Group

Figure 52. Cumulative Distribution of the Differences in Signal Strength between the Top Terrestrial Cell and the Strongest Interfering Cell – Test 52



Source: Signals Research Group