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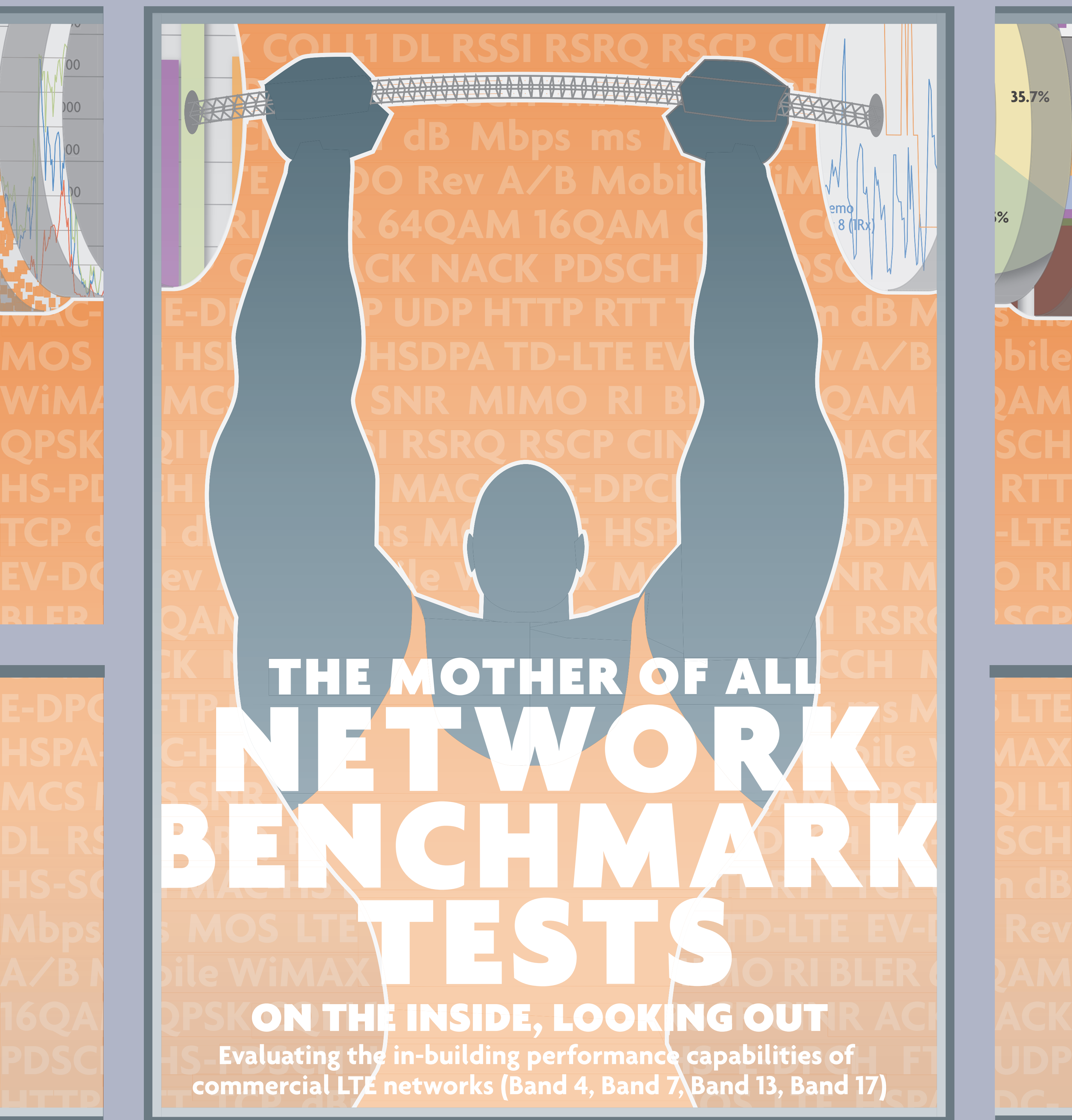

THE MOTHER OF ALL NETWORK BENCHMARK TESTS

ON THE INSIDE, LOOKING OUT

Evaluating the in-building performance capabilities of commercial LTE networks (Band 4, Band 7, Band 13, Band 17)

SIGNALS Research Group

YOUR ATTENTION PLEASE

With Mobile World Congress just around the corner, we want to remind readers that we'll be there the entire week and we're open to meeting with you on a formal or informal basis. Just drop us an email and we will try to set something up.

1.0 Executive Summary

As we enter the fourth year of commercial LTE networks, operators who have been at it for a while are starting to transition from providing basic macro network coverage across a large swath of territory to improving and enhancing the performance of their networks. As revealed in this report, one critical area that requires a lot of [immediate] attention is in-building coverage along with the requisite capacity to satisfy the needs of the in-building mobile data subscriber.

We leveraged the Accuver XCAL-M drive test solution and its enhanced support for in-building testing to evaluate the performance of four LTE networks.

With the continued support of Accuver, we leveraged its XCAL-M drive test solution and its enhanced support for in-building testing to evaluate the performance of four LTE networks encompassing Band 4, Band 7, Band 13, and Band 17. In addition to drive testing the outdoor macro network as we have done numerous times in the past, we ventured indoors to map out the network performance in a number of prominent publicly-accessible buildings, including five major airport terminals, two shopping malls, two hotels and a large convention center. Once we completed the testing campaign, we used the Accuver XCAP post-processing solution to analyze the data and to reach our conclusions on how LTE performs in an in-building scenario. SRG takes full responsibility for the analysis and conclusions that we provide in this report. We've leveraged the Accuver tools numerous times in the past to provide the industry with what we believe is very valuable and insightful information and we look forward to working with them in the future.

We documented much higher loading of the LTE networks when we tested indoors than when we tested in the outdoor macro networks.

We tested the Rogers Wireless LTE networks in Vancouver (Band 7 and Band 4), the AT&T LTE network (Band 17) and the Verizon Wireless LTE network (Band 13). By and large, we concluded that in aggregate the networks were fairly lightly-loaded in the outdoor macro network. Averaged over lengthy drive tests, the LTE networks were assigning our mobile device at least 70% of the theoretical maximum number of network resources and in some cases the percentages exceeded 90% over the entire drive test. This observation doesn't preclude the likely event that there were pockets within the network where the traffic density from other mobile devices was much higher, but in aggregate our observation is accurate. It was an entirely different story once we moved indoors where the implied network loading was considerably higher, albeit nowhere near what we could consider to be a loaded network.

Given the immaturity of today's commercial LTE networks, some of the buildings that we tested had an in-building LTE solution (e.g., a distributed antenna system or DAS) while it was evident that outdoor macro cell sites were providing coverage to other buildings that we tested. In either situation, it was evident that network performance problems existed today or will exist in the not-too-distant future.

The magnitude of the decline in the SINR was disproportionate to the increase in network traffic.

Although it didn't occur with all in-building networks that we tested, we measured a considerable drop-off in the quality of the LTE signal (SINR) for a very modest amount of network loading. One would expect the SINR to drop with increased traffic levels, but the magnitude of the decline in the SINR in our in-building testing was disproportionate to the increase in network traffic, and far greater than what we experienced in the outdoor macro networks. Consequently, some of the key features associated with LTE, such as 64 QAM and MIMO, were less effective or virtually nonexistent and the throughput suffered. In a couple of cases, the SINR was quite good with light network traffic, but MIMO was hardly ever used. This finding is consistent with our understanding that some legacy DAS solutions need to be upgraded to support MIMO and that in some cases an operator may decide to forgo the upgrade on the belief that the subsequent performance gain, if any, wouldn't justify the cost.

The AWS spectrum is intended to provide a capacity layer, yet the capacity is needed indoors where 1700 / 2100 MHz is even less effective from a coverage perspective than 700 MHz.

In some of the buildings that we tested it was evident that our mobile device was accessing the outdoor macro network. Even at 700 MHz there was strong evidence of coverage-related problems since the mobile device would enter search mode or even switch to a legacy 3G technology. Ironically, in one shopping mall the in-building DAS solution that supported HSPA+ at 1900 MHz meaningfully outperformed the same operator's 700 MHz outdoor macro LTE network. So much for 700 MHz being the panacea that solves all prior coverage problems. Worth mentioning, AT&T and Verizon Wireless are intending to use their AWS spectrum as a capacity layer, but the additional capacity will be needed indoors where 1700 / 2100 MHz is even less effective from a coverage perspective than 700 MHz. The only viable option is to use 1700 MHz in a dedicated in-building solution that scales to support traffic levels that are massively higher than what are present today.

In other test results, the in-building throughput was quite good despite our mobile device accessing the outdoor macro network. However, it was evident in some of the other underlying metrics that a coverage problem still existed, even though the problem didn't manifest itself in the measured throughput. Specifically, we could see clear evidence that the network was artificially limiting the mobile device's uplink transmit power due to uplink interference issues at the adjacent cell sites. By limiting the transmit power, the network was also reducing the potential throughput, and surprisingly the lower transmit power in the uplink also impacted the downlink throughput, although not as significant as the uplink throughput.

Coverage problems will become more apparent when the network loading increases.

In this situation the coverage problem will become more apparent when the network loading increases. Today, in a lightly-loaded network, the network is able to compensate for poor coverage by assigning the mobile device all of the network resources. One example is the Rogers network where the edge of cell throughput was higher in Band 7 (DL = 2650 MHz) than it was in Band 4 (DL = 2115 MHz), but only because the Band 7 network used a 2 x 20 MHz channel with 100 available resource blocks while the Band 4 network was limited to a 2 x 10 MHz channel and 50 resource blocks. Once the Band 7 network begins to experience network loading it will no longer be able to assign 100 resource blocks on a continuous basis and the throughput will favor the lower frequency network.

Radiating buildings from the outside is the easiest solution, but it is also the least effective solution.

Regardless of an operator's spectrum holdings, it needs to maximize its network resources to ensure it provides excellent coverage and ample capacity that scales to meet the forecasted increase in mobile data traffic. Radiating buildings from the outside is the easiest solution, but it is also the least effective solution. An in-building mobile data subscriber requires a disproportionate amount of network resources to achieve the same throughput as an outdoor mobile data subscriber. When LTE networks are, by and large, lightly loaded the outdoor network serves its purpose.

When LTE networks become loaded, the number of network resources (e.g., sub-frames and resource blocks) still remains constant, meaning that the available network resources need to be used more efficiently. The use of in-building solutions, including a scalable DAS solution for coverage and capacity, combined with multi-RAT small cells to provide ample capacity where it is needed, is the only viable option. In-building mobile data users benefit by being closer to the serving cell site and outdoor mobile data users benefit because the network resources that were previously supporting the in-building users are available to support their mobile broadband requirements.

As part of our testing, we spent a fair amount of time conducting outdoor drive testing of the Verizon Wireless and AT&T LTE networks. Even after we normalized the data for equivalent network loading, it was still apparent that one of the networks delivered much higher user throughput than the other network – consistent with what we observed during our last benchmarking exercise. While great for marketing purposes, it probably won't be noticed by the typical user. All this and more in this issue of *Signals Ahead*.

A HIGH RESOLUTION VERSION OF THIS REPORT IS AVAILABLE ON OUR WEBSITE. PLEASE CONTACT US IF YOU NEED YOUR LOG-IN ID AND PASSWORD.

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2.0 Key Findings and Observations

Based on in-building testing of three operators' networks with the Accuver XCAL-M drive test tool in four different frequency bands from 709 MHz (Band 17 UL center frequency) to 2650 MHz (Band 7 DL center frequency), we offer the following key findings and observations.

To the extent LTE networks are experiencing loading, it is highly concentrated and far more likely to occur indoors. During our analysis of the data with the Accuver XCAP post-processing tool we calculated the implied level of network loading based on the number of network resources that our mobile device received. Specifically, we could individually identify and count each 1 ms sub-frame that our mobile device received, and based on the overall length of the test we knew the total number of sub-frames that the network assigned to all devices. We also knew and validated once again that with the current implementation of the Ericsson scheduler that it only assigned downlink resources to one mobile device within a sub-frame (e.g., it was limited to time-based scheduling and it didn't support frequency-based scheduling). If the scheduler had supported frequency-based scheduling we would have analyzed the resource block allocation since we also had access to this information.

It was then a simple calculation to determine the percentage of resources that the network assigned our mobile device versus the total number of resources (sub-frames) that were available, although we'll admit to using a calculator. We defined this value as the utilization rate, or the percentage of network resources that our mobile device received versus the theoretical maximum number of network resources that were available during the period of the test. Note that this methodology doesn't tell us how many other mobile devices were connected to the network or the total network throughput. However, it is very reasonable to assume that the network scheduler was applying some degree of fairness to make sure all devices were being adequately served, and that it would not intentionally keep from assigning all available resources.

At its worst, the network was still assigning our mobile device more than 70% of the possible network resources and occasionally more than 90% of the possible network resources.

Throughout all of our outdoor drive testing in the four networks (Rogers had two networks by our definition), the average utilization rate throughout any given lengthy drive test ranged from the low 70s to the high 90s on a percentage basis. In other words, at its worst, the network was still assigning our mobile device more than 70% of the possible network resources and occasionally more than 90% of the possible network resources throughout the entire test duration. This fact does not suggest that we didn't encounter hot spots and occasionally a much lower utilization rate, but these incidents were few and far between. We can only conclude that the outdoor macro networks in their totality were fairly lightly loaded when we conducted our tests.

In our in-building testing the utilization rate was as low as 35% (SFO Terminal 3), indicating the level of other network traffic was much higher than it was in the outdoor macro network.

It was a different picture when we moved indoors. Airport terminals seemed to be the most problematic, although we still documented very high utilization rates (e.g., light network loading) on occasion. At SFO Terminal 3, at a time when the number of passengers seemed moderate, the utilization rate on the Verizon Wireless LTE network was only 35%. Another example is Chicago O'Hare Terminal C where our mobile device on the AT&T network had a 46% utilization rate. AT&T was only using 2 x 5 MHz of spectrum for LTE in Chicago, which partly explains the lower utilization rate. In both cases, the utilization rate might have been much lower if we had tested during a peak day and time, but unlike Viktor Navorski, we had better things to do than hang out in an airport terminal for several weeks.

Given our test methodology, in which we were trying to send or receive as much data as possible (e.g., hog all of the bandwidth), a utilization rate of 35% still seems awfully good in the sense it means that during the ~ten minute span of a single in-building test the network was giving us a full third of the network resources. We wouldn't consider a network loaded if a single device was getting a full third of the network resources, but on a relative basis the network was still more loaded on indoor networks than it was in the outdoor macro networks. We discuss how network loading impacted throughput and other KPIs in another bullet.

Serving in-building users with an outdoor macro network results in performance degradation, especially in the uplink. In our in-building testing, we believe that in many cases our mobile device was using a preexisting in-building DAS solution while in other tests we are certain that our mobile device was obtaining resources from the outdoor macro network. In the latter situation, we observed numerous indications that the diminished RF signals were directly impacting the results. In some cases the impact was extreme and the mobile device would drop the connection and enter search mode, or it would switch to another network, such as EV-DO Rev A. In many cases, the throughput was "good" but we could tell from other KPIs that the throughput could have been a lot better.

We leveraged RSRP and Power Headroom KPIs to provide further insight into how each building's exterior and interior walls were impacting performance. In the downlink, the RSRP dropped appreciably while indoors and this phenomenon was more evident at 2650 MHz than it was with lower spectrum bands. At the extreme, we observed an 18.2 dB drop in the average RSRP simply by moving from outside of a major convention center in downtown Vancouver to the lobby immediately inside of the building. The drop was also evident at 2115 MHz (Band 4) but it was not as significant or only 11.95 dB. On an absolute basis the RSRP in Band 4 was always higher than the Band 7 RSRP. To be fair, in some cases the in-building RSRP levels were surprisingly high relative to the outdoor measurements, but in at least one case we fully believe that the outdoor site was specifically deployed to cover the building. Further, this dedicated cell site didn't solve the uplink issue.

Uplink coverage constraints, including at 700 MHz, frequently impacted the achievable uplink and downlink throughput.

The uplink (Power Headroom) was almost always the limiting factor and more often than not, uplink power constraints artificially lowered the throughput. In many cases, the Power Headroom was negative, indicating the network was artificially limiting the mobile device's transmit power and consequently its uplink throughput. Surprisingly, this situation also occurred during downlink throughput testing, meaning that the uplink coverage constraints were impacting the downlink throughput. Power Headroom will always be worse during uplink throughput tests than downlink throughput tests, all things being equal, since in an uplink throughput test the mobile device is trying to send more data.

In one example that we show in this report the Power Headroom during a Band 17 (700 MHz) downlink throughput test dropped by nearly 11 dB simply by walking into a large room at a hotel. The 11 dB difference is relative to what we measured on the same floor of the hotel but outside of the room. Relative to the Power Headroom that we measured outside of the hotel, there was a 23 dB decrease. We also observed a meaningful drop in the downlink throughput and a large increase in the transmit power once we entered this room, which was nearly adjacent to the exterior wall of the hotel. Coincidentally, we spent the better part of two days in this room during a recent conference and we can attest from first-hand experience that the battery life of our Samsung Galaxy S III and notebook computer with Sierra Wireless dongle was terrible.

700 MHz isn't a panacea for coverage. A wise sage once said, "You can't always get want you want, but if you try sometimes, you get what you need." Most likely, he had something else on his mind when he coined the phrase, but the philosophy holds true for wireless as well. According to our test data, operators didn't skimp when it came to deploying LTE. Although there are exceptions in outer regions of a market, especially a newly deployed market, the LTE grid at 700 MHz that AT&T and Verizon Wireless have deployed is almost exactly a one-for-one grid with the legacy 850/1900 MHz cellular network. If the pre-auction hype was anything close to reality then there would be ubiquitous coverage throughout any building, regardless of the building material. This isn't the case, and interestingly we show in this report that an in-building HSPA+ 1900 MHz DAS solution handily outperformed a 700 MHz outdoor macro LTE network when it came to providing coverage and high data rates to an urban shopping mall.

By and large, a 700 MHz LTE deployment on an 850 MHz 3G cell grid will have coverage that is comparable to, but not substantially better than, the legacy technology it is intending to replace one day. The secondary problem is that there will inherently be higher expectations for how the LTE network performs. Sub-par 3G data rates may suffice today, but they won't suffice with LTE or eventually LTE-Advanced. The RF signal threshold required to establish and sustain a VoLTE call (or any VoIP connection) will also be far more stringent than a simple 9.6 Kbps circuit switched connection.

The existing cell grid that operators have deployed will likely not meet the FirstNet network design and performance criteria.

Finally, one cannot ignore FirstNet and the requirements for a public safety network that serves the nation's first responder units. If they ever get around to building the network, it will likely involve some sort of collaborative effort with a large mobile operator or operators. If nothing else they will want/need access to existing cell sites to deploy their new network. The problem is that unless they have loosened their network design criteria since the last time we checked, they won't be able to come even remotely close to meeting the requirements. Deploying a denser cell grid would be prohibitively expensive and it would be logistically challenging to secure building permits and backhaul, not to mention being very time consuming.

Ironically, Verizon Wireless and AT&T plan to use their AWS spectrum (DL ~2100 MHz, UL ~1700 MHz) to provide the capacity layer for their 700 MHz network. This strategy is [potentially] ironic because the capacity layer is needed indoors yet the AWS spectrum will struggle even more than the 700 MHz to reach the in-building subscribers. The only viable solution is to use the AWS spectrum in dedicated in-building solutions so that the spectrum serves its purpose and provides the concentrated layer of capacity where it is needed the most.

In some of the in-building testing there was a surprising and somewhat concerning large degradation in the SINR for a very modest level of network loading. There is an extremely high correlation between good SINR and high throughput. No surprise given that SINR merely defines the ratio of the good signal to the bad signal (interference and noise). Two key features of LTE, namely higher modulation schemes and MIMO, require at least a decent SINR, otherwise they will be ineffective or not even available due to poor channel conditions. Ironically, these two key features, which help increase network capacity, are the least effective when they are needed the most, or when there are high levels of network traffic. We note that interference and noise increase with more mobile devices and with increased traffic levels.

The most disappointing finding from our study was that the in-building SINR in a few prominent locations fell appreciably to relatively low, if not poor, values with only very modest network loading. The same scenario did not occur in the outdoor macro networks. For example, in SFO Terminal 3 the average SINR on the AT&T network was a paltry 0.64 dB, and consequently 64 QAM was nearly extinct and QPSK ruled the day. The average throughput was sub 5 Mbps. One would think that the in-building network was heavily loaded but our mobile device received 65% of the network resources – lower than what we observed in our outdoor testing, but nowhere close to what we could classify as network loading. At Dulles, the SINR was a more respectable 6.46 dB with a 77% utilization rate. Finally, at Boston Logan the SINR was 9.49 dB, but the calculated utilization rate was a remarkable 90.2%, indicating the network had very little network traffic other than our mobile device. For comparison purposes, in our more extensive outdoor macro network testing, the average SINR on both networks was a double digit number – on the Verizon Wireless network the average SINR was 10.84 dB with a 73.7% utilization rate.

Some of the currently deployed in-building solutions won't scale in their current configuration to meet even the most basic mobile broadband traffic demands.

For other in-building tests that we conducted the drop-off in SINR for modest network loading wasn't as evident so we suspect / hope that the problems were isolated and that they can be resolved through better network optimization and a more efficient means of scheduling available resources. Additional DAS capacity, including the use of more spectrum and/or more sectors, combined with the use of small cells to provide targeted capacity where it is most needed will also help address the issue, since it is evident that some of the currently deployed in-building solutions won't scale in their current configuration to meet even the most basic mobile broadband traffic demands.

Once network loading becomes more prevalent it will have a greater impact on in-building coverage + performance. As previously indicated the LTE networks were lightly loaded. With the highest in-building loading that we observed, our mobile device still received an impressive 35% of the network resources and generally the percentages were much higher. Once traffic in the outdoor macro network or in the in-building network increases to more meaningful levels, the in-building end user throughput will suffer far greater relative to the outdoor network performance.

In a lightly-loaded network it is possible to make up for poor coverage by assigning more network resources. For example, the results from our last report indicate that Band 7 edge of cell throughput was higher than the Band 4 edge of cell throughput, despite the higher frequency. The simple explanation is that the Band 7 network with a 20 MHz downlink channel could assign 100 resource blocks while the Band 4 network could only assign 50 resource blocks. If we had normalized the edge of cell throughput to the number of assigned resource blocks then the Band 4 throughput would have been higher. Put another way, once the network isn't able to assign all of the resource blocks because it must also serve other mobile devices, the throughput advantage will favor Band 4.

When the network is only able to assign a limited number of resources to a single user, it must make the most out of each resource block.

The same analogy applies to in-building coverage for all frequency bands. When the network is only able to assign a limited number of resources to a single user, it must make the most out of each resource block. However, this scenario isn't possible since more active users not only limits the number of available sub-frames and resource blocks, it also degrades the SINR, just as penetrating a few walls degrades the SINR – something we prove in this report.

As discussed in other observations, the uplink is even more problematic. In our Vancouver testing, we observed arguably great in-building throughput in both directions, and to the casual observer there wasn't an in-building coverage problem. However, it is also evident in the data that the network was limiting the transmit power due to uplink interference issues at the neighboring cell sites. We saw a similar situation when testing the two 700 MHz networks in the United States. With more users, the uplink interference will be more prevalent so the transmit power will be further reduced. Additionally, there will be more mobile devices competing for network resources (sub-frames and resource blocks) versus the lightly-loaded network conditions that we experienced.

The correlation between increased traffic levels and lower throughput was far more evident in the in-building networks.

Worth reiterating, the correlation between increased traffic levels and lower throughput was far more evident in the in-building networks that we tested than the outdoor macro networks. For various reasons, many, but not all, of the in-building networks simply weren't able to cope with what we believe was very modest network loading. Given that most cellular usage occurs indoors, it is inevitable that the typical in-building mobile data user experience will suffer the most as network traffic levels increase. Proper in-building coverage and capacity planning that leverages a host of solutions, from small cells to distributed antenna systems, is imperative.

In some buildings that presumably leveraged an in-building solution there was a noticeable drop-off in the availability of MIMO (Rank Indicator 2). A few years ago we listened to a European operator who lamented about the challenges of deploying and using MIMO with its legacy in-building DAS solution. We couldn't find the presentation or our notes, but if memory serves us correctly, the operator basically concluded after reviewing the trial data that it didn't make since to upgrade its in-building network so that it supported MIMO.

A lot has probably changed in the last few years and we know that multiple in-building solutions from various vendors support MIMO, but these solutions may differ from what the operators have deployed. Further, we know that operators in North America are currently dealing with the issue of MIMO and their in-building solutions, and that in some cases they may not upgrade their in-building networks.

Across our entire outdoor macro network testing, Rank Indicator 2 was available 43.5% of the time on the Verizon Wireless network and 68.8% of the time on the AT&T network. The higher availability on the AT&T network was probably due to a combination of higher SINR, lower traffic levels, and mounting the active radio electronics at the antenna mast.

In the in-building tests the results vary dramatically. In some cases, the low availability of MIMO can be attributed to the low SINR. We can't explain, or at least justify, the abnormally low SINR, but that is another issue. In other situations, the SINR was very favorable, but we felt that the availability of MIMO was disproportionately low. At Chicago O'Hare, for example, the average SINR on the AT&T network was an impressive 17.03 dB but the Rank Indicator 2 percentage was only 18.8%. At DFW, the average SINR on the Verizon Wireless network was 12.11 dB but Rank Indicator 2 was almost nonexistent at 4.3%.

Separate from whether or not MIMO (open loop spatial multiplexing) was used, there is also the question of whether or not there was a performance gain. In theory, 2x2 MIMO could theoretically double the downlink throughput, but in reality the gain is probably less, and at the extreme there wouldn't be any gain. We believe the European operator showed a negative gain from its in-building testing. We hope to explore the incremental impact of open loop and closed loop MIMO on user throughput and how it varies with network loading in a future issue of *Signals Ahead*.

We observed material differences in the downlink throughput between the AT&T and Verizon Wireless LTE networks. When we did our drive testing campaign last year we observed material differences in the two LTE networks. Part of the differences we rightfully attributed to vendor selection since we easily identified performance differences between Alcatel Lucent and Ericsson, especially with respect to uplink performance. However, there was another important distinction that was operator-specific and which couldn't be attributed to loading or more favorable RF conditions in one network versus the other network.

Specifically, while both networks delivered downlink throughput in excess of 5 Mbps for an overwhelming majority of the tests, the AT&T network was far more likely to deliver downlink throughput in excess of 30 Mbps than the Verizon Wireless network. This outcome is still true today, even after we normalize the throughput for equivalent utilization rates.

Approximately 24% of the time, the throughput on the AT&T network was higher than the highest throughput that we recorded on the Verizon Wireless network.

We spent an afternoon collecting drive test data in and around downtown San Francisco, not to mention other testing which we did not include in this report – the results were very similar. During our downtown San Francisco testing we transferred a combined 16+ GB on the two networks – arguably a statistically meaningful sample. The average throughput on the AT&T network was 21.43 Mbps and on the Verizon Wireless network the average throughput was 12.76 Mbps. Doing the math, the AT&T network was 68% faster than the Verizon Wireless network. More importantly, approximately 24% of the time, the throughput on the AT&T network was higher than the highest throughput that we recorded on the Verizon Wireless network.

The utilization rate was higher with the AT&T device than the Verizon Wireless device, indicating that the Verizon Wireless network was carrying more data traffic from other subscribers, but this difference does not come close to explaining the outcome. In fact, the Pantech dongle (VZW) was more likely to report the highest possible CQI values. If we normalize the average downlink throughput in the Verizon Wireless network to the utilization rate that we observed in the AT&T network than the average throughput in the Verizon Wireless network would have increased to 15.2 Mbps, still 29% lower than the average throughput in the AT&T network.

In this report we show a plot of the downlink throughput as a function of the SINR for the two networks. It is clearly evident in the figure that beyond a certain SINR threshold, the throughput in the Verizon Wireless network didn't improve while in the AT&T network the relationship between more favorable SINR and higher throughput continued. Our understanding is that Verizon Wireless may have implemented service level agreements (SLAs) which artificially limit the potential user throughput in its backhaul network in some of its markets. In theory, there isn't a technical reason why this situation exists and it could presumably disappear overnight if the operator chooses to do so. For marketing purposes the advantage goes to AT&T, but we highly doubt that most subscribers will notice the difference with normal user behavior.

In Case You Missed It

- **12/5/12 "LTE Band 7 versus LTE Band 4 - GAME ON!"** With the support of Accuver, we used its XCAL-M and XCAP drive test solutions to conduct a network benchmark study of LTE Band 7 and LTE Band 4. This benchmark study leveraged the Rogers Wireless network in Vancouver, Canada where they have deployed both frequency bands in virtually every single cell site. In addition to looking at basic throughput, we include a host of other device-reported KPIs to analyze the downlink and uplink performance characteristics of the two frequency bands under identical network conditions, including edge-of-of cell and in-building.

- **11/6/12 "M2M – toward the Internet of things"** We analyze the M2M landscape and some of the key players involved in realizing this vision. The business models for M2M are still in flux and eventually multiple business models will have to be implemented. We look at the new business models being explored by mobile operators and MVNOs. The global connectivity requirements of M2M services make it natural fit for cloud services so there will need to be new cloud platforms in both the operator networks and enterprises to support M2M services. We also analyze the requirements and vendors for such platforms. More importantly, the radio and core networks will require enhancements to support the deluge of new M2M connections. We discuss some of the major issues and how the 3GPP standards body and operators are planning to address these issues.

- **10/15/12 "Lost and Found"** As a follow-on report to Chips and Salsa XV, we examine the real world A-GNSS performance capabilities of leading smartphones. We also evaluate the performance attributes of the most popular navigation applications, including the amount of data traffic they generate, the length of time the smartphones remain connected to the network, and the amount of signaling traffic that they generate. Ultimately, we conclude that there are fairly dramatic performance differences for both the A-GNSS platforms and the navigation applications that have user experience and network implications.

- **9/13/12 "Chips and Salsa XV - Disparately Seeking Satellites"** In collaboration with Spirent Communications, we provide the industry's first independent analysis of A-GNSS platforms. The study includes conducted tests of vendor supplied A-GPS and A-GNSS (A-GPS + GLONASS) solutions and over-the-air testing of several leading smartphones. We demonstrate that while the performance across the platforms is largely comparable, there are significant differences in the performance of the solutions once they are implemented in the smartphone.

- **8/20/12 "The B Side of LTE - when your 'A Game' just isn't good enough"** We take a look at many of the proposed features being considered for 3GPP Release 12 and beyond, including advancements in the use of small cells, higher order MIMO and modulation schemes, 3D beamforming, network optimization, machine type communication, and device to device discovery and communication.

- **7/2/12 "Mobile Core Network 2.0 - the new reality or a fly-by-night catch phrase?"** Moving to an all-IP core network presents fresh challenges for operators. The EPC provides operators with the platform for the delivery of basic data services. However, operators need to prepare the EPC to deliver enhanced services beyond basic data services. Areas addressed include the centralized or decentralized approach, the Diameter protocol, network offload and optimization, the Content Delivery Network (CDN), and policy control.

- **6/8/12 "Debbie Downer Does Barcelona"** We provide highlights from this year's LTE World Summit, which was held in Barcelona, Spain. Unlike years past where the issue was on technical issues and challenges, the focus of this year's event was on the business case for LTE. To the extent technology issues were discussed, they were more futuristic, including network optimization, Cloud RAN, and small cells.

- **5/23/12 "Improve your [RF] Front-End in Seven Easy Steps!"** LTE, either directly or indirectly, poses several challenges for mobile devices, in particular for the RF front end. In addition to band fragmentation, LTE introduces MIMO and carrier aggregation, while its characteristics, such as a higher PAPR, can be problematic to support. In addition to exploring these technical challenges in detail, we examine seven potential solutions, all involving the RF front-end design, that should be considered.

- **4/16/12 "LTE Advanced and CoMP: what goes around, comes around"** CoMP is a Release 11 feature that leverages the simultaneous support of multiple transmission points to serve mobile devices in the high interference areas that occur between cells (inter-cell) and between sectors within a given cell (intra-cell). In theory it can provide stellar gains on the order of high double-digit percentages for edge of cell user throughput while also providing at least some increase in overall network efficiency. In practical terms, the benefits of CoMP are less clear and there is at least some justified reservations regarding its potential impact on an operator's network. In addition to explaining the technical details of the various CoMP implementations, we examine the potential benefits, key challenges, potential alternatives, and the likely rollout strategies.

- **3/28/12 "Cellular and Wi-Fi: A match made in Heaven?"** Based on interviews with leading stakeholders and a thorough analysis of the standardization processes, we discuss how and why Wi-Fi networks will become more closely integrated with cellular networks.

- **2/23/12 "It's a Small World After All - and other key trends for MWC and 2012"** In advance of this year's MWC, we discuss many of the key trends that we see emerging for 2012. These trends include the return of Nokia, a renewed focus on Evolved HSPA+ and LTE-Advanced, small cells and TD-LTE.

3.0 Band 7 versus Band 4 – Redux

In our December *Signals Ahead* report (*SA* 12/05/12: "LTE Band 7 versus LTE Band 4 – Game On!") we provided the industry with the first in-depth and independent analysis of how LTE Band 7 performs relative to LTE Band 4, based on the Rogers Wireless network in Vancouver, Canada. As noted in that report, Rogers has deployed LTE in both bands at virtually every single cell site throughout the greater Vancouver area so it made for an ideal testing ground to quantify the relative performance differences. That particular report focused almost entirely on outdoor drive test results. In this report we provide results from testing inside a shopping mall, a hotel, and a large convention center.

3.1 Oakridge Mall

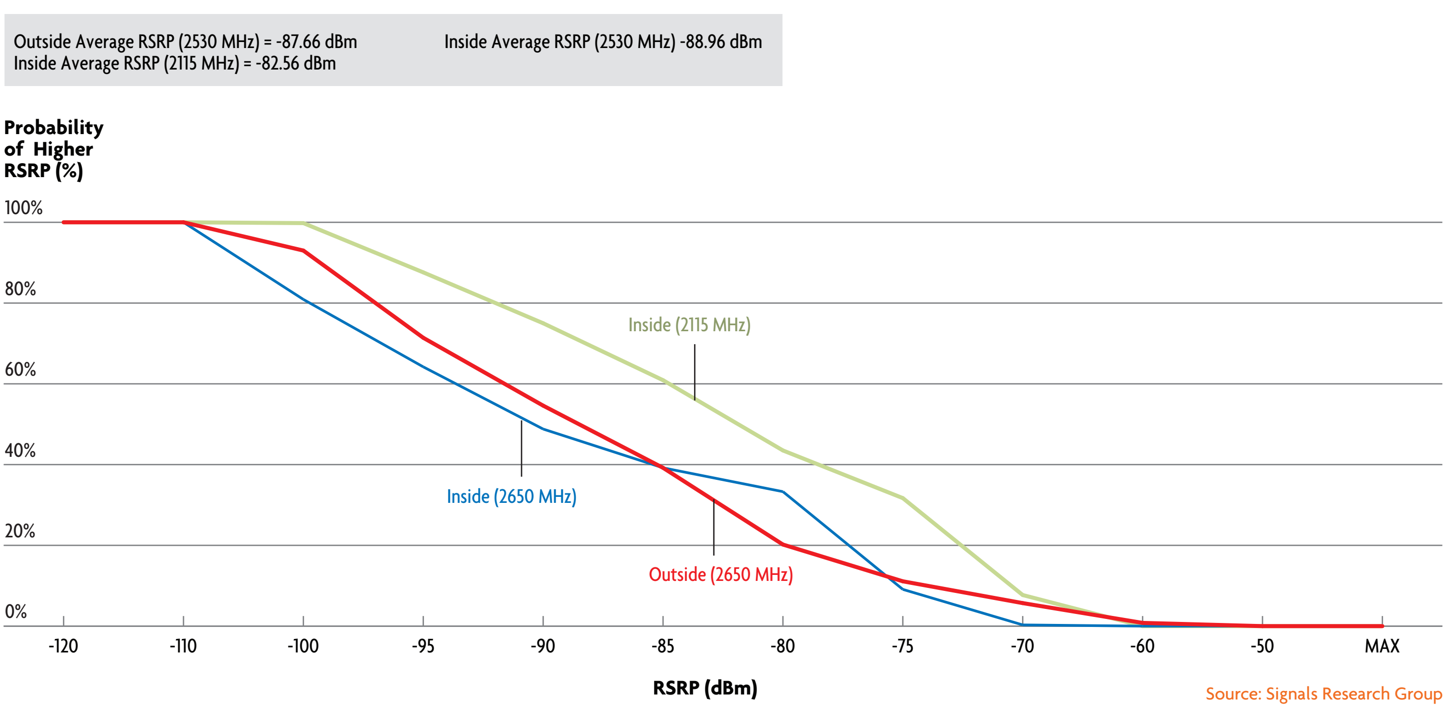
The Oakridge Mall is located in a quasi-urban area of Vancouver, about midway between downtown Vancouver and the airport. It is a decent sized mall, complete with an Apple store that had the latest LTE-enabled devices on display, although the mall is nowhere near the size of many megamalls that exist south of the border. In addition to testing around the perimeter of the building – Band 7 downlink only – we tested Band 7 and Band 4 within the mall, including file transfers in both directions.

When we were collecting the data we were extremely impressed by the measured downlink and uplink throughput in both bands throughout the entire building. We are not showing the results since we know that we had a TCP Window size issue that impacted the Band 7 results. For the record, we fixed this issue when we did the testing in the AT&T and Verizon Wireless networks. We can, however, show other KPIs which help quantify the performance differences between the two bands with respect to in-building coverage.

The RSRP in Band 4 was 6 dB more favorable than the in-building Band 7 results.

Figure 1 shows probability plots of the RSRP for both bands while inside the mall. For readers that are not certain how to interpret the figure, each point on the lines shows the probability associated with obtaining a higher RSRP. For example, there was a 93% probability that the RSRP at 2650 MHz outside of the mall was greater than -100 dBm. Surprisingly, there was less than a 1 dB difference between the in-building and outside RSRP at 2650 MHz (Band 7). The RSRP at 2115

Figure 1. Oakridge Mall RSRP – Band 7 and Band 4 Probability Plots

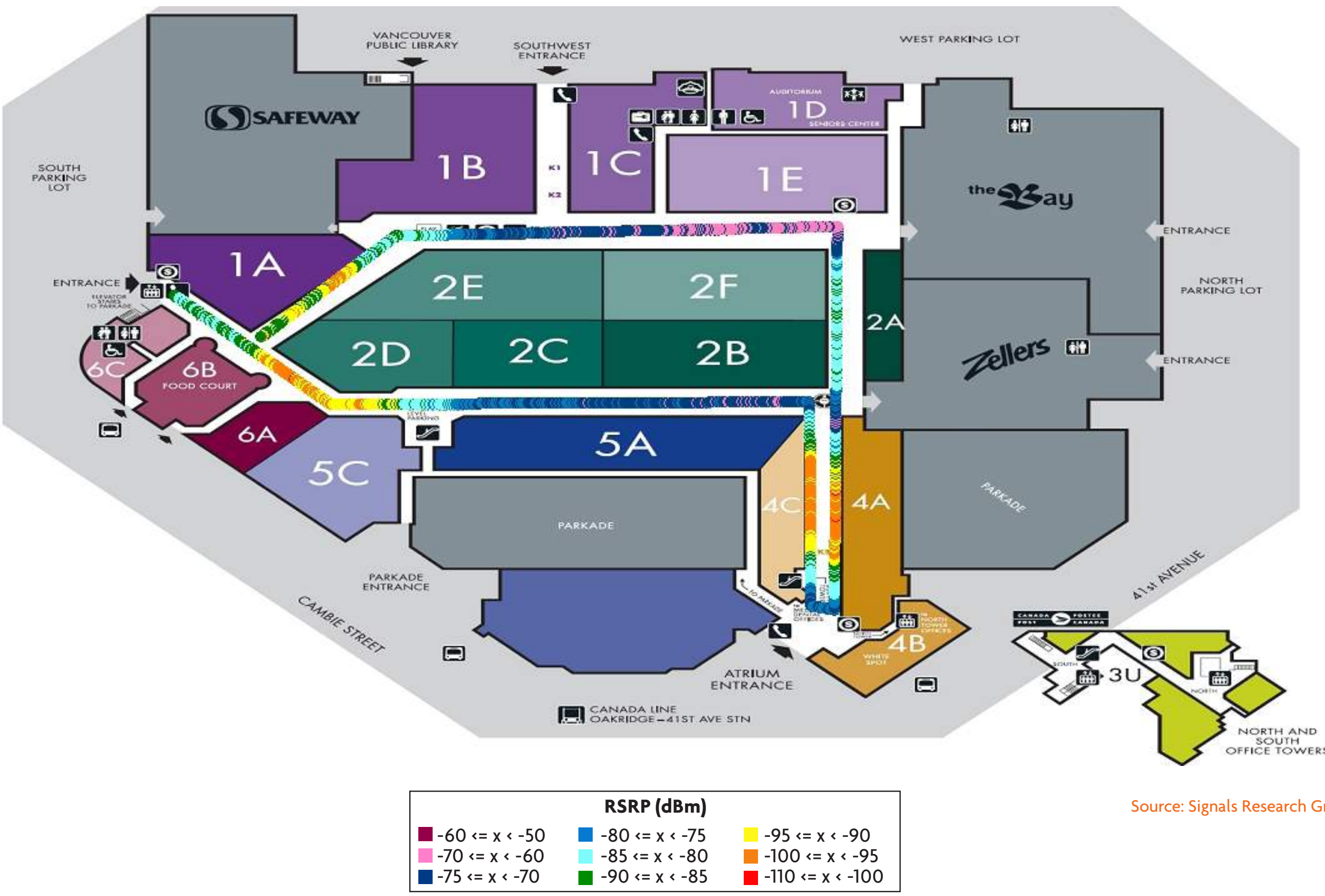


Source: Signals Research Group

MHz (Band 4) was 6.4 dB more favorable than the in-building Band 7 results. Based on our conversations with the operator, we do not believe that Rogers had deployed an in-building DAS solution. We also note that we observed the same Cell PCI during our outdoor tests as we observed within the mall – we used the same cell throughout the entire mall. A geo plot of the Serving Cell PCI is provided in Figure 59 in the Appendix. The green color in the figure identifies the area outside of the mall where we tested that was covered by the same cell which provided the in-building coverage.

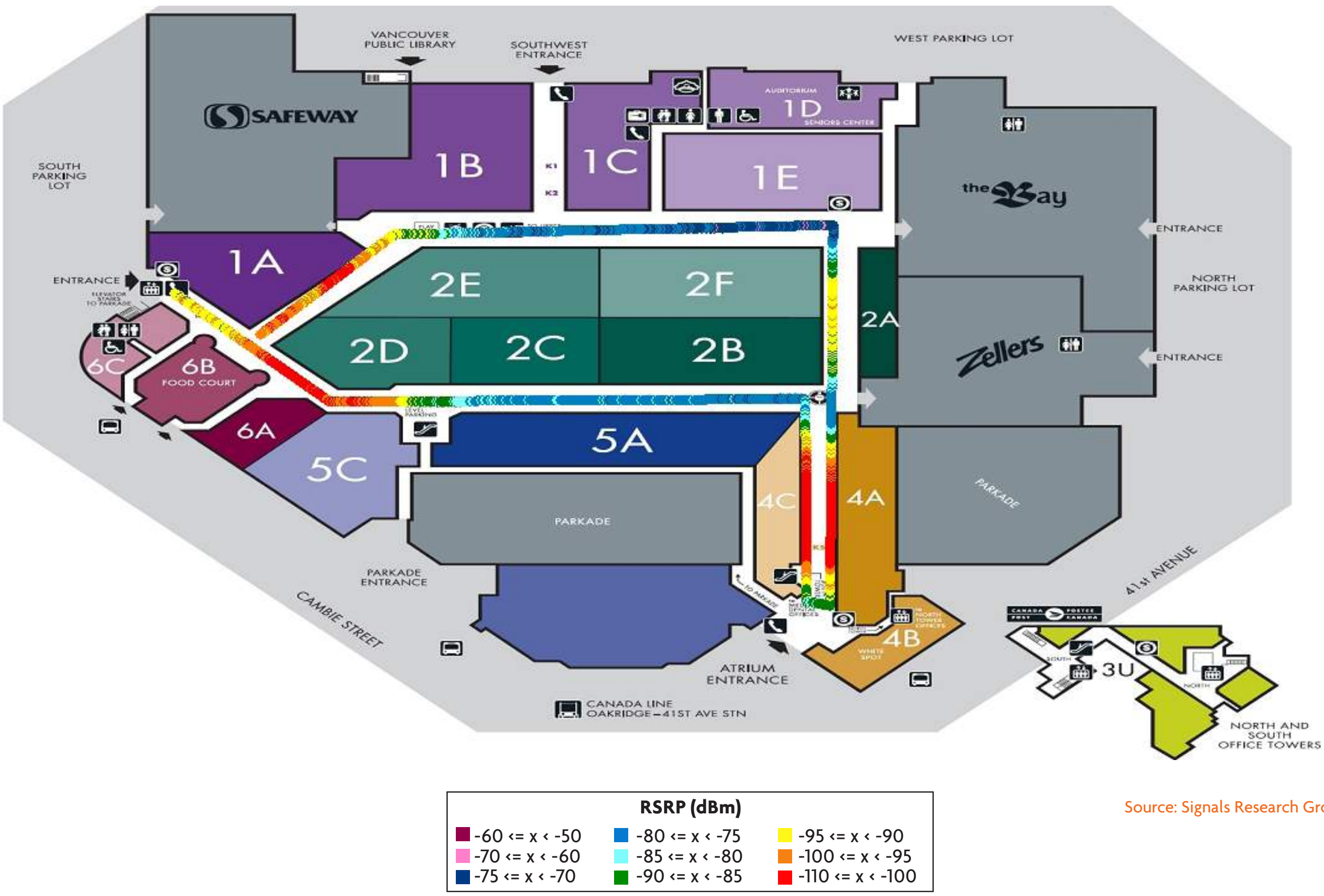
Figure 2 (2115 MHz) and Figure 3 (2650 MHz) provide plots of the RSRP along the path that we followed while testing inside the mall. In the Appendix, Figure 58 provides a similar plot for the outside perimeter of the mall. Although we do not show it in this report, it appears to us that the cell site which was serving the inside of the mall was also covering the outside of the mall on the North, East, and Southeast sides of the mall (e.g., the green line in Figure 59).

Figure 2. Oakridge Mall RSRP – Band 4 Geo Plot



Source: Signals Research Group

Figure 3. Oakridge Mall RSRP – Band 7 Geo Plot

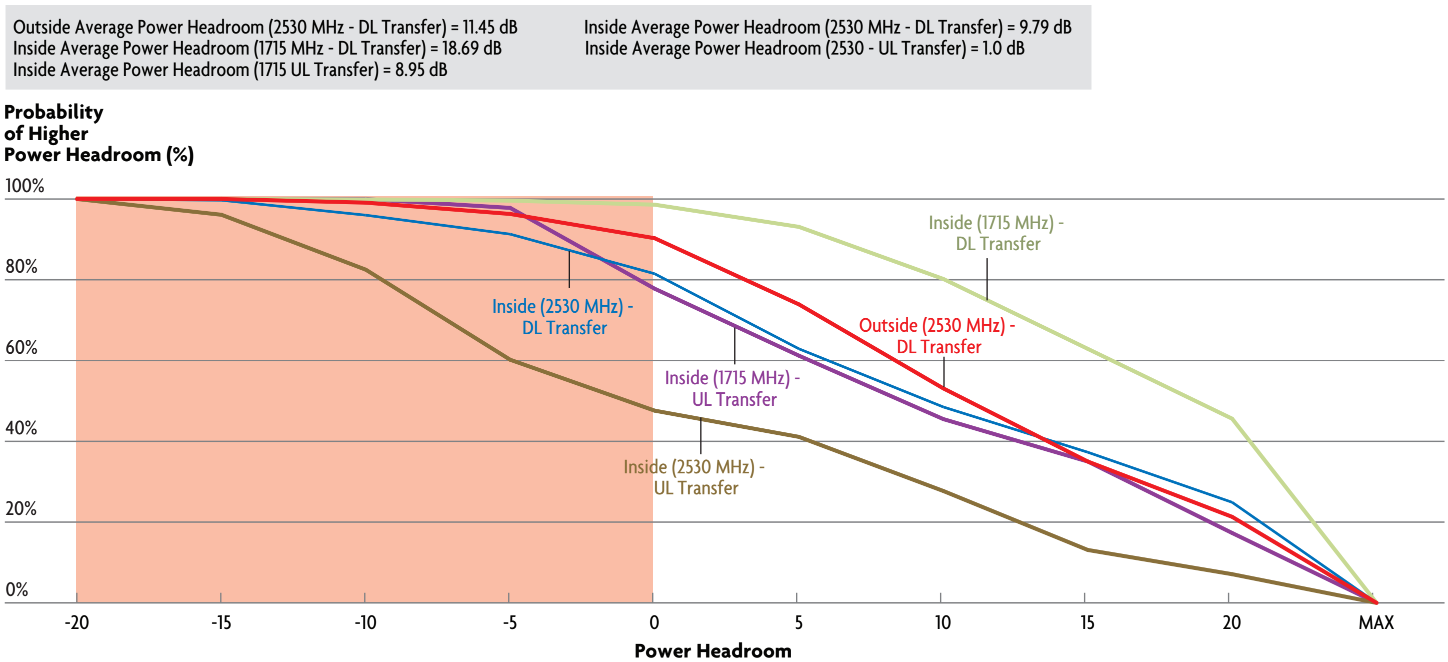


Source: Signals Research Group

At 2530 MHz (Band 7), the in-building uplink throughput was artificially limited nearly 50% of the time.

Figure 4 provides probability plots for the power headroom. We included the Power Headroom results associated with the downlink and uplink throughput tests from inside the mall. A negative value indicates that the uplink throughput was limited due to transmission power restrictions from the network. Not surprisingly, the results were worse at 2530 MHz than they were at 1715 MHz, just as the results were worse during uplink data transfers since during those tests we were trying to send as much data as possible. The figure shows that at 2530 MHz (Band 7), the in-building uplink throughput was artificially limited nearly 50% of the time. Put another way, while the uplink throughput may have been stellar, it could have been much higher.

Figure 4. Oakridge Mall Power Headroom – Band 7 and Band 4 Probability Plots

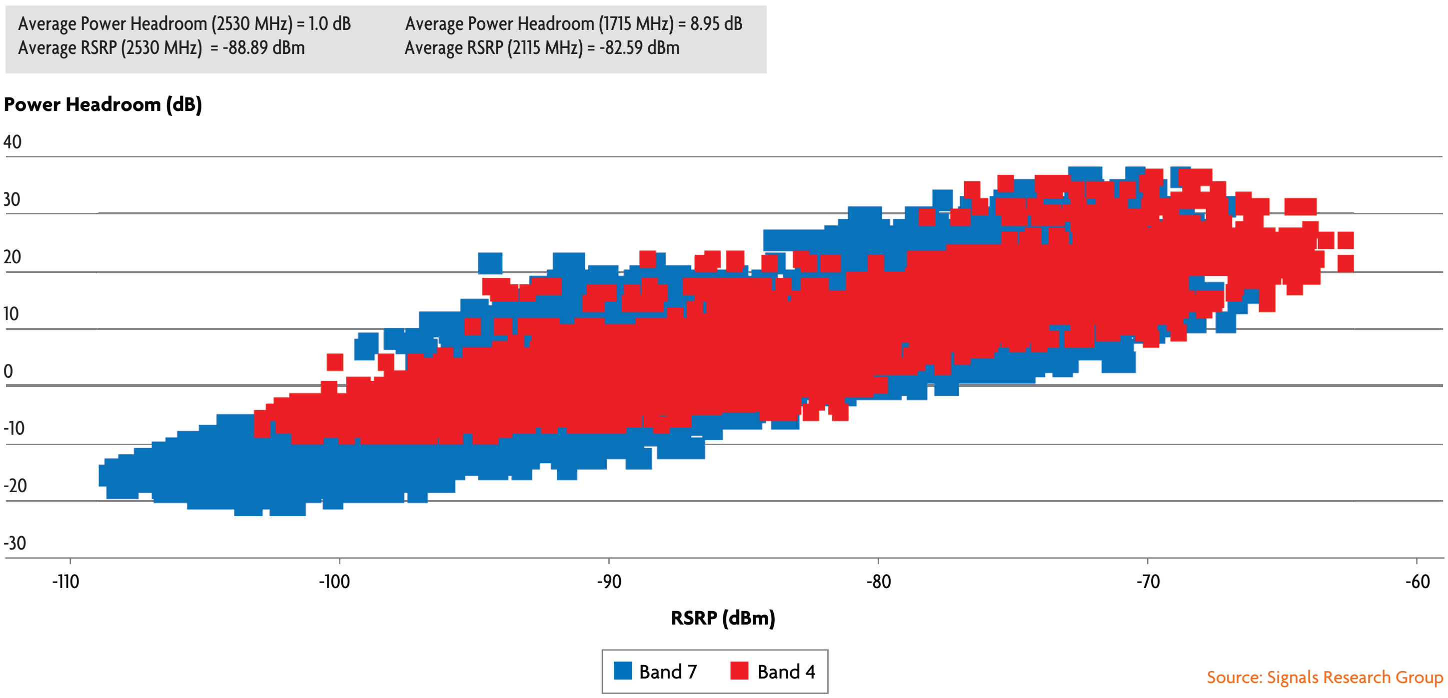


Source: Signals Research Group

Figure 5 is interesting, we think, but we are not quite sure what conclusions can be drawn. First, it is evident that there is a strong correlation between Power Headroom and RSRP – no surprise. It is also evident that for a given RSRP value starting at roughly -90 dBm through the lowest possible RSRP values that the corresponding Power Headroom value was more likely to be worse in Band 7 than Band 4. One might conclude that the uplink was more forgiving in Band 4 than in Band 7 with more challenging network conditions, which is logical given that the Band 4 uplink channel (1715 MHz) is considerably lower than the Band 7 uplink channel (2530 MHz).

The Appendix includes an additional figure (Figure 60) which provides probability plots for the downlink path loss.

Figure 5. Oakridge Mall Power Headroom versus RSRP – Band 7 and Band 4 Scatter Plots



Source: Signals Research Group

3.2 Marriott Hotel

The Marriott Hotel is located in downtown Vancouver, approximately ½ mile from our hotel – we provided the results from our hotel in the last report. Thanks to some sweet talking, we were able to get access to a banquet room that was being set up for an evening event. We alluded to the idea that we were part of the organization hosting the event – no harm, no foul.

At first glance the downlink and uplink throughput for both bands looks pretty good. As shown in Figure 6 the Power Headroom was always positive with the one exception being the uplink transfer test using 2530 MHz. However, if we focus exclusively on the results within the large banquet room (reference Figure 7 – between points 2 and 5), it is evident that performance within this room was impacted by the coverage.

In the case of Band 7, the Power Headroom was 8.5 dB lower and the RSRP was 8.7 dB lower in the banquet room than it was throughout the other areas of the hotel that we tested.

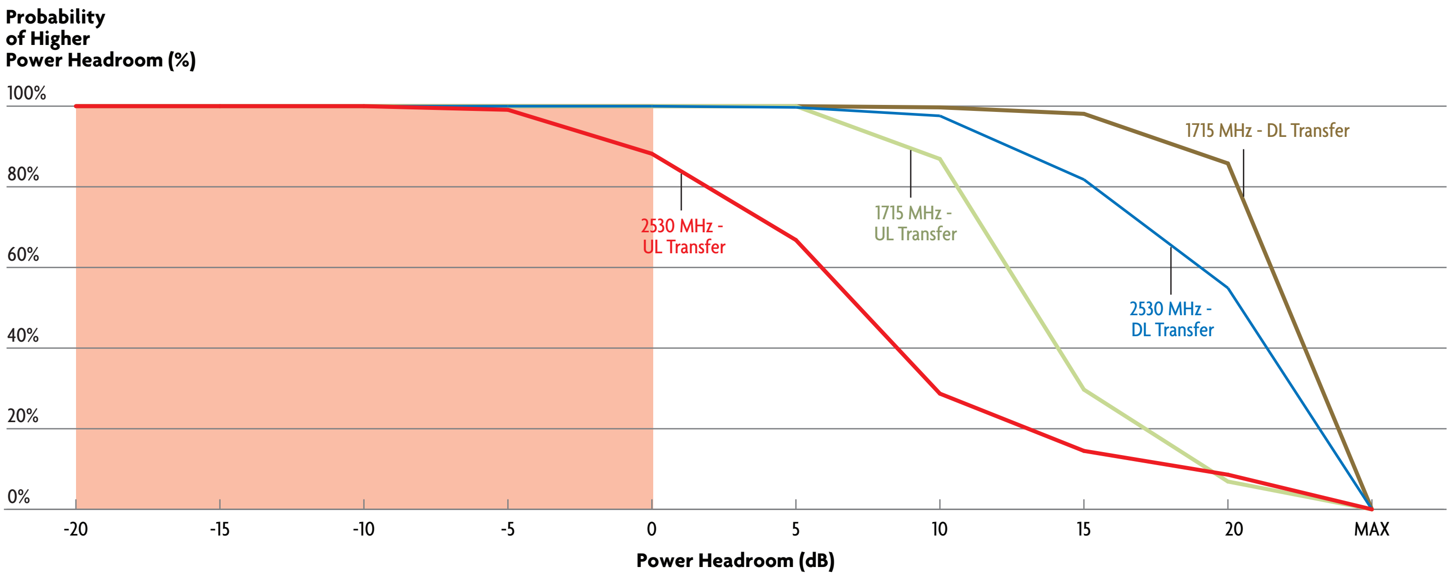
Figure 8 (Band 7) and Figure 9 (Band 4) provide scatter plots of the Power Headroom and the RSRP. We have separately identified the results which were recorded within the large banquet room. It is evident that the performance within the room was impacted with both bands. In the case of Band 7, the Power Headroom was 8.5 dB lower and the RSRP was 8.7 dB lower in the room than it was throughout the other areas of the hotel that we tested (also inside). With Band 4, the Power Headroom was 3.3 dB lower and the RSRP was 6.1 lower in the room.

The performance differences between the two bands associated with being in the large banquet room was more evident in the uplink than it was in the downlink.

Comparing the two bands, the Power Headroom was 5.2 dB lower and the RSRP was 2.5 dB lower in Band 7 than it was in Band 4. Note that the difference was more significant in the uplink (Power Headroom) than it was in the downlink (RSRP). We assume this result stems from the wider separation between the uplink channels (815 MHz) than the downlink channels (535 MHz) of the two bands, combined with the limited transmit power of the mobile device.

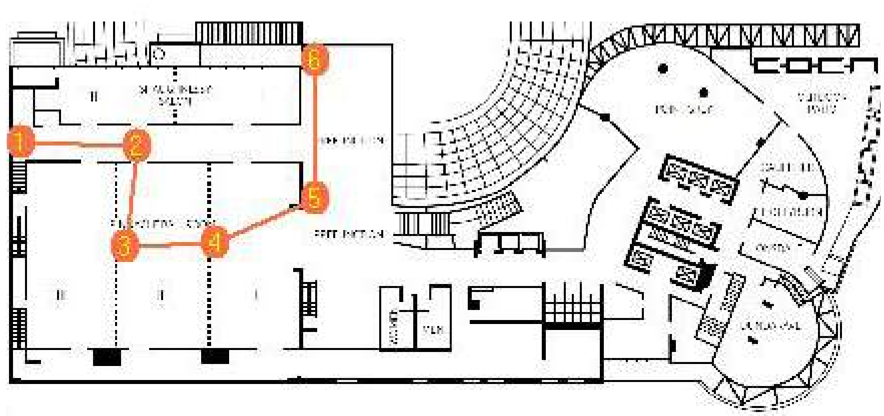
Figure 6. Marriott Hotel Power Headroom – Band 7 and Band 4 Probability Plots

Average Power Headroom (2530 MHz - UL Transfer) = 7.48 dB
Average Power Headroom (1715 MHz - UL Transfer) = 13.08 dB
Average Power Headroom (2530 MHz - DL Transfer) = 20.0 dB
Average Power Headroom (1715 MHz - DL Transfer) = 26.11 dB



Source: Signals Research Group

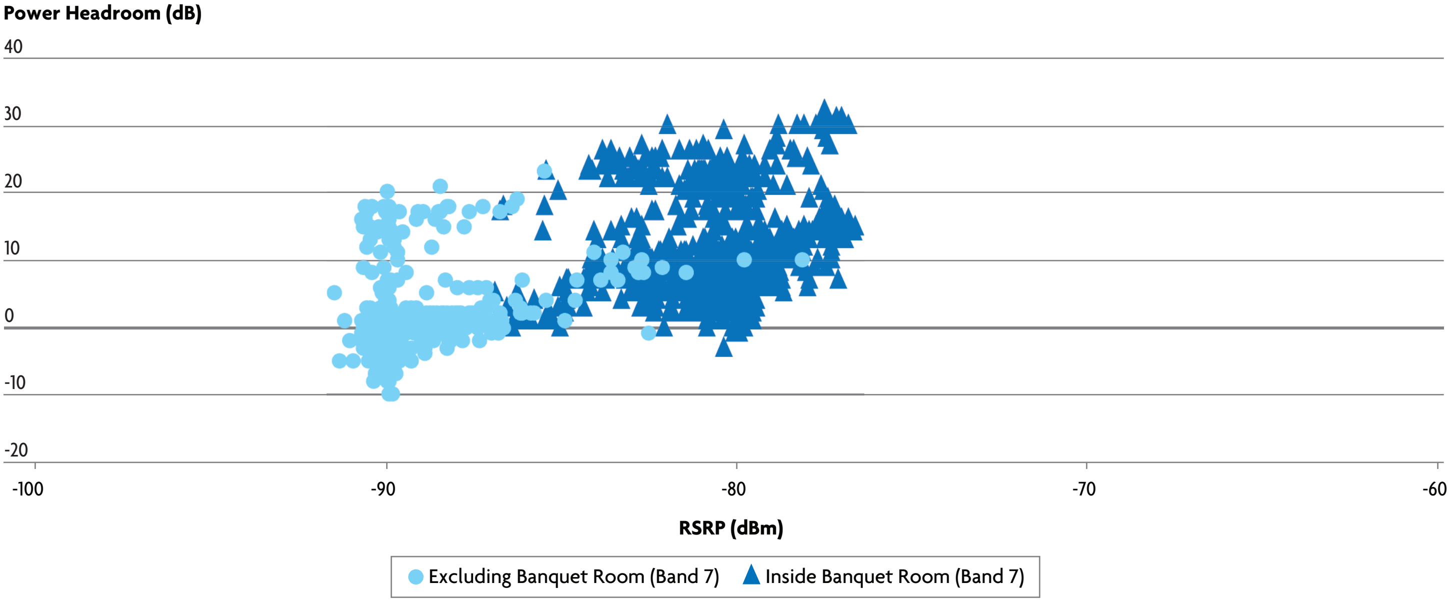
Figure 7. Marriott Hotel Test Route



Source: Signals Research Group

Figure 8. Marriott Hotel Power Headroom versus RSRP – Band 7 Scatter Plot

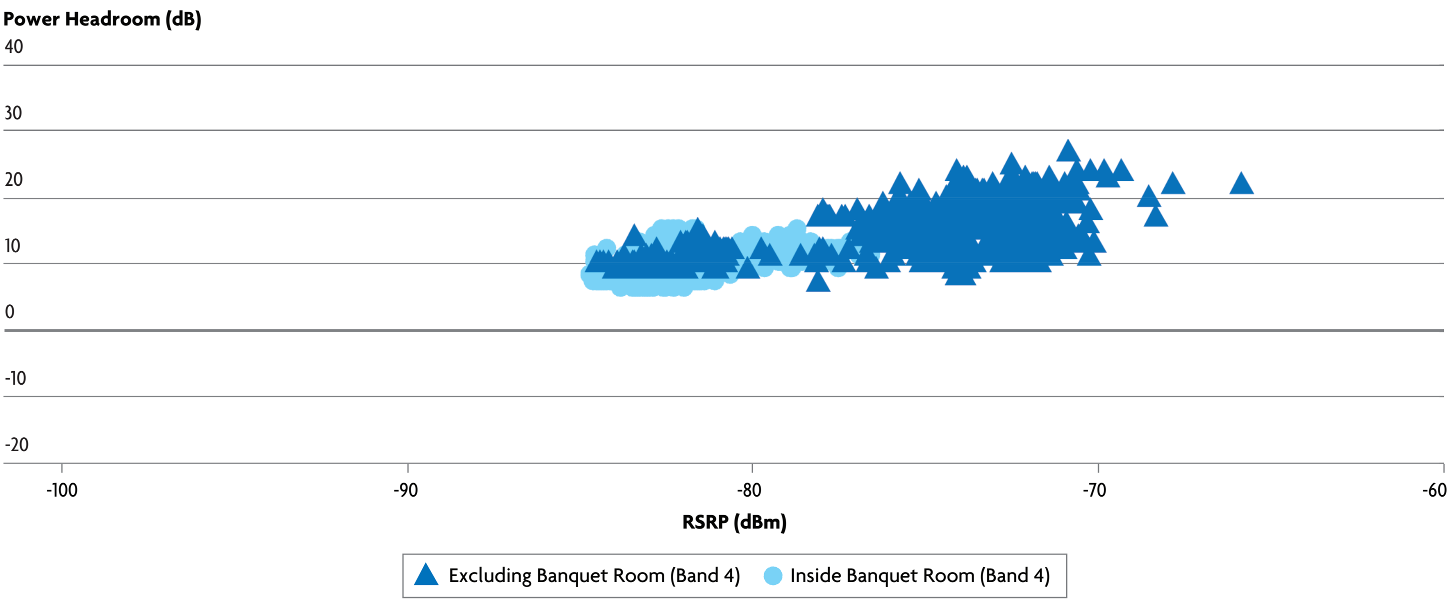
Average Power Headroom Excluding Banquet Room = 9.77 dB	Average RSRP Excluding Banquet Room = -80.61 dBm
Average Power Headroom Inside Banquet Room = 1.24 dB	Average RSRP Inside Banquet Room = -89.27 dBm



Source: Signals Research Group

Figure 9. Marriott Hotel Power Headroom versus RSRP – Band 4 Scatter Plot

Average Power Headroom Excluding Banquet Room = 14.14 dB	Average RSRP Excluding Banquet Room = --74.49 dBm
Average Power Headroom Inside Banquet Room = 10.84 dB	Average RSRP Inside Banquet Room = -80.61 dBm



Source: Signals Research Group

3.3 Oh Canada!

For the last set of tests we turn to the Canada Place Convention Center which was adjacent to our hotel. Given the layout of the convention center we are showing the results a bit differently in this section. Figure 10 provides the walking path that we followed during our testing. Although the figure is a bit hard to read and interpret, the key point is that the path between Point 1 and Point 4 is outdoors. Between Point 4 and Point 8 we were indoors, but immediately adjacent to the exterior portion of the building – in some cases glass and in other cases a solid material of some sorts. Given other events taking place at the convention center we were not able to test in the more interior sections of the building.

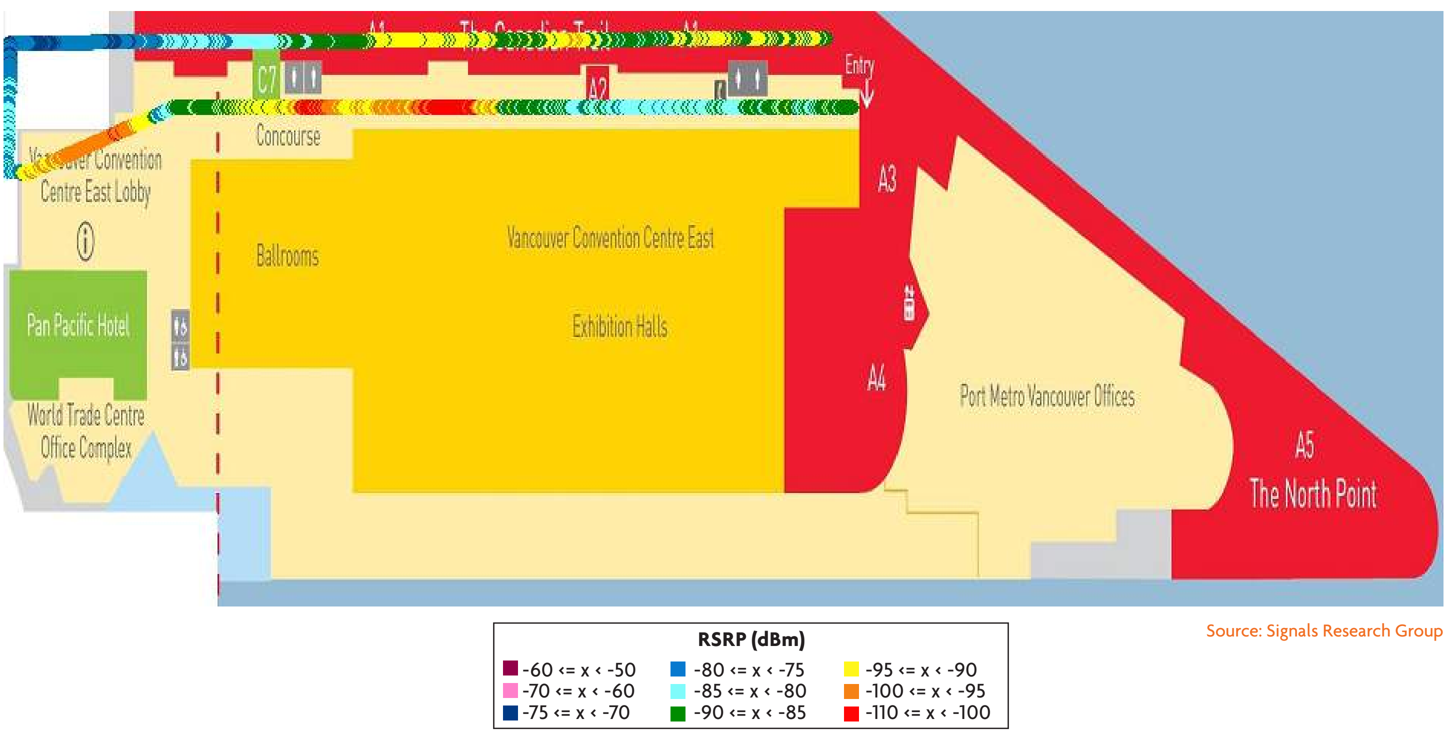
As soon as we entered the building the RSRP values dropped fairly significantly.

Figure 11 provides a geo plot of the RSRP. Outside of the building the performance was the best in the upper left-hand corner, or as we approached Event Point #2. It is also evident that as soon as we entered the building the RSRP values dropped fairly significantly – note the orange colors in the East Lobby, as well as the reddish colors down the long corridor next to the exterior wall or exterior glass, depending on the exact location.

Figure 10. Canada Place Test Route

Source: Signals Research Group

Figure 11. Canada Place RSRP – Band 7 Geo Plot

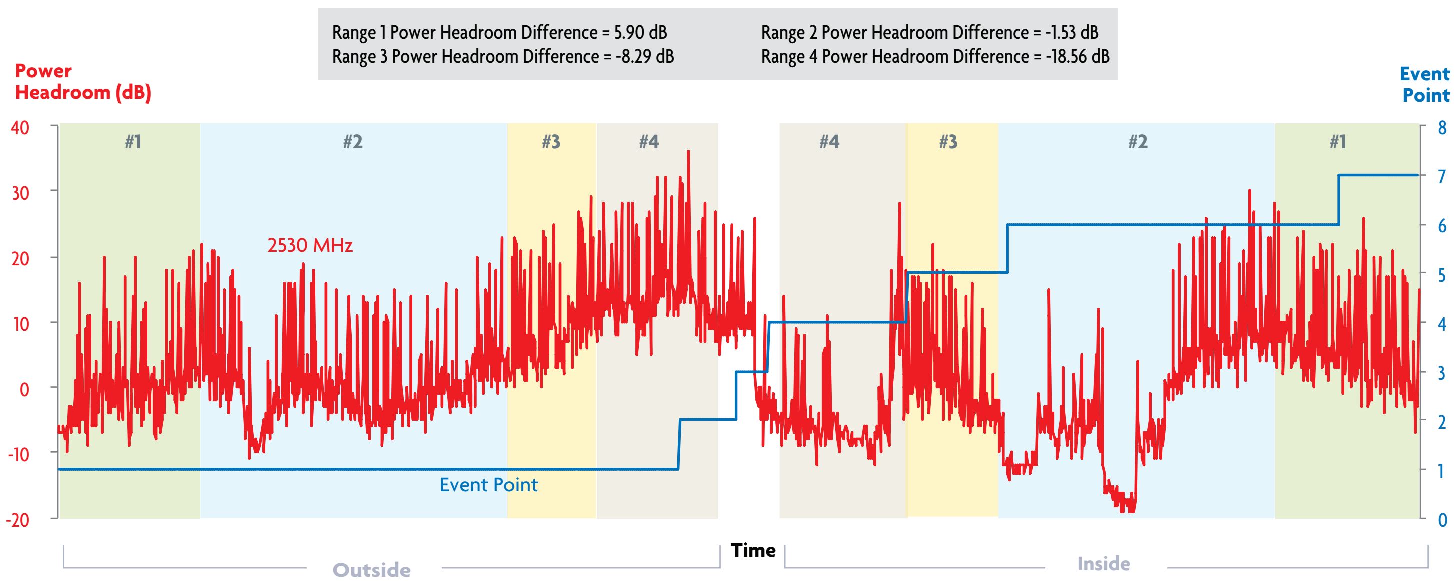


Source: Signals Research Group

Figure 12 (Band 7) and Figure 13 (Band 4) provide time series plots of the Power Headroom. For easy reference we have also plotted the Event Points from Figure 10 along the secondary Y axis and we have color-coded the figure so that readers can easily compare nearly identical locations where we were testing. The left-hand side of the figure shows results from the outside of the convention center and the right-hand side of the figure shows results from the inside of the building.

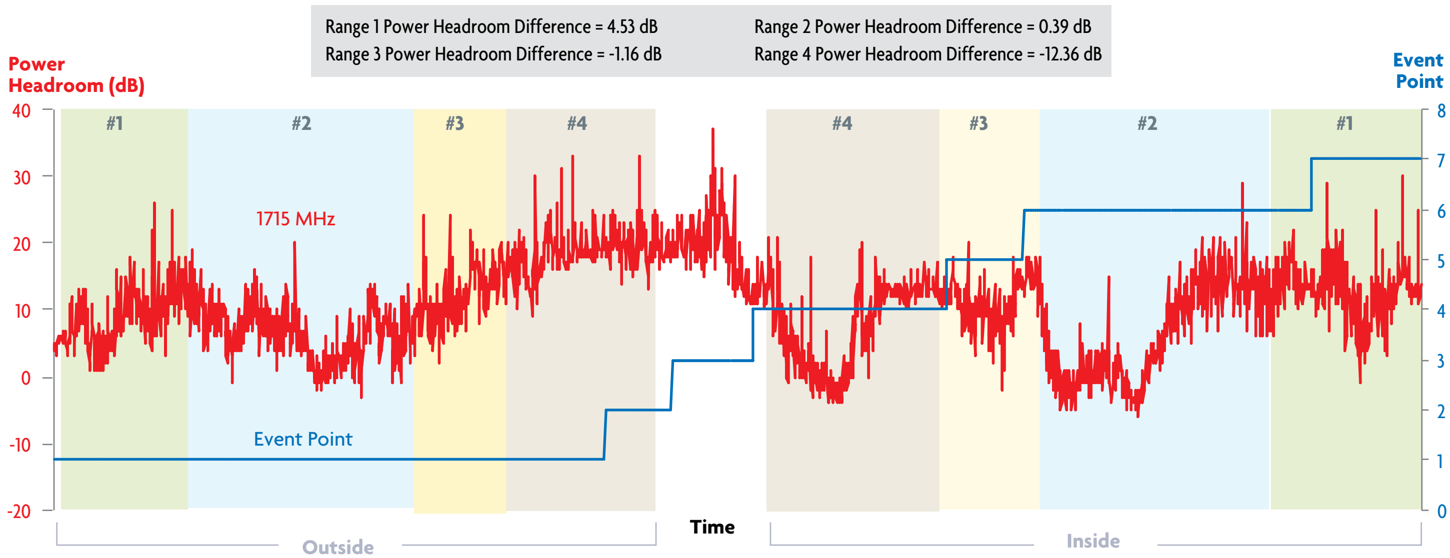
Section #1 on the left-side of the two figures refers to the area near the starting point of the test (Event Point #1 in Figure 10) and Section #1 on the right-hand side of the two figures refers to the area near the ending point (between Event Point #7 and #8 in Figure 10). We did a circular loop so the test route ended pretty much where it started, although we started the test outside of the building (Event Point #1) and finished the test inside the building (Event Point #8). Section #2 in the two figures provides results for the lengthy section along the hallway corridor and its outside equivalent. Section #3 shows the portion of the test between Event Point 5 and Event Point 6, plus the corresponding outside area. Section #4 shows the results from outside the building as we were turning the corner while outside the building (in the vicinity of Event Point #2 in Figure 10) and the results once we entered the lobby.

Figure 12. Canada Place Power Headroom – Band 7 Time Series Plot with Location Tags



Source: Signals Research Group

Figure 13. Canada Place Power Headroom – Band 4 Time Series Plot with Location Tags



Source: Signals Research Group

Upon entering the Convention Center lobby the Power Headroom became 18.56 dB more unfavorable than it was immediately outside of the Convention Center.

With one exception, which we will address in a bit, the results are fairly consistent and reflect the impact of the RF signals entering/exiting the building's exterior walls. There were not any interior walls since our walking route was fairly adjacent to the exterior walls. The most noticeable difference was in Area #4, which corresponds to the area outside of the building near Event Points #2, #3 and #4, and the East Lobby between Event Point #4 and Event Point #5. At 2530 MHz there was a difference of 18.56 dB between the interior and exterior values and at 1715 MHz there was a difference of 12.36 dB. Comparing the two bands, the Band 4 Power Headroom was 3.6 dB more favorable than Band 7 outside of the building in Area #4, while in the East Lobby the Band 4 Power Headroom was 9.8 dB more favorable than Band 7.

It took us a while to figure out why the Area #1 results are the opposite of what we expected in both bands – the performance was more favorable indoors than outdoors. We eventually determined that our mobile device was using a different cell/sector when we finished the test (Area #1 – right side of the figures) than when we started the test (Area #1 – left side of the figures). In the Appendix, we show a geo plot of the Serving Cell PCI (reference Figure 61) which shows this phenomenon. We also show a geo plot of the RSRP for Band 7 and we provide time series plots of the RSRP for both bands using a similar approach to what is provided in Figure 12 and Figure 13. The RSRP results exhibit a trend that is similar to the Power Headroom results that we provided in this section.

4.0 Closer to Home

In addition to testing Band 7 and Band 4 in Vancouver, we also took the opportunity to test the AT&T and Verizon Wireless LTE networks in the United States. We were opportunistic when it came to doing the testing and we leveraged a few business trips to test in various airports and a hotel in Dallas, Texas. We started this campaign back in September 2012 and we returned to it with vigor toward the end of the year.

There is a Qualcomm chipset inside both dongles, but not necessarily the same chipset so there could be modest differences in how they report and make network measurements.

We used the Sierra Wireless manufactured AT&T USBConnect Momentum 4G, which to us appears identical to the USB dongle that we used in the Rogers Wireless network, although if nothing else the devices supported different frequency bands. We used the Pantech 4G LTE USB Modem UML290 on the Verizon Wireless network. Worth noting, we've owned this particular modem since the operator first launched LTE services so it is an "old" device, but the operator still offers it on its website. Further, we ensured that we had the latest and greatest firmware. There is a Qualcomm chipset inside both dongles, but not necessarily the same chipset so there could be modest differences in how they report and make network measurements.

In addition to comparing and contrasting the in-building performance of the two operators, we also examined how the two operator's networks performed in some outdoor testing that we conducted in and around downtown San Francisco. Most interestingly, in all cases we provide what we believe is a very reliable indication of how loaded these networks were when we conducted the tests.

4.1 Leveling the Playing Field – a view from the outside

After completing a lot of the in-building analysis we realized that it would be beneficial to take a more in-depth look at how the two operator's networks performed in a side-by-side comparison during an outdoor drive test. We conducted this testing on Sunday afternoon (December 30th) in and around downtown San Francisco. It was a beautiful day and the streets were full of shoppers. There was also an NFL playoff game at Candlestick Park and a college bowl game at AT&T Park taking place that day. So while the number of people in downtown San Francisco may not have been as high as it would have been during a normal workday, it was a busy day in the city by the Bay – it took forever to leave the city and get back home that night.

We were able to lock the AT&T device to the LTE band, but we couldn't prevent the Verizon Wireless device from falling back to EV-DO Rev A when conditions warranted.

One important distinction between the two devices was that we were able to lock the AT&T device to "LTE Only" so that it couldn't handover to HSPA+ if/when there was poor coverage. In the case of the Verizon Wireless device, we weren't able to force it to work in a particular frequency/technology so if the LTE coverage was subpar it would switch to EV-DO Rev A. Surprisingly, this situation occurred a couple of times while driving into the city along a major thoroughfare, including near the Bay Bridge, so we had to exclude two test files in the data that we included in the analysis. We suspect, or at least hope, that the issue was device specific and that it could be resolved with some adjustments to various network parameters. Otherwise, this situation could make it problematic for VoLTE.

The average throughput was 68% higher in the AT&T network than in the Verizon Wireless network.

Figure 14 provides an analysis of the PDSCH (downlink Physical (PHY) Layer) throughput for both networks. The data shown in the figure is based on concurrent testing during which time we transferred 10.16 GB in the AT&T and 6.05 GB in the Verizon Wireless network. Both networks delivered at least 5 Mbps approximately 90% of the time – 87.1% for VZW and 91.4% for AT&T. However, the average throughput was 68% higher in the AT&T network. This outcome stems from the large differences in throughput at the upper-range of the scale where AT&T had a distinct advantage. Approximately 24% of the time, the throughput in the AT&T network was higher than the highest throughput that we recorded in the Verizon Wireless network.

As discussed in our network benchmark study, which we published in a series of reports in late 2011 through early 2012, we believe that the shortcoming in the Verizon Wireless network was due to how the operator provisioned the backhaul and the SLAs that they have in place with their various backhaul service providers. From a technical/network architecture perspective we believe that the performance should be comparable. In fairness to Verizon Wireless, its LTE network has much better coverage than AT&T's network in the far East Bay (Walnut Creek, Dublin, Pleasanton, etc.) where we know from firsthand experience that the AT&T LTE coverage is fairly spotty – or at least it was spotty back in November when we did some extensive testing in the area.

For the record, we had resolved the TCP Window size issue that we had in Canada when we did this testing and the window sizes were identical in both notebook computers. Further, in several of the tests that we present in the forthcoming sections, we used the same notebook computer on both networks. Figure 15 shows the random drive route that we used when we tested the two networks.

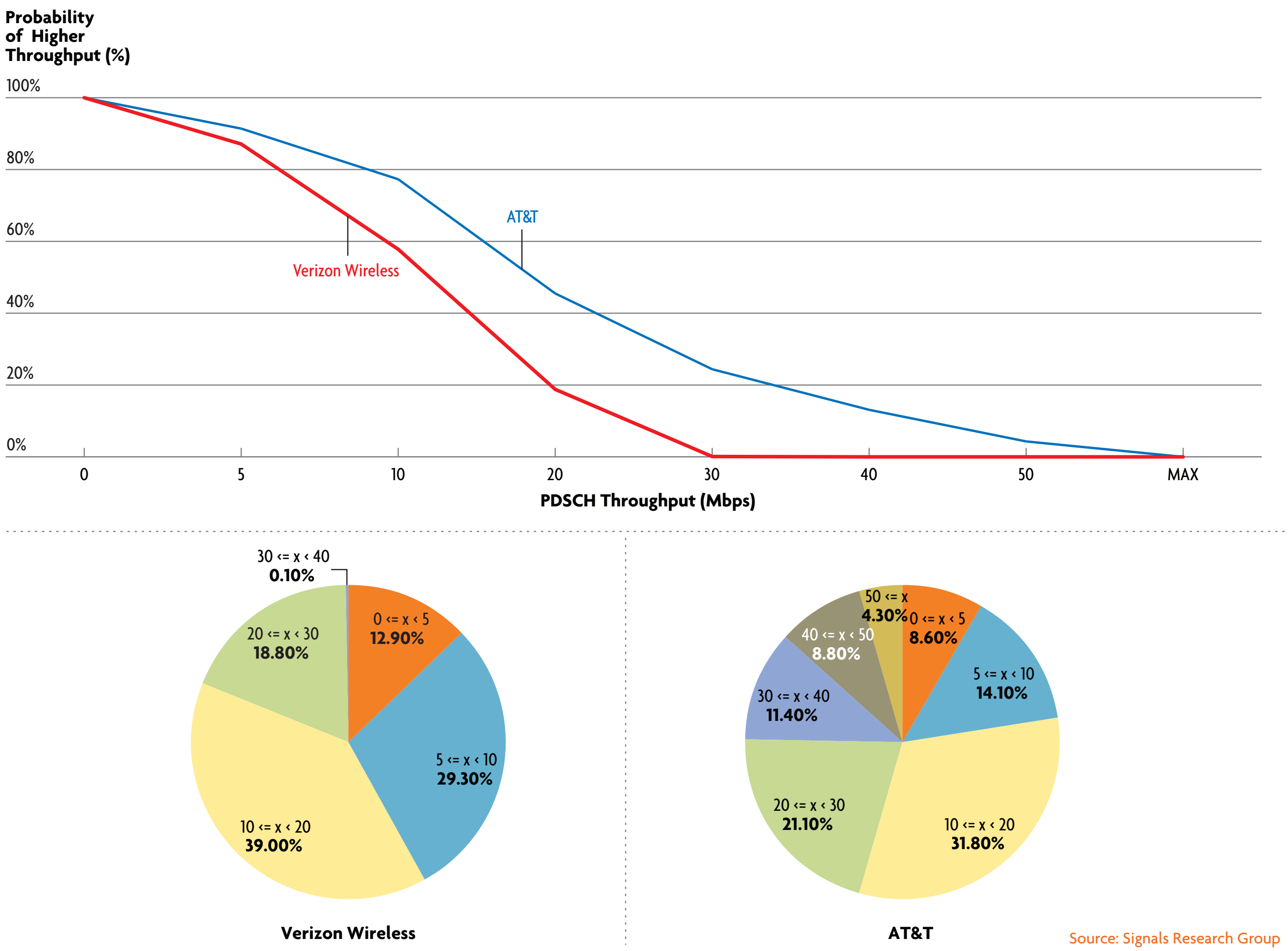
The utilization rate, in percentage terms, defines the amount of network resources that the LTE network provided the device during the test.

Figure 14 introduces a new and very useful KPI that we call the Utilization Rate. The utilization rate, in percentage terms, defines the amount of network resources that the LTE network provided the device during the test. Using the Accuver tools we were able to individually identify and quantify the number of sub-frames that the network assigned to the device throughout the entire test. Since we knew the length of the test and the length of a sub-frame (1 millisecond) we could calculate the ratio of assigned sub-frames to total sub-frames.

Figure 14. PDSCH Throughput Analysis – Verizon Wireless and AT&T

VZW Average Throughput = 12.76 Mbps
VZW Utilization Rate (est) = 73.7%

AT&T Average Throughput = 21.43 Mbps
AT&T Utilization Rate (est) = 87.8%



Source: Signals Research Group

In its current implementation, the Ericsson scheduler only assigns one mobile device per sub-frame.

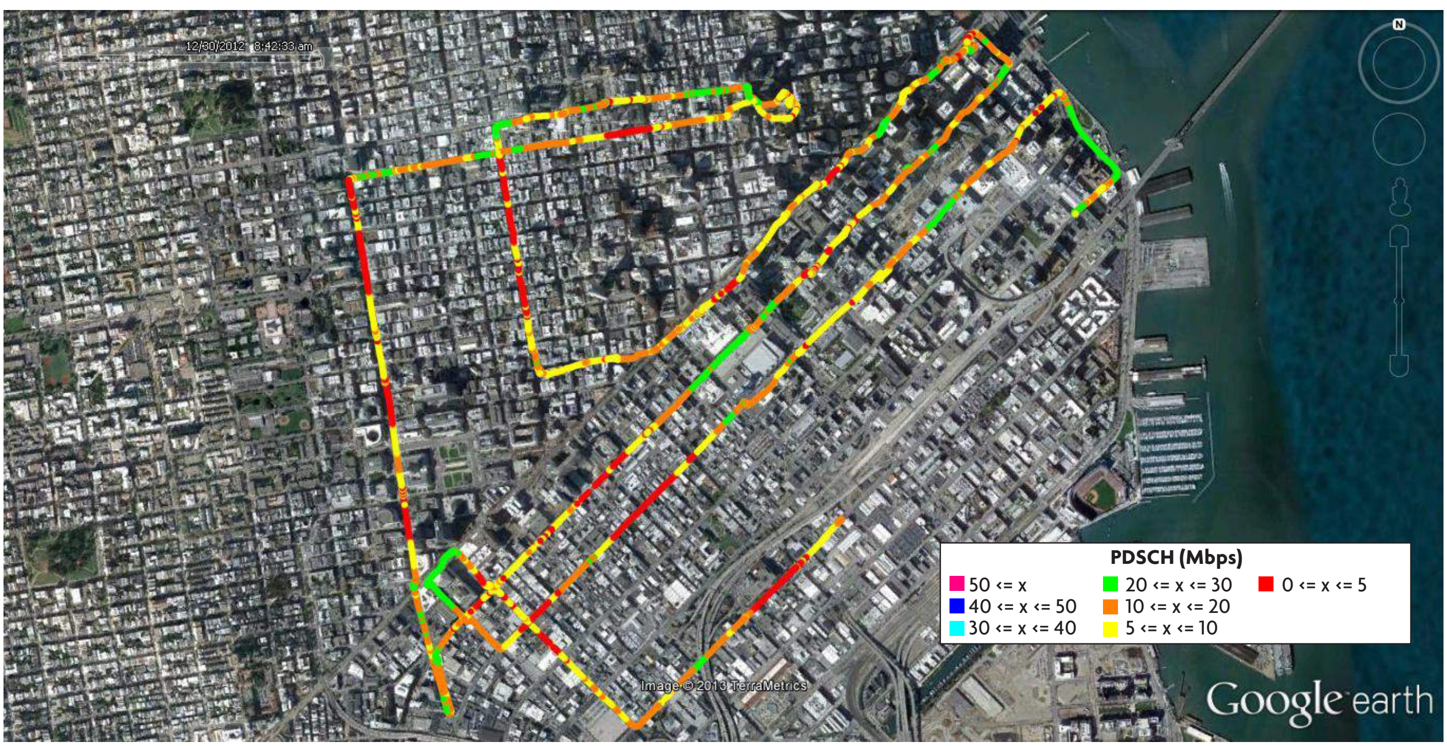
For example, if during a 20 minute test our mobile device was assigned 960,000 sub–frames then we would know that the network was assigning our mobile device 80% of the potential sub-frames (e.g., network resources). The remaining 20% could have been assigned to other devices or left unassigned – we have no way of knowing. It is also worth pointing out that in its current implementation with both network operators, the Ericsson scheduler only assigns one mobile device per sub-frame in the downlink, so if our mobile device was assigned a sub-frame at a given point in time then we know that our device was the only device using the downlink resources in our sector at that same exact moment. We confirmed this viewpoint when we did some concurrent testing with two AT&T devices and two Accuver XCAL solutions.

Although we don't necessarily know how many other active mobile devices were in the network, one can still infer the network loading and use this information to provide pretty accurate insight into the loading on today's commercial LTE networks and to normalize the throughput results between the two networks. According to the results, the AT&T dongle received 87.8% of the sub-frames and the Verizon Wireless dongle received 73.7% of the sub-frames, or network resources, during the test. This information strongly suggests that the Verizon Wireless network was experiencing slightly heavier loading – or at least it was assigning our mobile device fewer sub-frames. The lower utilization rate, however, doesn't fully explain the performance differences. If we normalize the results to equivalent utilization rates, the throughput on the Verizon Wireless network would be 15.2 Mbps.

It is apparent to us that the two LTE networks were fairly lightly loaded.

More importantly, in aggregate across both networks it is apparent to us that the two LTE networks were fairly lightly loaded. This observation does not negate the likely situation that there was network congestion at some point during the testing or that the presence of other mobile devices was impacting our throughput by increasing the interference levels. Although we are not providing the results in this report, we did some drive testing of the AT&T LTE network in downtown San Francisco during the late afternoon during a workday back in September – we were also doing A-GNSS testing for an earlier Signals Ahead report. The utilization rate during that testing 82.1% or within the range of what we observed during this particular Sunday afternoon drive test.

Figure 15. Downtown San Francisco Drive Test – Verizon Wireless PDSCH Throughput

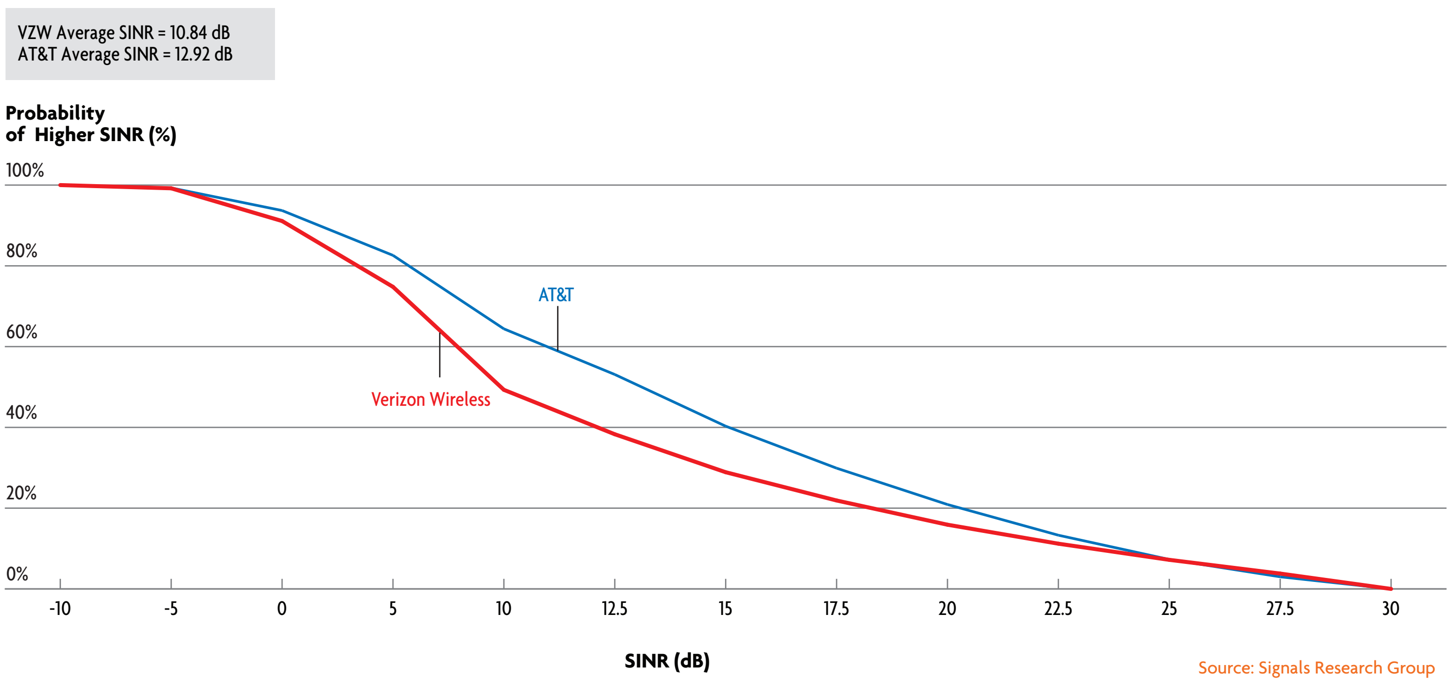


Source: Signals Research Group

We can't rule out the possibility that the two devices were measuring and reporting network conditions somewhat differently.

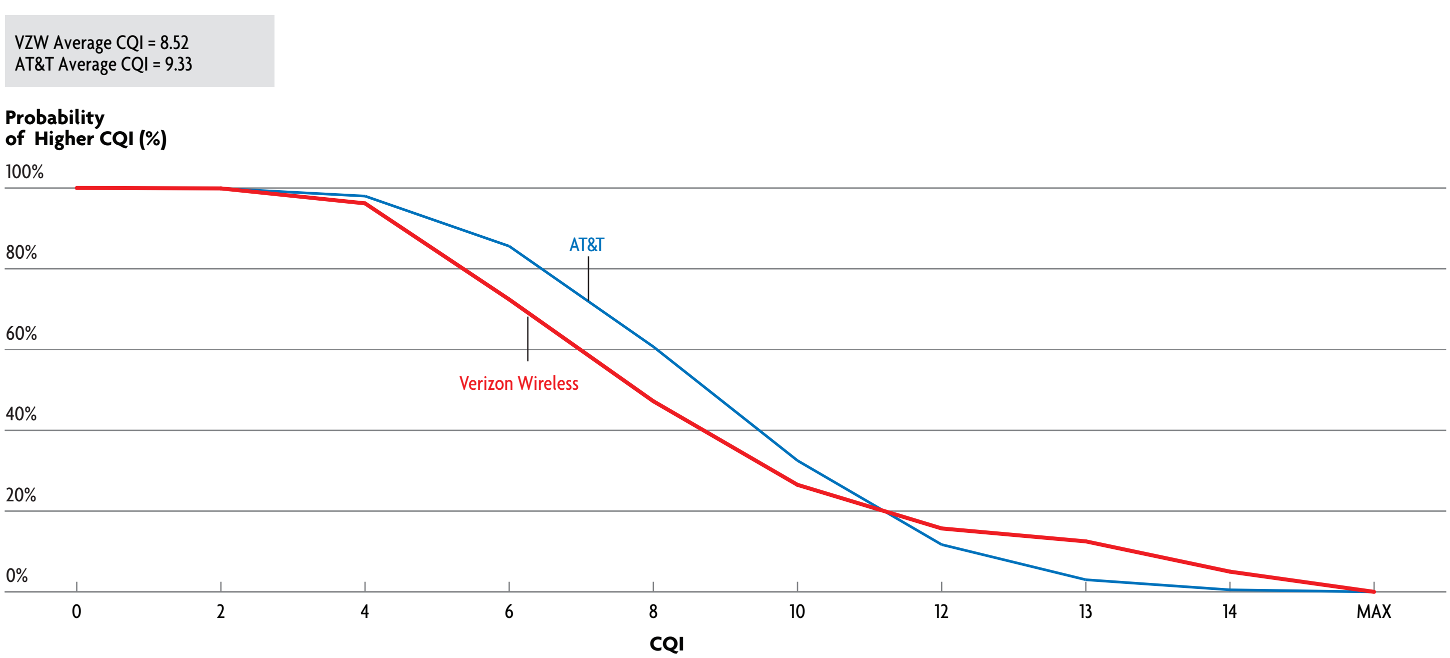
Two other important KPIs are the SINR and the CQI. These results are provided in Figure 16 (SINR) and Figure 17 (CQI). Both KPIs favor AT&T and they partially explain the differences in the throughput. That being said, the Verizon Wireless CQI results were actually better in the upper range (CQI > 11) and this outcome should have been reflected in the downlink throughput. Worth noting, since we were using different devices and potentially different Qualcomm chipsets, we can't rule out the possibility that the two devices were measuring and reporting network conditions somewhat differently.

Figure 16. Downtown San Francisco Drive Test SINR Results – Verizon Wireless and AT&T Probability Plots



Source: Signals Research Group

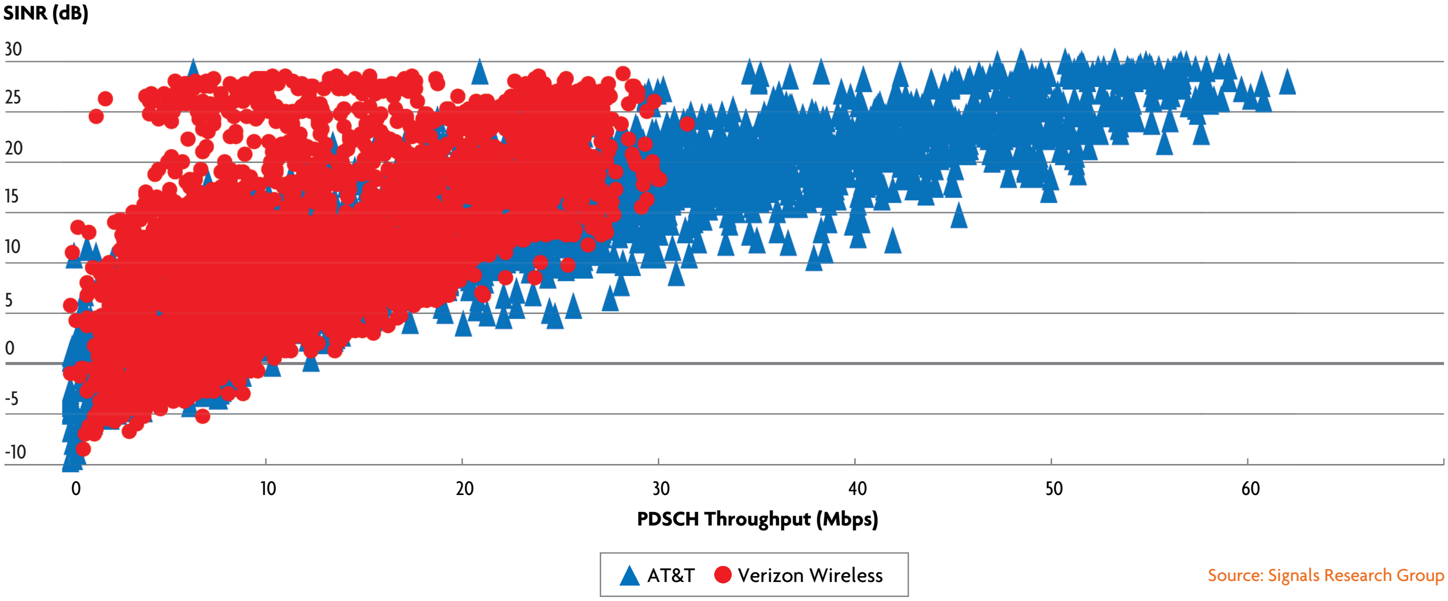
Figure 17. Downtown San Francisco Drive Test CQI Results – Verizon Wireless and AT&T Probability Plots



Source: Signals Research Group

Figure 18. Downtown San Francisco Drive Test SINR versus PDSCH Throughput – Verizon Wireless and AT&T Scatter Plots

VZW Average Throughput = 12.76 Mbps VZW Average SINR = 10.84 dB	AT&T Average Throughput = 21.43 Mbps AT&T Average SINR = 12.92 dB



Source: Signals Research Group

Now that we have shown the throughput and the SINR, we can bring the two KPIs together in a scatter plot and show how the results compare between the two networks. This information is provided in Figure 18. It is evident that the device on the Verizon Wireless network was not able to take full advantage of the channel conditions when the SINR was 15 and higher. Put another way, the throughput on the Verizon Wireless network was limited to approximately 30 Mbps. We doubt the typical user would notice the difference since most applications don't use, or require, that much throughput, but it is clearly evident in the test results.

Rank Indicator 2 indicates spatial multiplexing (Open Loop MIMO).

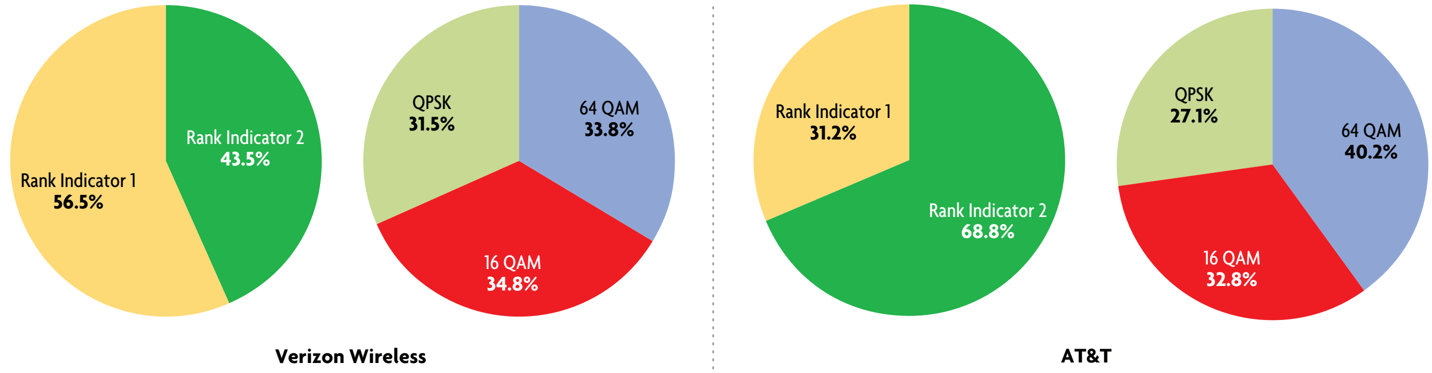
Figure 19 provides the distribution of modulation schemes and the rank indicator values. Rank Indicator 2 indicates spatial multiplexing (Open Loop MIMO) and Rank Indicator 1 indicates the less desirable transmit diversity. The distribution of modulation schemes was fairly consistent between the two networks but Open Loop MIMO was more likely to occur in the AT&T network. The more favorable SINR values partly explain the greater use of MIMO. Additionally, we note that AT&T typically places its radio electronics/remote radio heads near the antenna mast and we could be seeing the impact of this deployment philosophy in the data.

Figure 20 shows the utilization rate in a slightly different manner. In this figure we are providing probability plots for the number of assigned resource blocks for each device. The calculation takes into consideration the unassigned sub-frames (e.g., 0 resource blocks) for our mobile device. Otherwise the average number of assigned resource blocks would be closer to 50 in both networks.

Comparing the number of assigned resource blocks to the total number of available resource blocks would understate the implied network utilization rate.

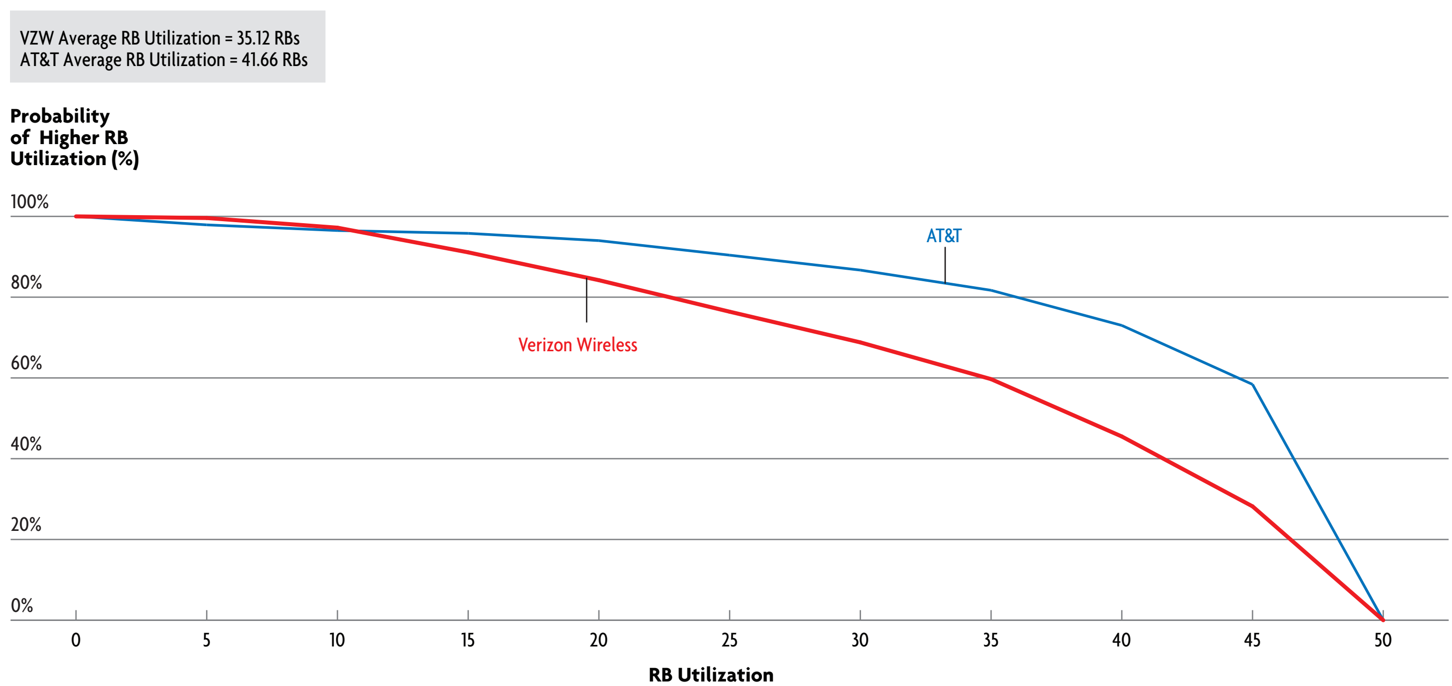
The information in this figure could also be used to infer the utilization rate in the two networks. However, the results would be artificially understated since it would infer that multiple devices could be assigned resources in the same sub-frame when we know this is not the case. We note that in a number of sub-frames the mobile device did not receive all 50 resource blocks, but we also know that these resource blocks were not assigned to other devices. A simple calculation of assigned resource blocks versus the total number of available resource blocks during a drive test ignores this nuance so that is why we compared the number of assigned versus unassigned sub-frames to calculate the utilization rate.

Figure 19. Downtown San Francisco Drive Test Rank Indicator and Modulation Scheme Distributions – Verizon Wireless and AT&T Pie Charts



Source: Signals Research Group

Figure 20. Downtown San Francisco Drive Test Resource Block Results – Verizon Wireless and AT&T Probability Plots



Source: Signals Research Group

4.2 Cleared for Takeoff

Thanks to various business trips during the last several months, we had the opportunity to visit several major airports in the United States. We didn't always have sufficient time to do all of the testing that we felt needed to be done, but we couldn't pass up the opportunity to check out one or both networks. Results in this section include San Francisco (Terminal 1 and Terminal 3), Chicago O'Hare (Terminal C), Boston Logan (Terminal C), Washington Dulles (Terminal C), and Dallas-based DFW (Terminal E).

4.2.1 SFO Terminal 3

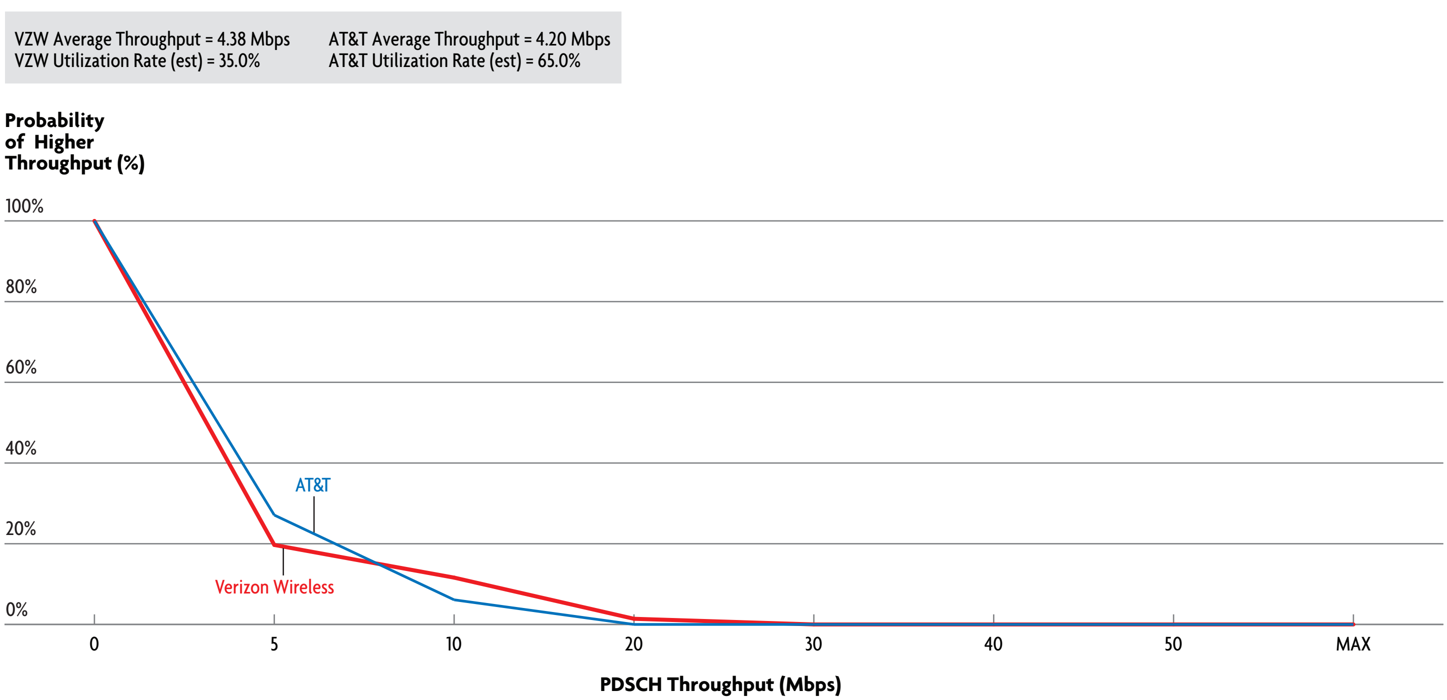
We tested SFO Terminal 3 in early December after returning from a trip to Boston (via Chicago) where we had the opportunity to also test the respective airports in those two cities. Needless to say, the results for SFO Terminal 3 were not very encouraging, perhaps even more so because we didn't think the airport was very crowded when we did the testing around mid-day on a Friday.

Figure 21 provides probability plots for the downlink throughput. As the figure illustrates, the average throughput on the two LTE networks was below 5 Mbps – slightly favoring Verizon Wireless. The distribution of the throughput is also disappointing since it indicates the throughput was almost always below 5 Mbps – brief occurrences of higher throughput helped pull up the averages to the average values that we report.

Both networks underperformed relative to our expectations, but in relative terms the AT&T network fared worse.

It is also evident in the figure that the Verizon Wireless network was more heavily loaded at the time we conducted the testing. Our mobile device "only" received 35% of the potential network resources compared with 65% of the network resources (potential sub-frames) on the AT&T LTE network. All things considered, both networks underperformed relative to our expectations and what we believe would be the expectations of most consumers, but in relative terms the AT&T network fared worse.

Figure 21. SFO Terminal 3 PDSCH Throughput Results – Verizon Wireless and AT&T Probability Plots



Source: Signals Research Group

Looking at it from a slightly different perspective and doing a bit of high school math, the implied spectral efficiency was 1.31 bits/Hz/sec (12.5 Mbps with 100% utilization in a 10 MHz channel). Not shabby, but lower than most industry claims. We doubt, however, that the remaining 65% of the network resources were delivering a comparable throughput, or 8.125 Mbps. This methodology also suggests that the AT&T network in downtown San Francisco was achieving a spectral efficiency of 2.6 bits/Hz/sec, which we strongly doubt was the case.

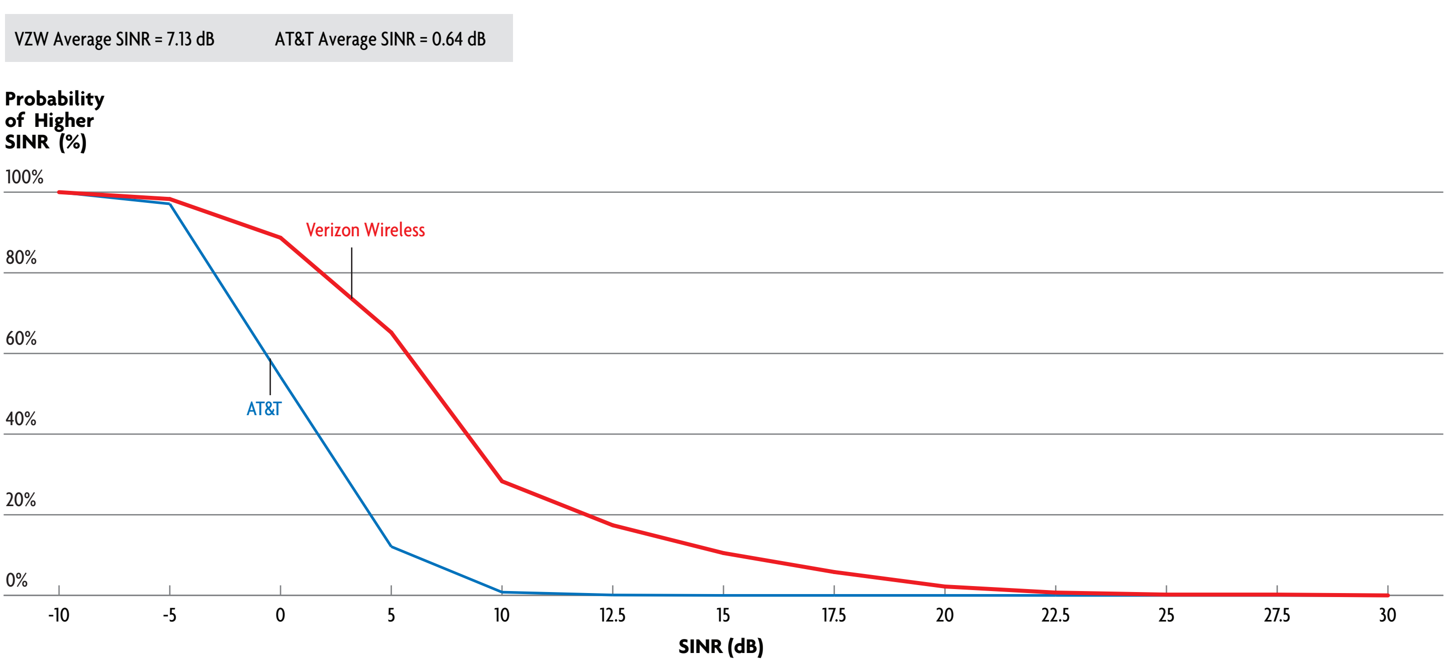
In any event, it is evident that the achievable throughput in an LTE network is highly dependent on the network loading – an obvious observation. In addition to the network assigning the mobile device fewer network resources (sub-frames and resource blocks), the SINR is much lower due to the higher interference so the achievable throughput for a given amount of network resources is also reduced – a double whammy if you will.

The low SINR values, especially in the AT&T LTE network, partially explain the low throughput.

The low SINR values, especially on the AT&T LTE network, partially explain the low throughput. This information is shown in Figure 22 – note the very low average SINR in the AT&T network. For comparison purposes, the average SINR from our outdoor drive test in downtown San Francisco was 10.84 dB in the Verizon Wireless network and 12.92 dB in the AT&T network. It is natural for the SINR to degrade with more devices in the network but in our opinion the degradation was far greater than we would expect – in particular for the AT&T network since the utilization rate implies that our mobile device was receiving 65% of the available network resources.

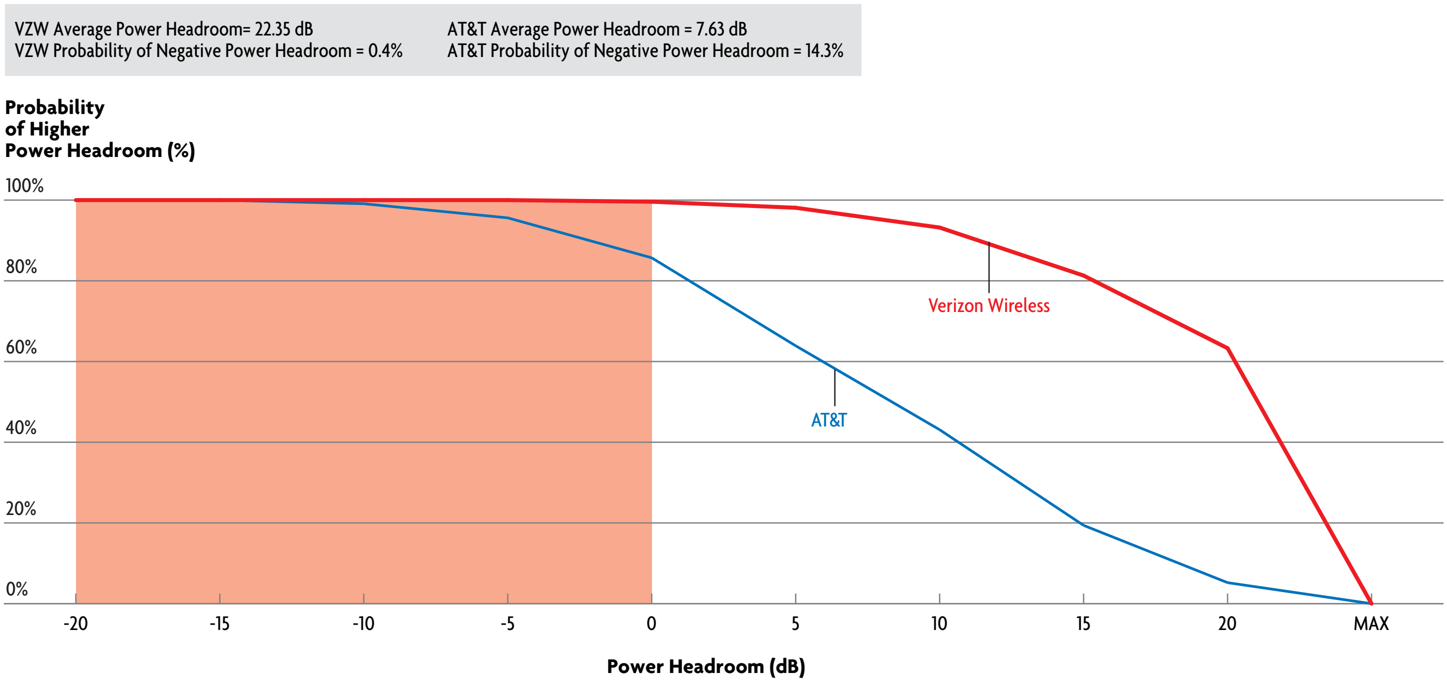
As previously mentioned, one possibility is that there were a lot of devices connected to the network and increasing the interference, even though the devices were not consuming a lot of network resources. Assuming there was an in-building DAS solution in SFO Terminal 3, it could also be the case that it wasn't designed or architected to handle the basic capacity demands of mobile data in an LTE network

Figure 22. SFO Terminal 3 SINR Results – Verizon Wireless and AT&T Probability Plots



Source: Signals Research Group

Figure 23. SFO Terminal 3 Power Headroom Results – Verizon Wireless and AT&T Probability Plots



Source: Signals Research Group

We didn't have the time or battery life in our notebook computer to test the uplink throughput. However, as shown in Figure 23, it appears that there were not any significant uplink power restrictions that were impacting the downlink throughput. Note that the Power Headroom was almost always greater than 0 dB. The results are, however, very different between the two networks with the results favoring Verizon Wireless.

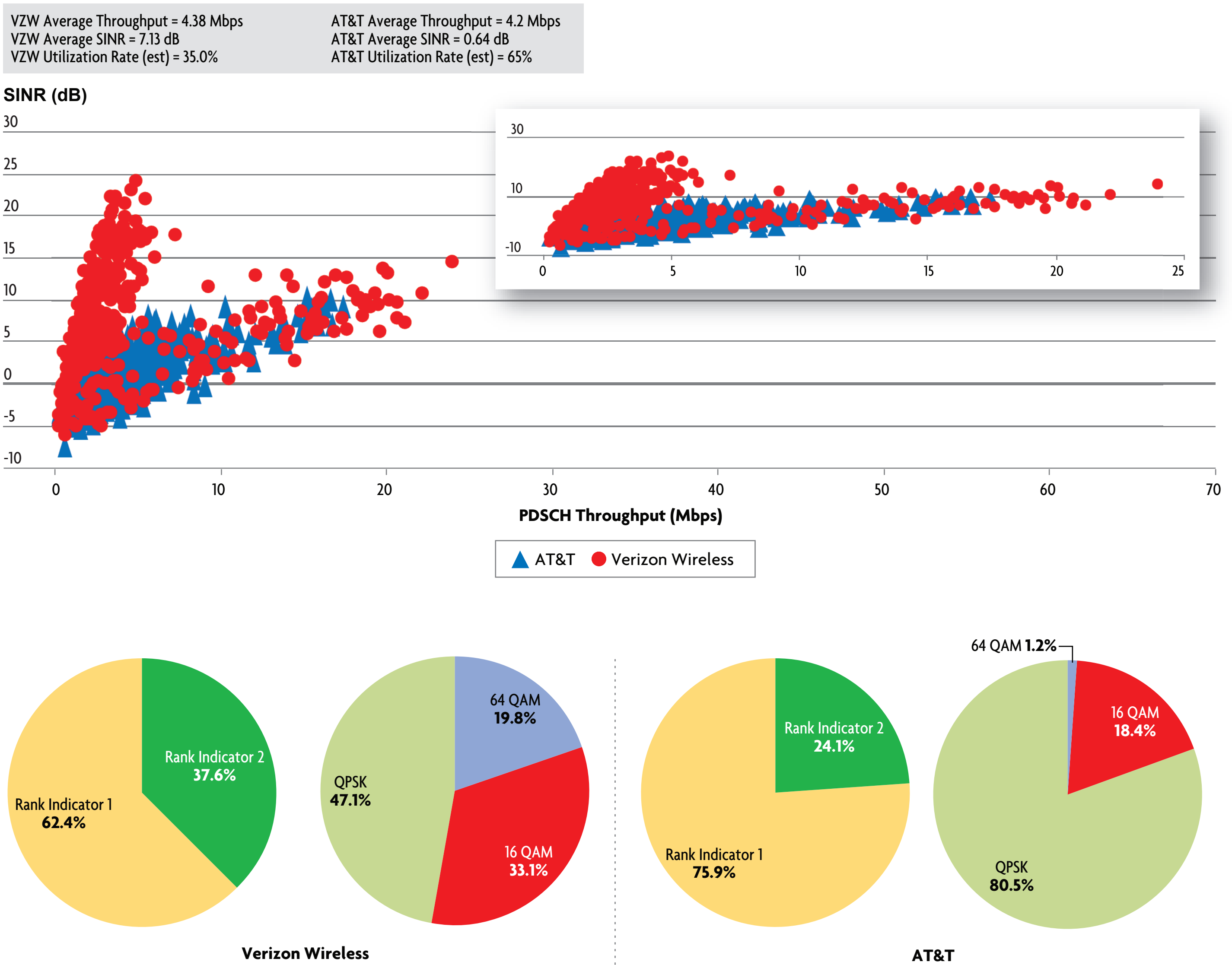
Figure 24 brings together the SINR and resultant throughput in one figure. Additionally, it shows the distribution of modulation schemes and rank indicator values for the two networks. All results favor Verizon Wireless and we point out that 64 QAM was barely detected on the AT&T network. Not surprising given the very low SINR.

Figure 24 also shows a very interesting phenomenon on the Verizon Wireless network. There appears to be two distinct correlations between the SINR and the throughput. It isn't clear to us why this situation occurred but we did go back and validate it in the data. We suspect that the two sets of data stem from being in different parts of the terminal, combined perhaps with how the backhaul or DAS was dimensioned.

The throughput immediately outside of SFO Terminal 3 was substantially higher in both networks than it was within the terminal.

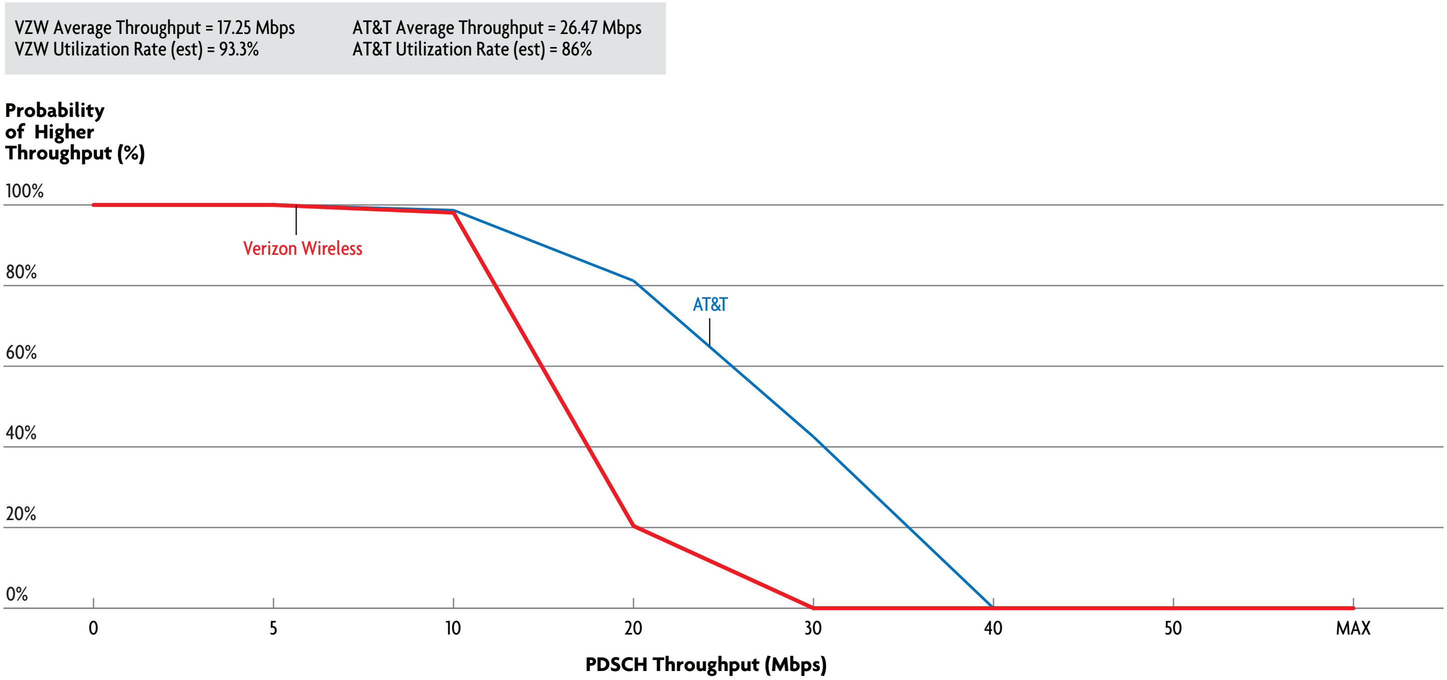
When results are as surprisingly disappointing as they were in Terminal 3, we always strive to ensure that the results were real and not an artifact of our test methodology. In this case, we feared that our FTP server was on death's doorstep. Right after collecting this data we went outside of Terminal 3 in the passenger pickup area and conducted a fairly short / stationary test of the two networks. As shown in Figure 25, the throughput in both networks improved dramatically. Both networks were also lightly loaded as reflected in the high utilization rates. The AT&T throughput was measurably higher than the throughput on the Verizon Wireless network. Additionally, from that particular spot where we did the testing, we observed a much higher assignment of Rank Indicator 2 on the AT&T network (95.4%) than on the Verizon Wireless network (12.25%).

Figure 24. SFO Terminal 3 SINR versus PDSCH Throughput – Verizon Wireless and AT&T Scatter Plots



Source: Signals Research Group

Figure 25. Outside of SFO Terminal 3 PDSCH Throughput Results – Verizon Wireless and AT&T Probability Plots



Source: Signals Research Group

In the Appendix we include two figures that map the downlink throughput to Terminal 3 for AT&T (Figure 65) and Verizon Wireless (Figure 66).

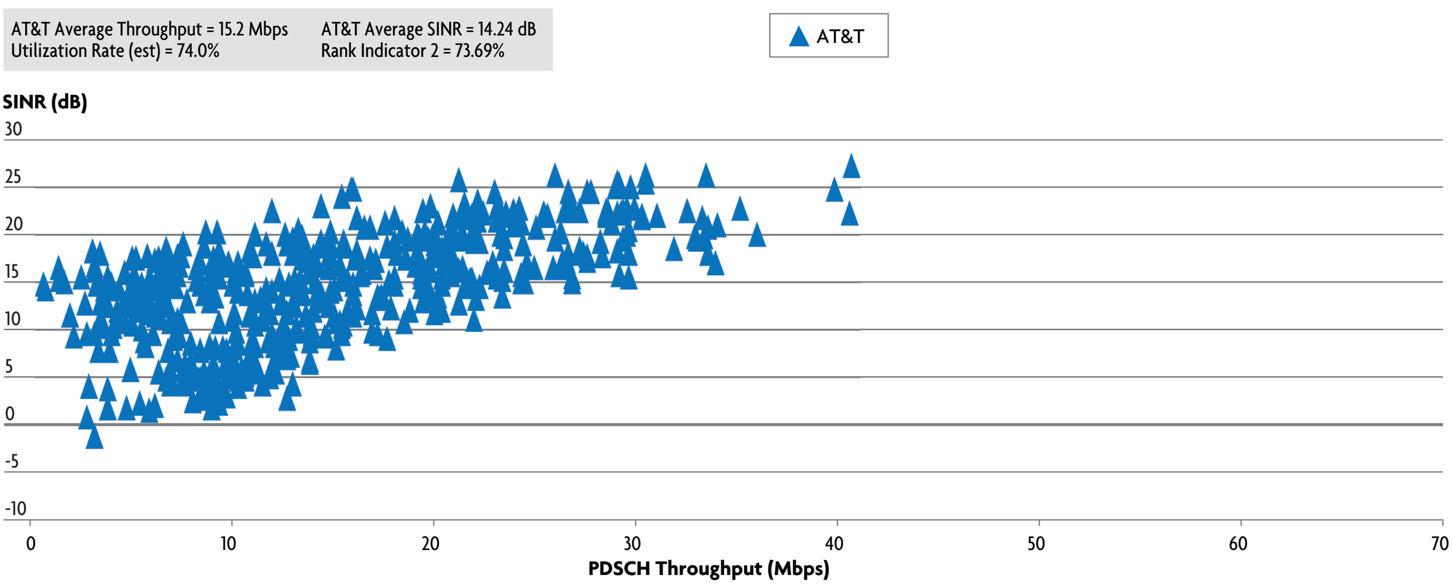
4.2.2 SFO Terminal 1

We tested SFO Terminal 1 in September at a time when we felt that the terminal was very busy with lots of passengers waiting for flights. Given our travel plans we didn't have the time to test the Verizon Wireless network.

Figure 26 provides a scatter plot of the SINR and the PDSCH throughput for the AT&T LTE network. Compared with the results from Terminal 3, the performance of the AT&T network in Terminal 1 was substantially better. The throughput was 3.6x higher and there was a 13.56 dB improvement in the SINR. The utilization rate (73.69%) was also higher than it was in Terminal 3 (65%), indicating that the network was assigning more network resources to our mobile device, and indirectly implying that the network loading was not as high as it was in Terminal 3.

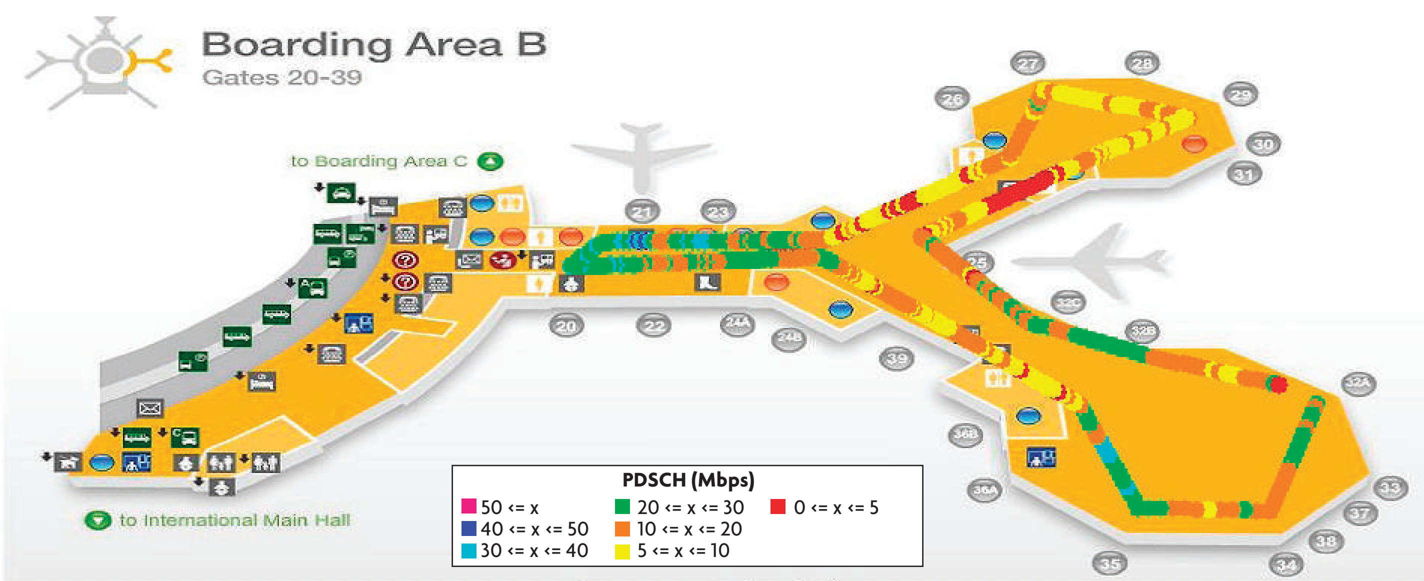
Figure 27 plots the throughput to the layout of Terminal 3

Figure 26. SFO Terminal 1 SINR versus PDSCH Throughput – AT&T Scatter Plot



Source: Signals Research Group

Figure 27. SFO Terminal 1 PDSCH – AT&T Geo Plot



Source: Signals Research Group

4.2.3 Washington Dulles Terminal C

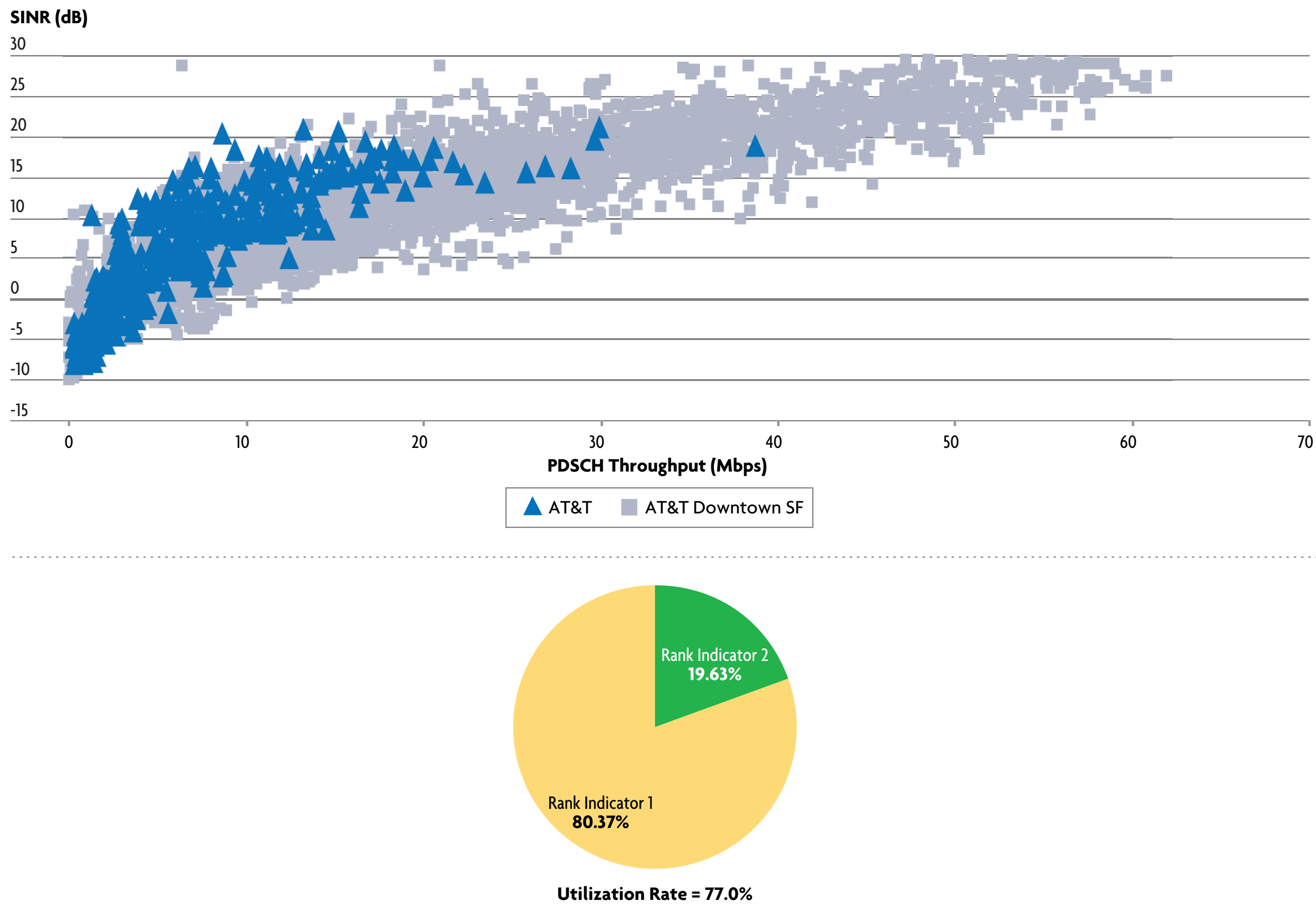
Thanks to the folks at United Airlines, we had a few extra hours to spare on our flight to Nice, France where we participated in the Informa SON Conference. Instead of spending all of our time in the airline's lounge, we walked up and down Terminal C a few times carrying an open laptop computer. Ironically, we almost missed our delayed flight and they closed the door behind us as soon as we entered the jetway. Since we weren't planning on the extended layover, we didn't bring our Verizon Wireless dongle so we were only able to test the AT&T network.

Figure 28 plots the throughput as a function of the reported SINR. For comparison purposes, we have included the results from our downtown San Francisco drive test. The comparison is interesting because it shows that for a given SINR value the outdoor network was able to achieve much higher throughput in many instances. Granted, the overall SINR was higher in the outdoor network, but we would have still expected there to be more instances of higher throughput in the terminal.

As shown in the bottom of the figure, the utilization rate was 77% so the network was assigning a very large portion of the network resources to our mobile device (e.g., the network was presumably lightly loaded). The availability of Rank Indicator 2 was also low, but that could be due to the SINR.

Figure 28. Dulles Terminal C SINR versus PDSCH Throughput – AT&T Scatter Plot

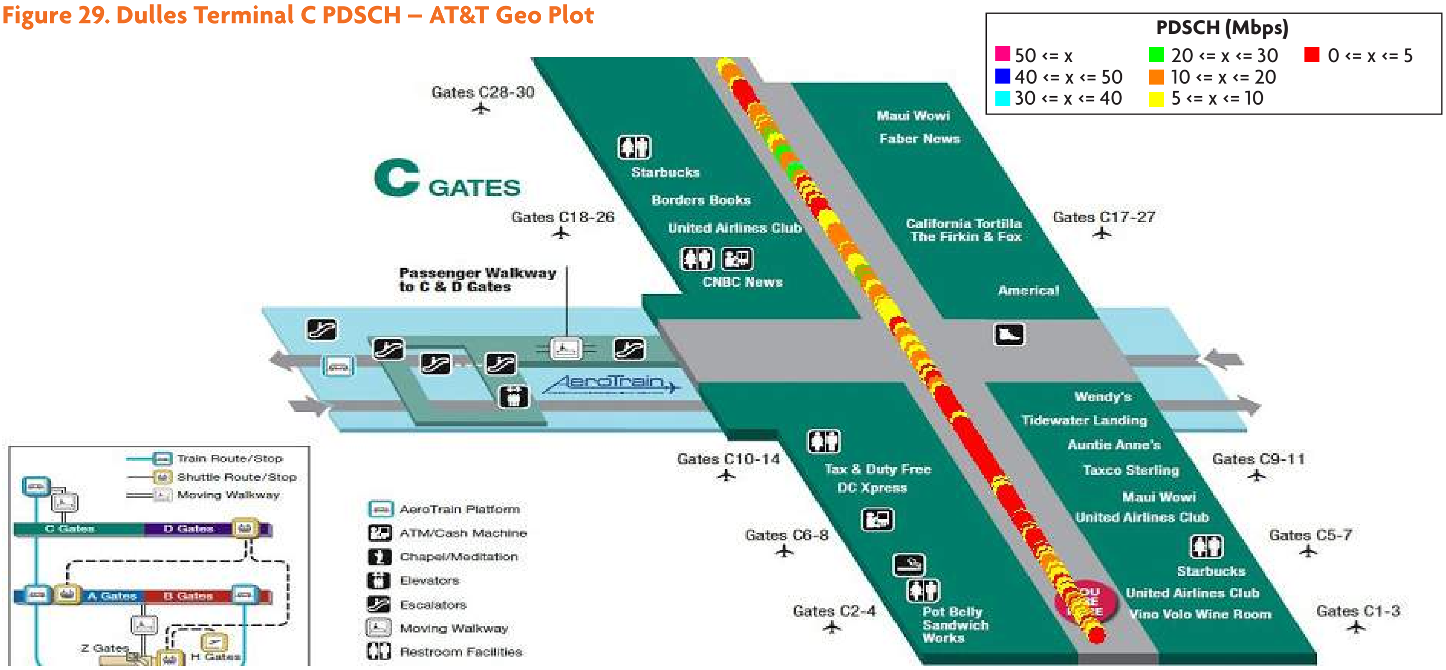
Average Dulles PDSCH Throughput = 7.29 Mbps Average Dulles SINR = 6.46 dB
Average Downtown PDSCH Throughput = 21.43 Mbps Average Downtown SINR = 12.92 dB



Source: Signals Research Group

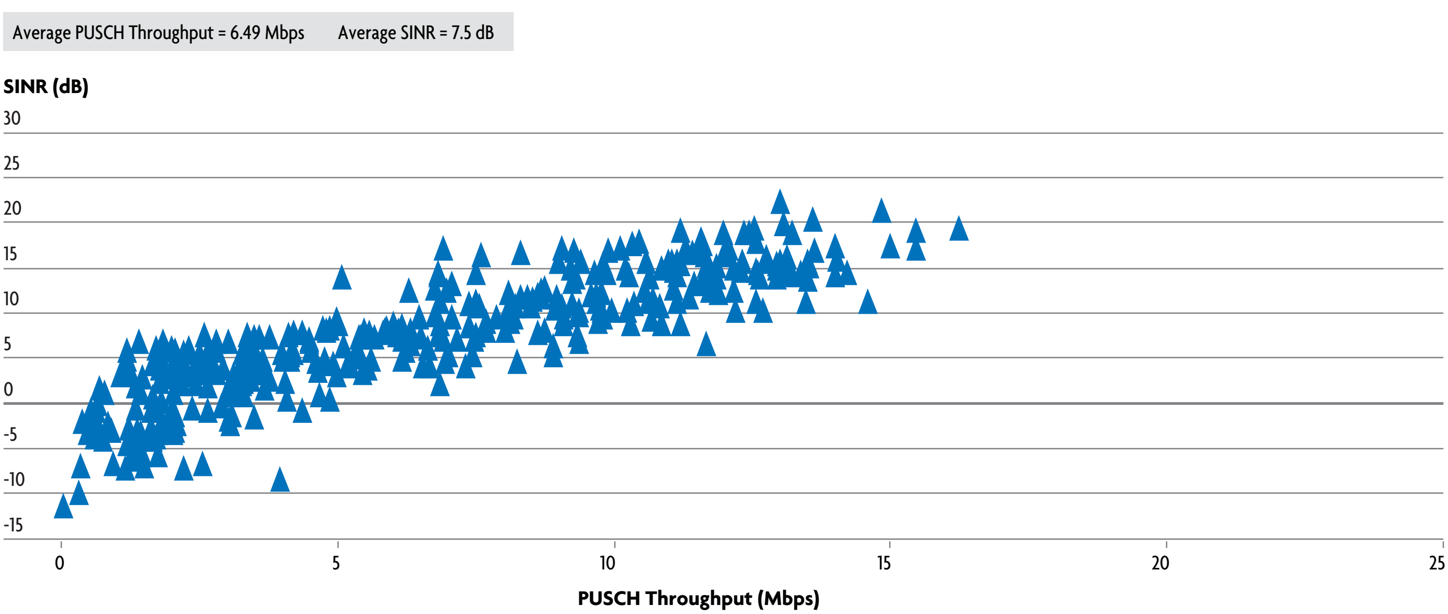
Figure 29 plots the downlink throughput to the layout of the terminal. In the Appendix, we show a similar plot for the uplink throughput. A scatter plot of the uplink throughput as a function of the downlink SINR is shown in Figure 30. As indicated in the figure, the average uplink throughput was 6.49 Mbps. In the Appendix we also include a geo plot of the PUSCH transmit power (average PUSCH transmit power = 20.69 dBm. Although it isn't evident in the figure, nearly 30% of the time the Power Headroom was negative, indicating the network was artificially limiting the desired throughput of the mobile device.

Figure 29. Dulles Terminal C PDSCH – AT&T Geo Plot



Source: Signals Research Group

Figure 30. Dulles Terminal C SINR versus PUSCH Throughput – AT&T Scatter Plot

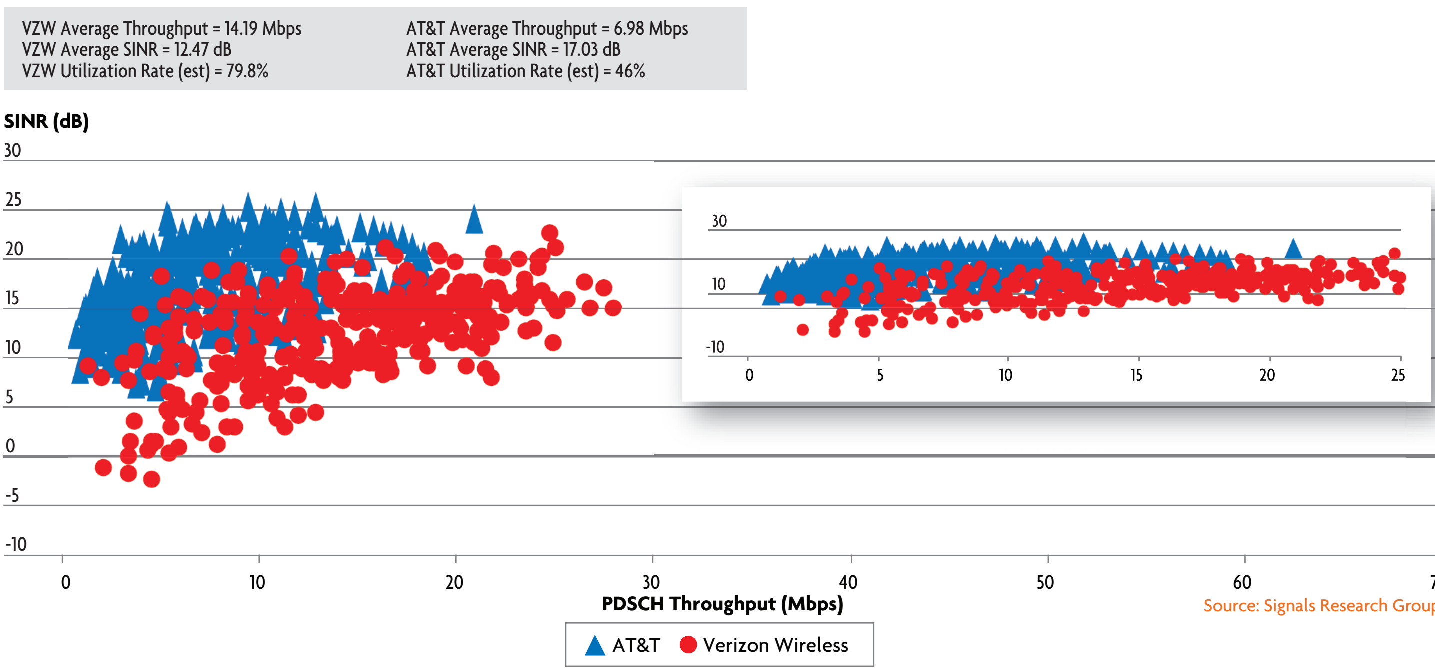


Source: Signals Research Group

4.2.4 Chicago O'Hare Terminal C

We had a lot of time to kill at the Chicago airport so we walked Terminal C, not once, not twice, not thrice, but four times – testing the downlink and uplink throughput on the two LTE networks. The testing took place in the late morning through early afternoon hours in early December. The airport was modestly crowded, but pretty typical for the large airport. Figure 31 provides a scatter plot of the SINR versus PDSCH throughput. Figure 32 provides the availability of Rank Indicator 2 and the distribution of modulation schemes.

Figure 31. O'Hare Terminal C SINR versus PDSCH Throughput – Verizon Wireless and AT&T Scatter Plots

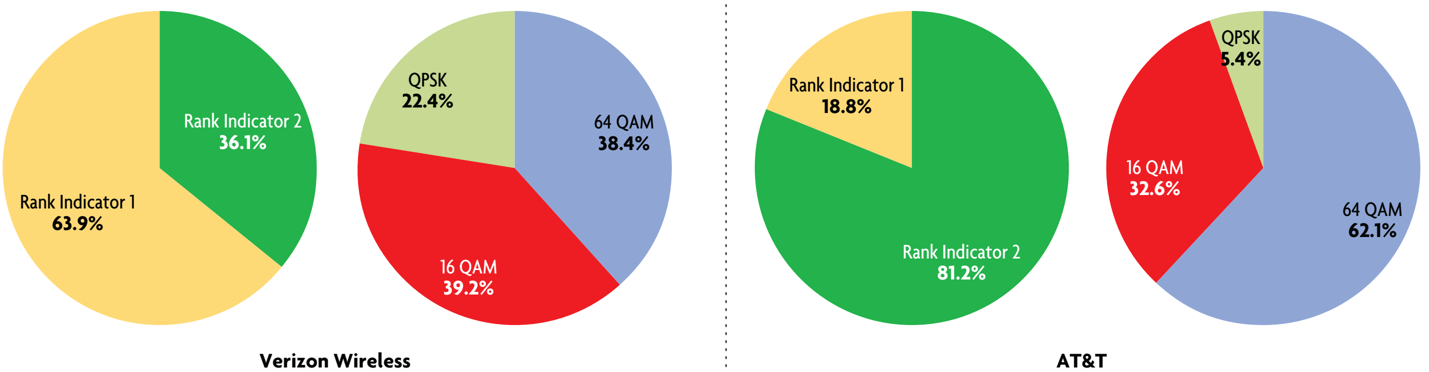


Source: Signals Research Group

AT&T only has 2 x 5 MHz of spectrum in Band 17 for its LTE network in Chicago,

From a SINR perspective, the AT&T results were extremely favorable. However, the throughput was quite low. There are two clear reasons. First, AT&T only has 2 x 5 MHz of spectrum in Band 17 for its LTE network in Chicago so the peak throughput rates would inherently be 50% lower than they would be in other markets where they have a full 2 x 10 MHz – or versus Verizon Wireless at O'Hare. Second, the utilization rate for our mobile device was only 46%, indicating a fair amount of network loading. The low utilization rate is directly related to the reduced amount of spectrum. In fact, the AT&T SINR results are even more impressive if we compare them with the other results where the utilization rate was higher (e.g., the network was more lightly loaded). What matters is throughput and in that regard Verizon Wireless came out on top.

Figure 32. O'Hare Terminal C Rank Indicator and Modulation Scheme Distributions – Verizon Wireless and AT&T Pie Charts



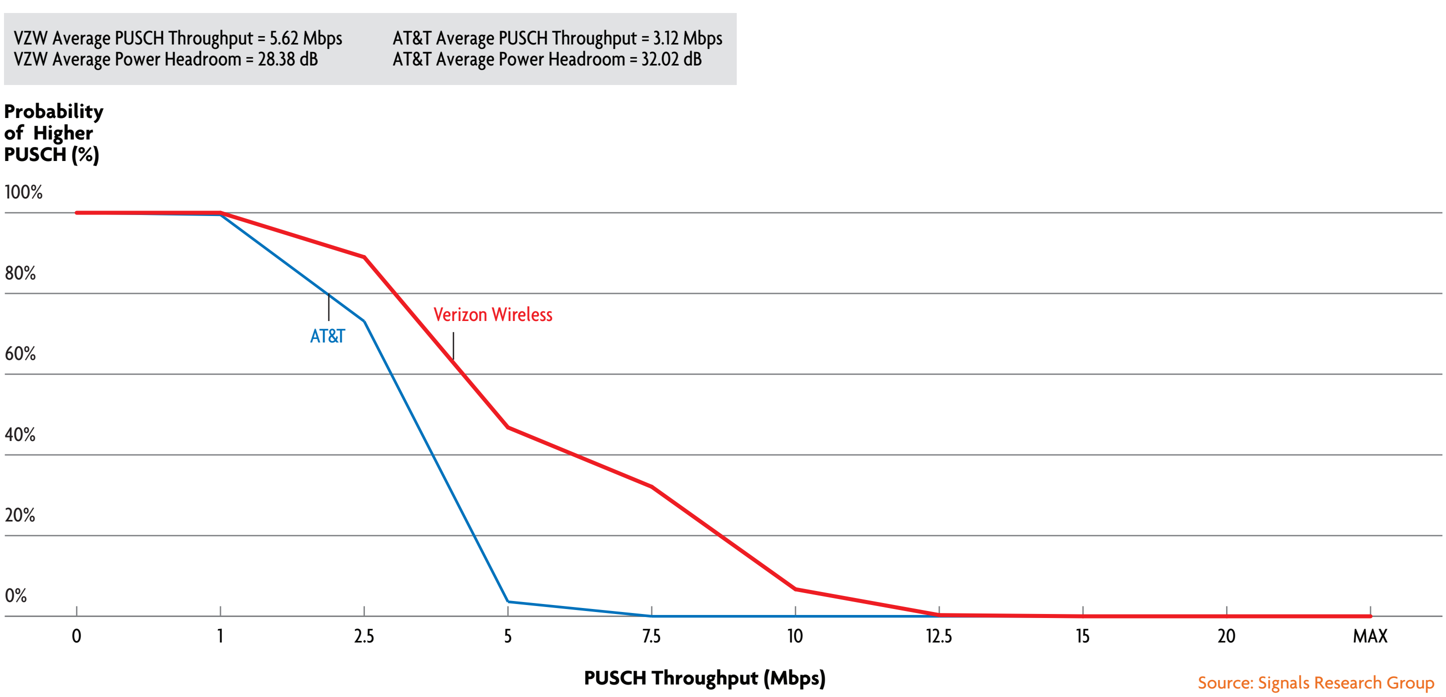
Source: Signals Research Group

If we normalize the results to the downtown San Francisco drive test results, taking into consideration the differences in the utilization rates and the channel bandwidths, but not the SINR, the AT&T downlink throughput at O'Hare Terminal C would have been 22.4 Mbps and the Verizon Wireless throughput would have been 15.36 Mbps. These two values are fairly similar to what we achieved in downtown San Francisco.

The uplink throughput was higher in the Verizon Wireless network (5.62 Mbps) than in the AT&T network (3.12 Mbps).

Figure 33 provides probability plots for the uplink throughput. Not surprisingly, the throughput was higher in the Verizon Wireless network (5.62 Mbps) than in the AT&T network (3.12 Mbps). For both networks the Power Headroom KPI was quite favorable, indicating that the network wasn't artificially limiting the throughput due to interference at the cell. In the appendix we include geo plots of the PUSCH transmit power for both networks - Figure 69 for AT&T and Figure 70 for Verizon Wireless. For both networks, the Power Headroom was never negative. Readers should compare these two figures with the AT&T transmit power from the Dulles terminal (Figure 68) where the uplink interference had a measurable influence on the throughput.

Figure 33. O'Hare Terminal C PUSCH Throughput Results – Verizon Wireless and AT&T Probability Plots



Source: Signals Research Group

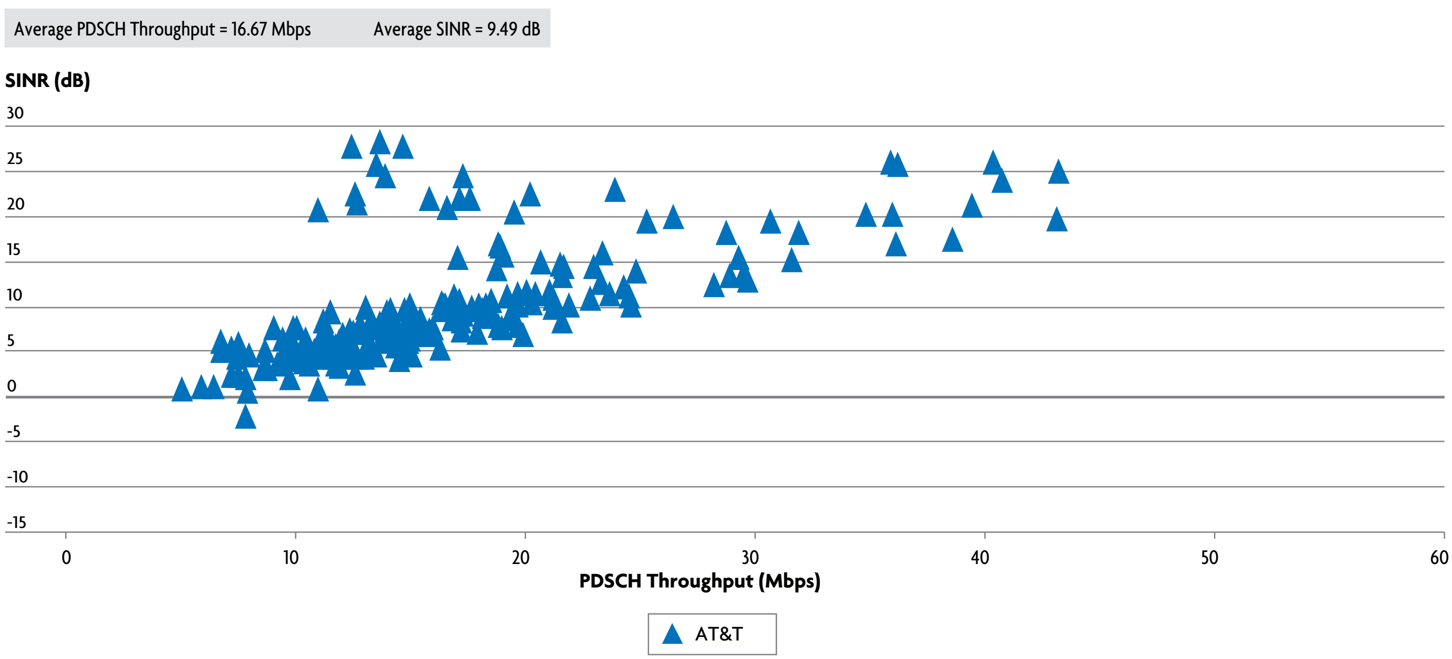
4.2.5 Boston Logan Terminal C

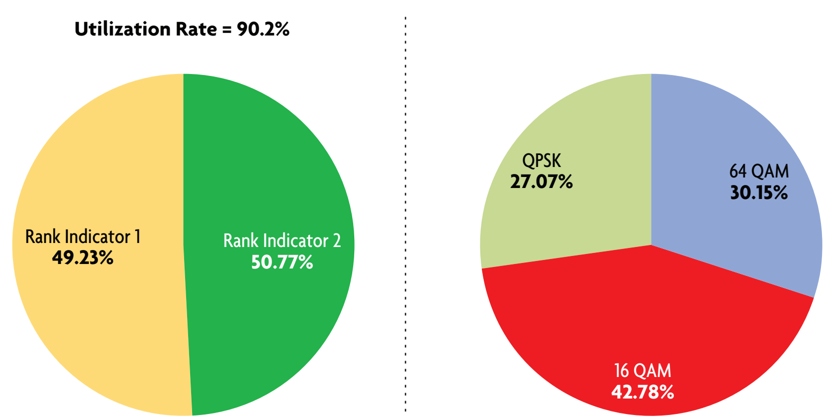
We attempted to test both networks at the Boston Logan airport early in the morning (pre 7 AM). For reasons that we can't explain our Verizon Wireless dongle couldn't find the LTE network and it kept trying to connect to the EV-DO Rev A network. When we tested later in the day at SFO Terminal 3 the dongle / network worked just fine. We were able to connect to the Verizon Wireless LTE network with a Samsung Galaxy S III and we performed a few basic throughput tests using SpeedTest.net. The results were in the high single- and low double-digits on a Megabit-per-second basis although we didn't have coverage in the Men's Room. Proper etiquette suggests that you shouldn't be conducting network testing in a room designed for other purposes, and that rationale might explain part of the problem. ☺

All of the AT&T results at Boston Logan were quite good, but the network was very lightly loaded.

Figure 34 provides a plot of the PDSCH throughput as a function of the SINR as well as the distribution of modulation schemes and the availability of Rank Indicator 2. All of the results were quite good, but the network was very lightly loaded since the network was assigning our mobile device 90.2% of the sub-frames.

Figure 34. Boston Logan Terminal C SINR versus PDSCH Throughput – AT&T Scatter Plot

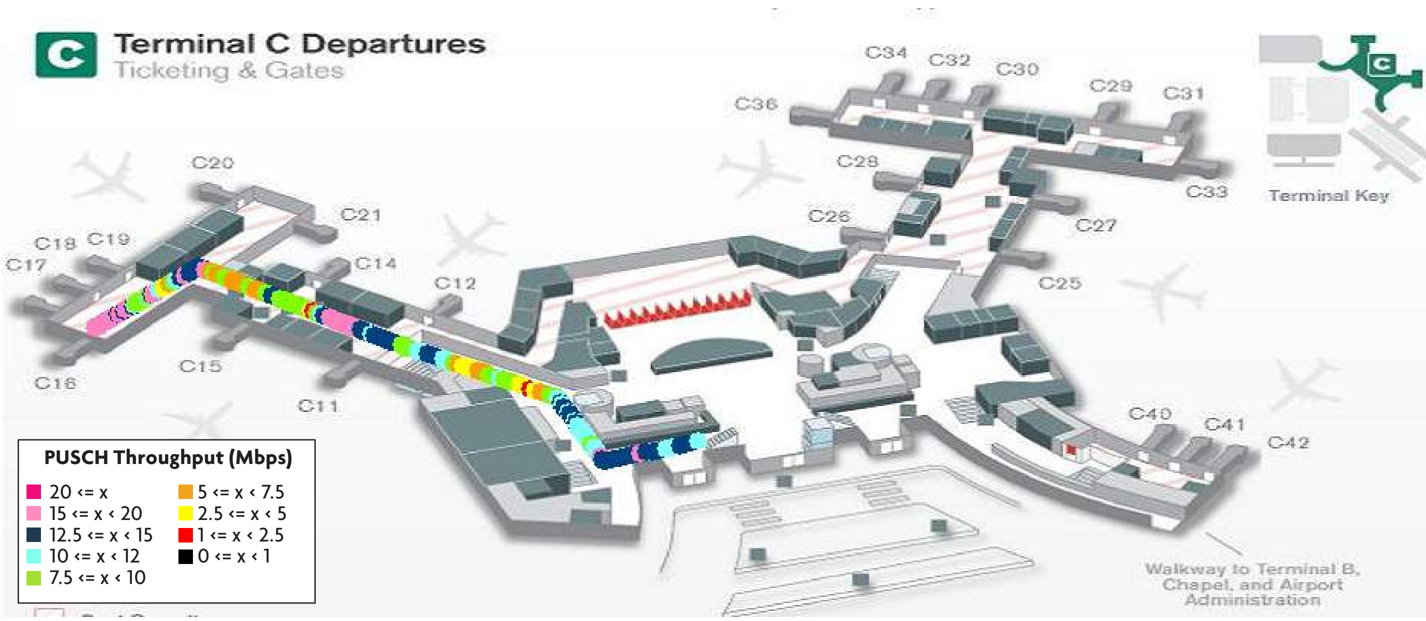




Source: Signals Research Group

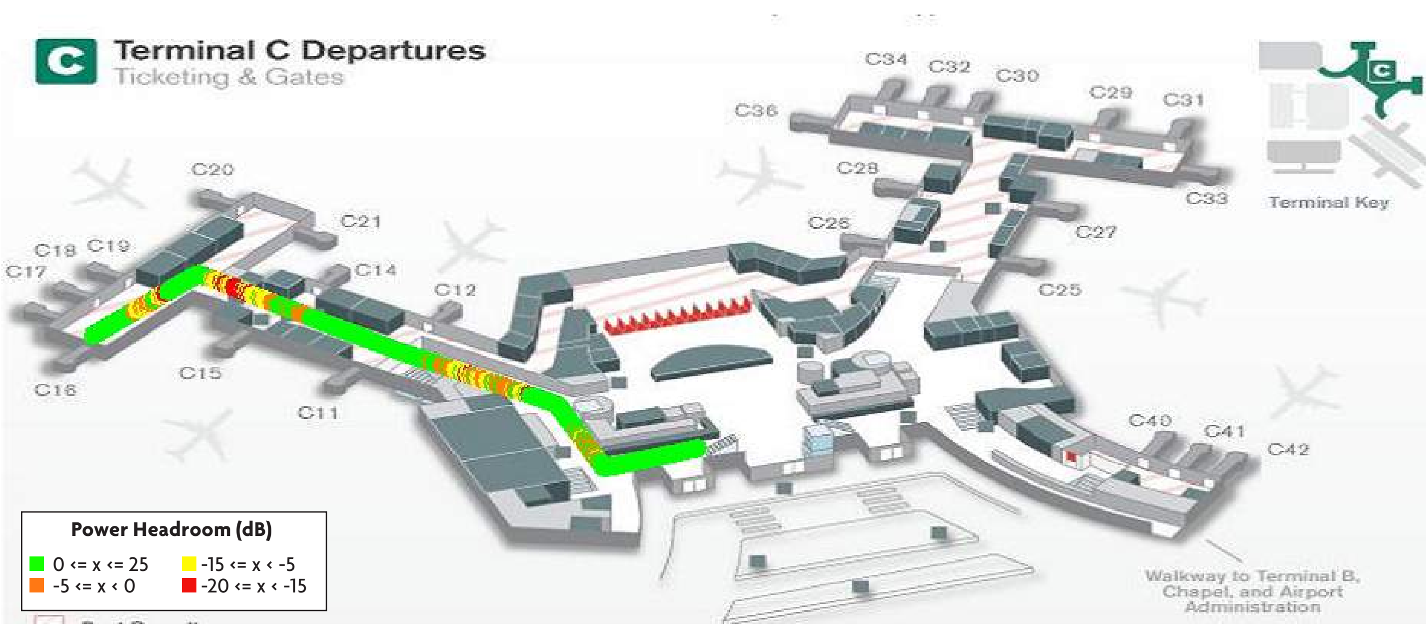
While we were writing this report and after we had relinquished the use of the Accuver tool, we realized that we hadn't fully analyzed the uplink results. However, we did create a few geo plots that we can share. Based on the two figures it appears that the throughput was quite good. We are including these two figures since it shows that in those areas where the PUSCH Throughput throughput was relatively low (reference Figure 35), the Power Headroom value was negative (reference Figure 36).

Figure 35. Boston Logan Terminal C PUSCH Throughput – AT&T Geo Plot



Source: Signals Research Group

Figure 36. Boston Logan Terminal C Power Headroom – AT&T Geo Plot



Source: Signals Research Group

4.2.6 DFW Terminal E

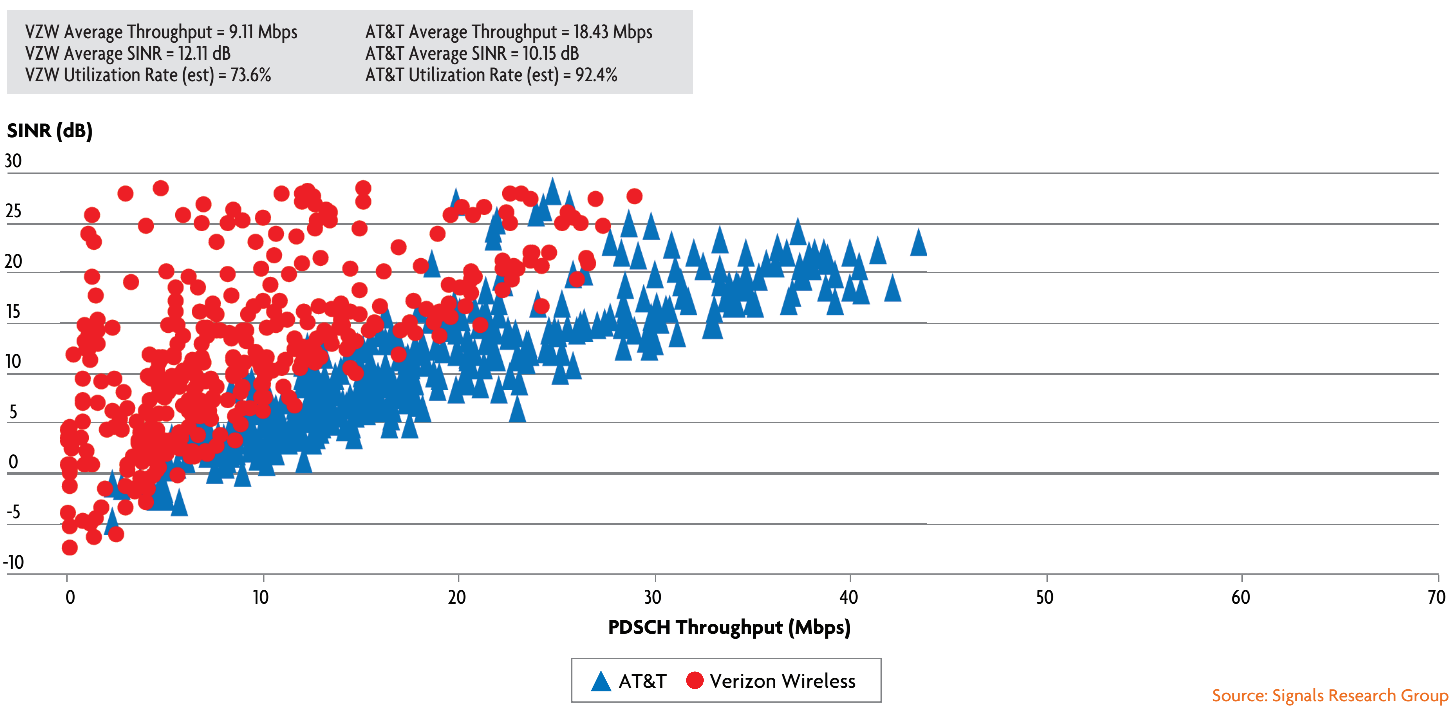
We tested the DFW airport back in late September. The testing took place in the mid- to late-afternoon hours during the work week. We tested the downlink throughput of both networks but we didn't have time to test the uplink.

Figure 37 provides scatter plots of the SINR and the PDSCH throughput for both networks. Figure 38 provides additional information pertaining to the distribution of the modulation schemes and the availability of Rank Indicator 2 and Rank Indicator 1. As the results indicate the throughput on the AT&T network was approximately twice that of the Verizon Wireless network even though the SINR favored Verizon Wireless. The difference in the utilization rates partly explains the throughput differences. If we normalize the AT&T throughput to the Verizon Wireless utilization rate then the throughput on the AT&T network would be 14.68 Mbps.

Rank Indicator 2 was virtually absent in the Verizon Wireless network despite the high SINR.

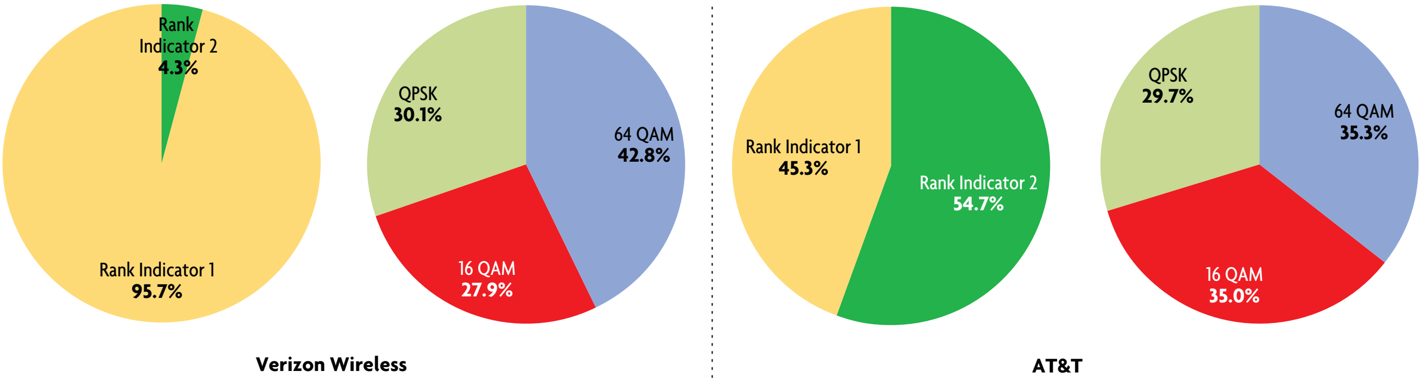
The most interesting observation in these results is the near absence of Rank Indicator 2 in the Verizon Wireless network, despite the high SINR. We don't know the specifics of the solution in place at DFW but we do know that some legacy DAS solutions and MIMO sometimes go together like oil and water. For this reason, and because the DAS solution could have required upgrading the antenna drops to support MIMO, it could be that the network didn't fully support MIMO throughout the entirety of the terminal. We know for certain that it was seldom used. We also don't know how effective MIMO was when it came to increasing the throughput. In theory, it could have doubled the throughput but in reality the gain would have been less and potentially even worse than without MIMO. We recall a presentation from several years ago in which a European operator made a strong case for not using MIMO in in-building DAS deployments due to this very reason.

Figure 37. DFW Terminal E SINR Versus PDSCH Throughput – Verizon Wireless and AT&T Scatter Plots



Source: Signals Research Group

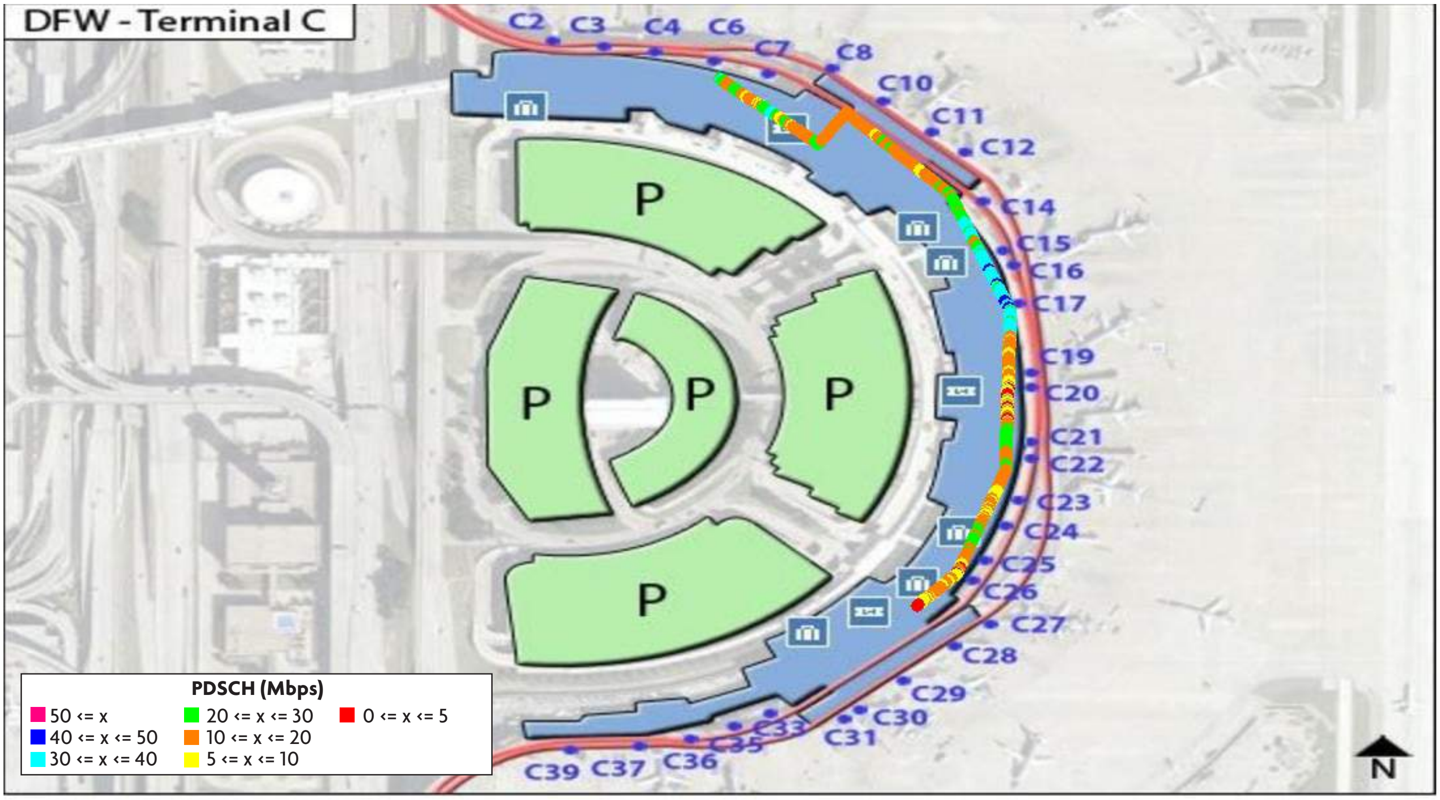
Figure 38. DFW Terminal E Rank Indicator and Modulation Scheme Distributions – Verizon Wireless and AT&T Pie Charts



Source: Signals Research Group

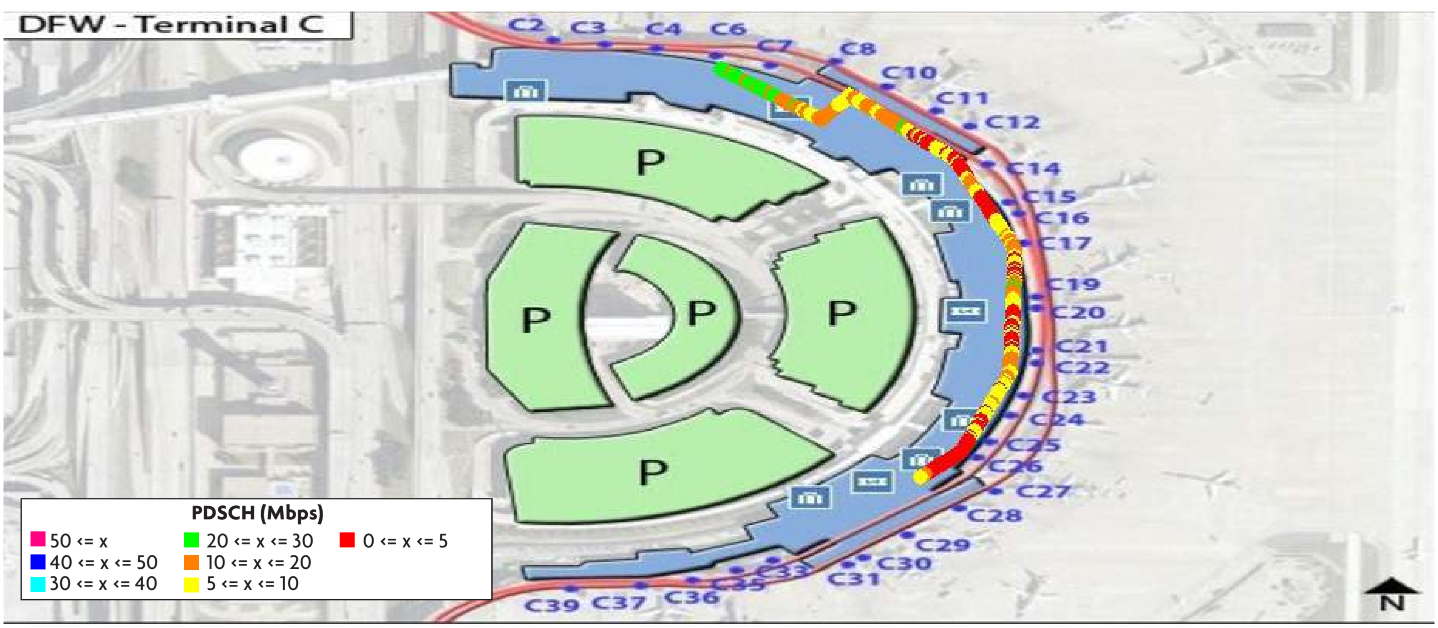
Figure 39 (AT&T) and Figure 40 (Verizon Wireless) map the throughput to the layout of DFW.

Figure 39.DFW Terminal E PDSCH Throughput – AT&T Geo Plot



Source: Signals Research Group

Figure 40. DFW Terminal E PDSCH Throughput – Verizon Wireless Geo Plot



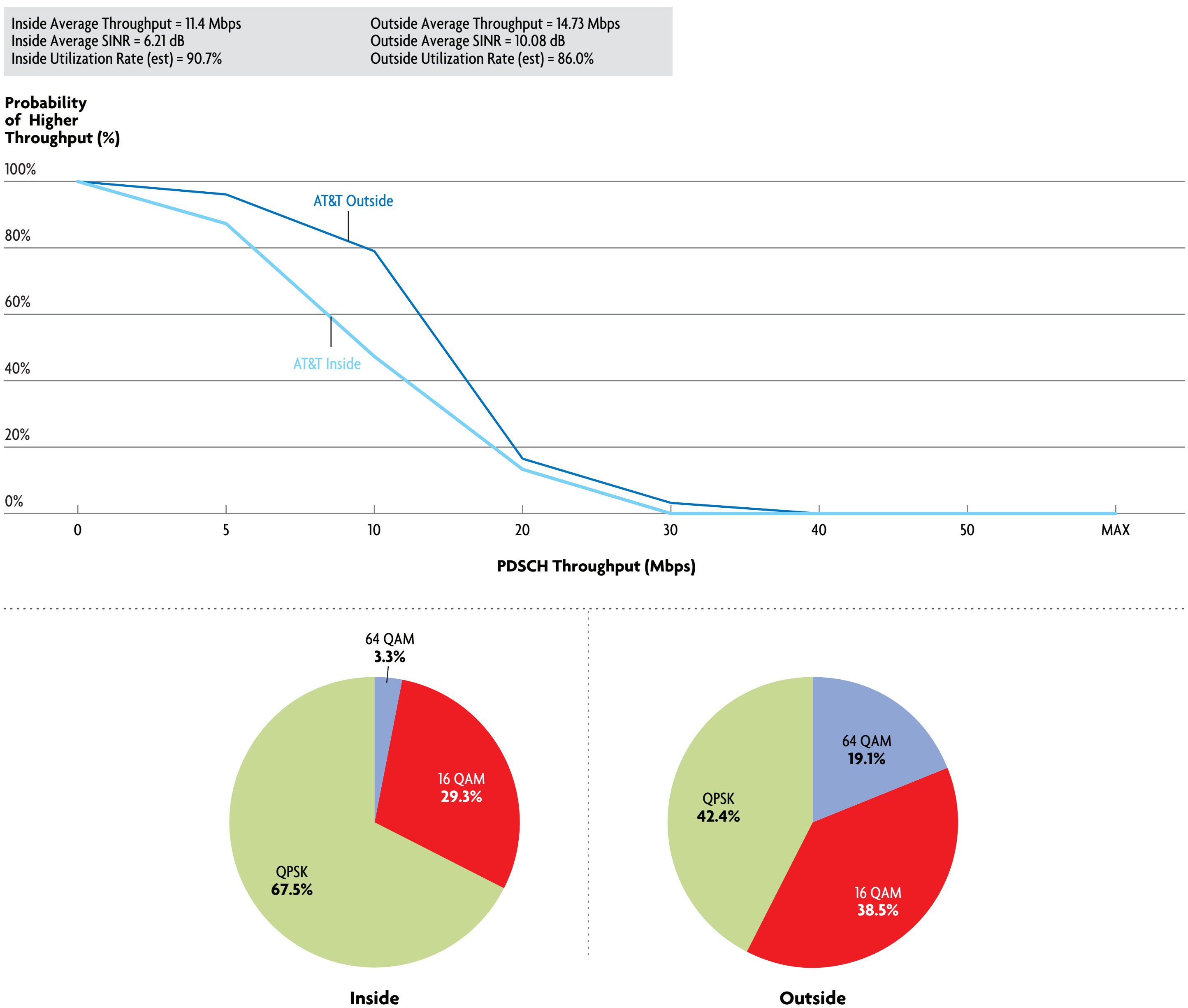
Source: Signals Research Group

4.3 Checking In?

Over the years we have spent far too much time at the Fairmont Hotel in downtown Dallas. In addition to the Informa LTE Americas event, there is always another industry analyst event that we attend each Fall. It was during this event that we took a little time to test the coverage and capacity inside the hotel and around its perimeter. We only tested the AT&T network.

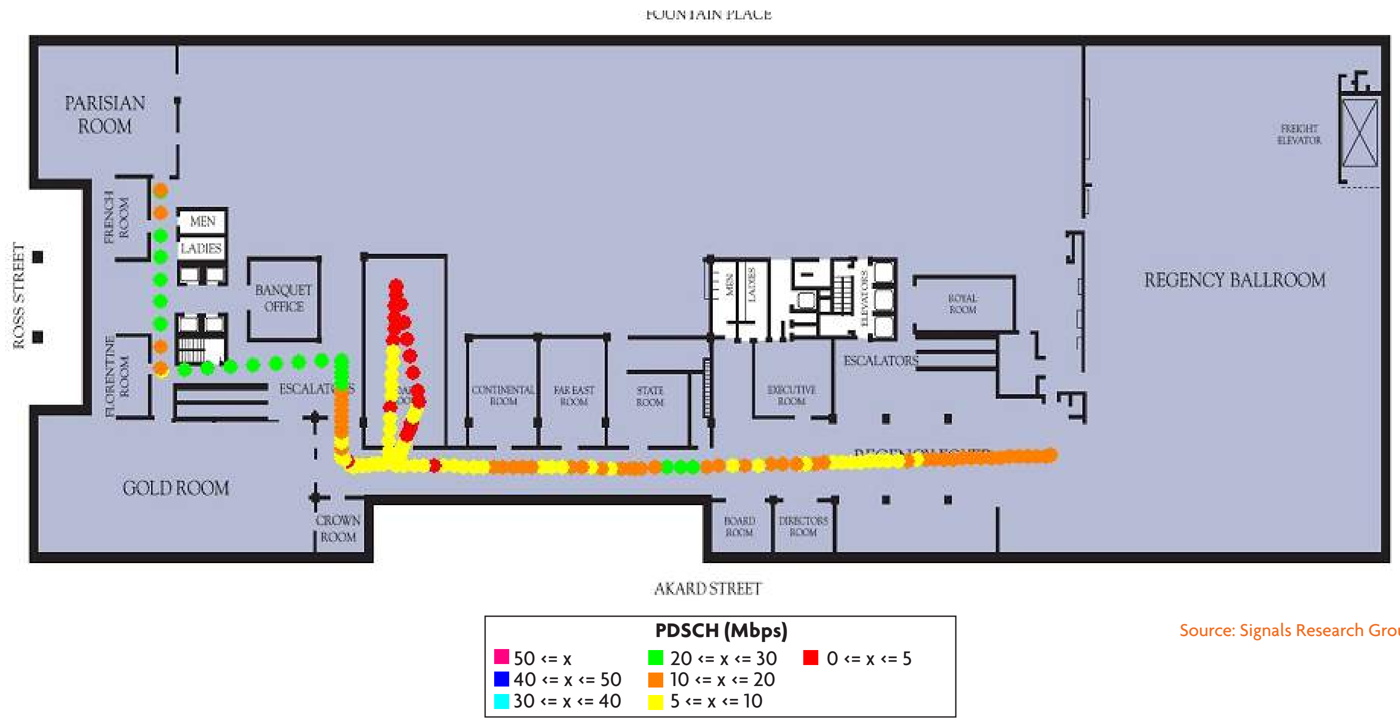
Figure 41 provides the probability plots for the PDSCH throughput inside of the hotel and around the outside perimeter of the hotel. The utilization rates were largely the same and the throughput, SINR and availability of 64 QAM favored the outside results as expected. The Fairmont Hotel does not have an in-building DAS solution. Figure 42 maps the throughput to the interior of the hotel. Figure 71, in the Appendix, provides a geo plot of the throughput around the perimeter of the hotel.

Figure 41. Fairmont Hotel PDSCH Throughput Results – Outside and Inside Probability Plots



Source: Signals Research Group

Figure 42. Fairmont Hotel PDSCH Throughput – AT&T Geo Plot



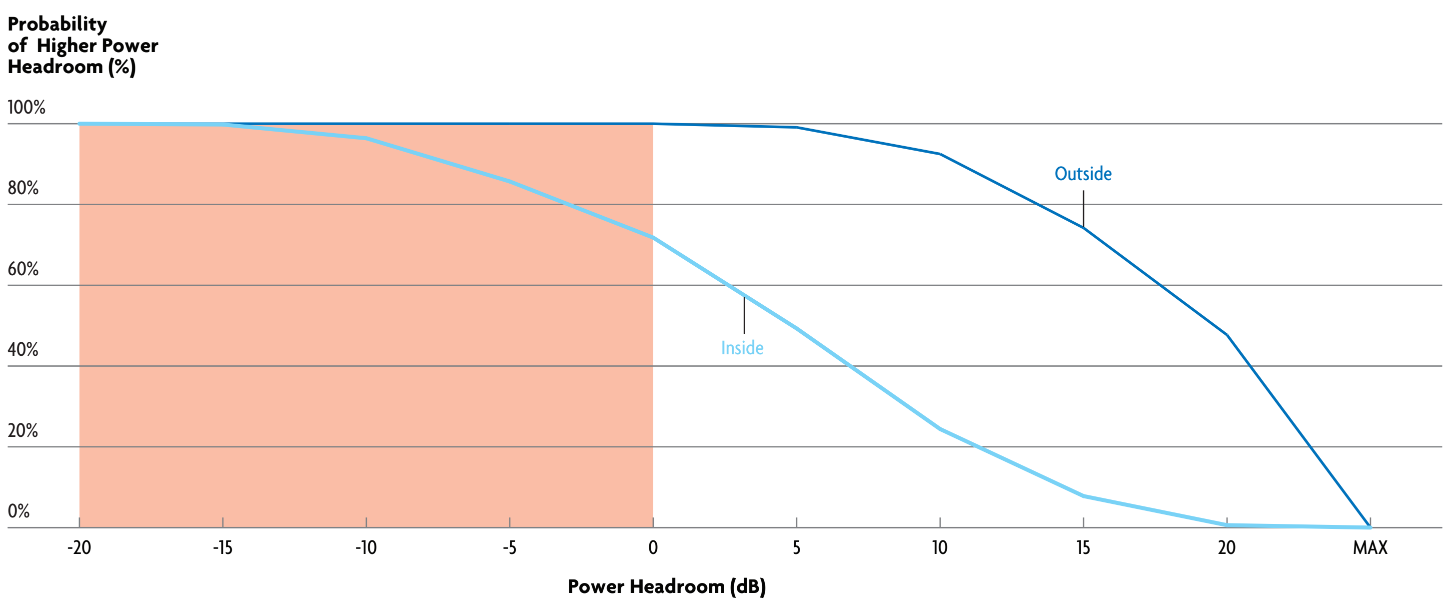
Source: Signals Research Group

Although we only conducted downlink throughput testing, the uplink still influenced the results within the hotel. This information is shown in Figure 43. Outside of the hotel the Power Headroom was always positive. Inside the hotel the probability was 28.2% that the Power Headroom was negative, indicating that the downlink throughput was artificially limited by uplink constraints. If we had been transferring data files in the uplink then the percentage of negative Power Headroom values would have been substantially higher.

Figure 43. Fairmont Hotel Power Headroom – Outside and Inside Probability Plots

Inside Average Power Headroom= 3.84 dB
Inside Probability of Negative Power Headroom = 28.2%

Outside Average Power Headroom = 19.5 dB
Outside Probability of Negative Power Headroom = 0%



Source: Signals Research Group

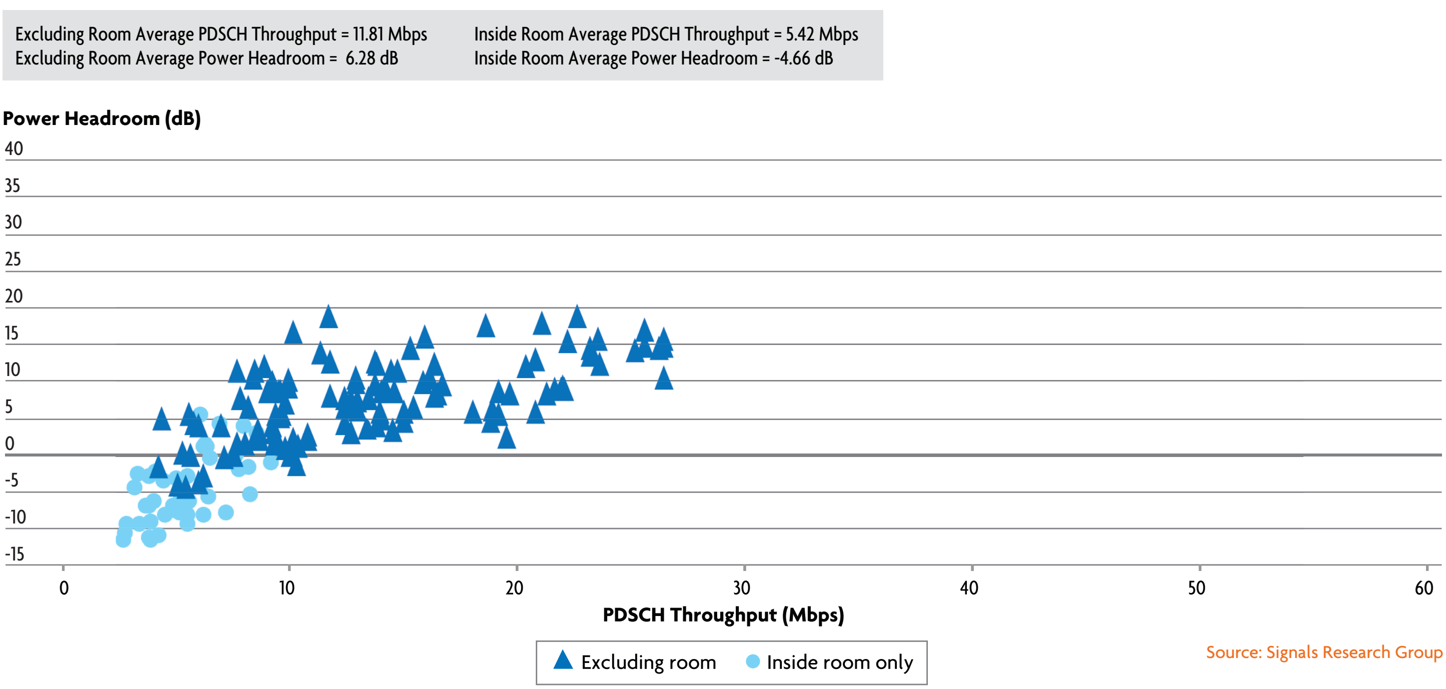
The poor performance that we measured within the Oak Room coincided with our personal experiences within this room when we attended the LTE Americas event.

Figure 43 doesn't tell the whole story since within the hotel the throughput and Power Headroom varied quite a bit. This observation is evident in Figure 42, which shows the throughput turning to red (sub 5 Mbps) in the Oak Room. In a consistent manner, the Power Headroom was also far more unfavorable in this room. In the Appendix (reference Figure 72), we show a geo plot of the Power Headroom throughout the interior of the hotel and it is evident that the Power Headroom impacted the performance within this room. Coincidentally, we spent the better part of two days in this room chairing a signaling workshop and moderating several panels during LTE Americas. Despite only modest amounts of data usage with our notebook computer, the battery didn't last very long. The same was true for our Samsung Galaxy S III. We show a geo plot of the PUSCH transmit power in Figure 73 in the Appendix, which reinforces our poor user experience.

Figure 44 and Figure 45 provide scatter plots of the PDSCH throughput as a function of the Power Headroom. In Figure 44 we have grouped the results into two buckets – the throughput and Power Headroom throughout the inside of the hotel, but excluding the Oak Room, and the throughput and Power Headroom within the Oak Room. It is evident that there was a distinct impact by being in the room. The average throughput was reduced 55% and the Power Headroom dropped by nearly 11 dB. Keep in mind that we are comparing results within the hotel.

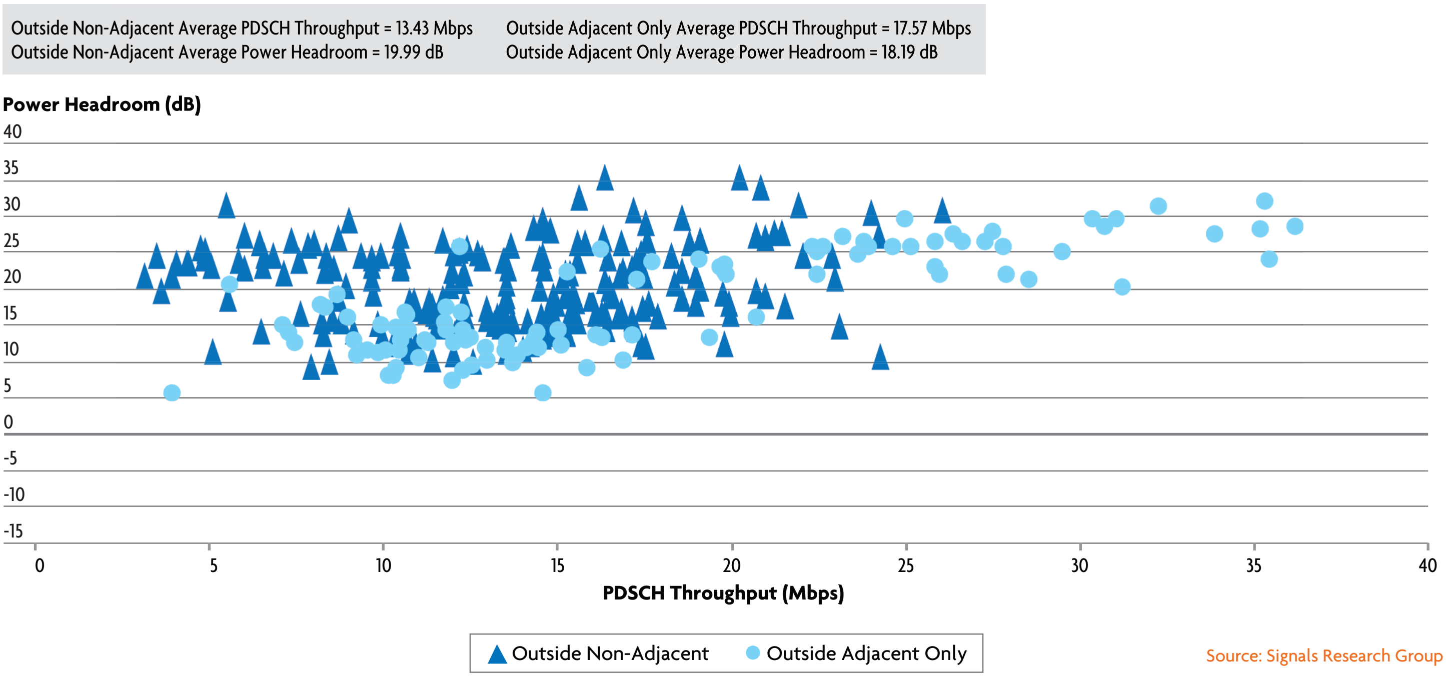
Figure 45 plots results from outside of the hotel. We have separately identified those results which were measured outside of the hotel on the same side of the building where we conducted our in-building testing. The "Outside Non-Adjacent" results reflect the performance on the backside of the hotel. Readers who want to compare the in-building performance with the outdoor performance should probably focus their attention on the "Outside Adjacent" results.

Figure 44. Fairmont Hotel Power Headroom – Outside Room and Inside Room Scatter Plots



Source: Signals Research Group

Figure 45. Fairmont Hotel Power Headroom – Outside Adjacent and Outside Non-Adjacent Scatter Plots



Source: Signals Research Group

4.4 Cleanup in Aisle 3

In the case of AT&T, the operator's HSPA+ network actually performed much better than its LTE network on occasion.

We tested both networks at the Westfield Mall in downtown San Francisco. The data for both networks potentially suggests that the in-building DAS solution was not supporting LTE. For example, we observed the same Serving Cell PCI values inside the mall as well as outside of the mall. At a minimum, if the operators were sharing a cell site's capacity between the macro network and the in-building DAS solution, then they had severely under-dimensioned their networks. Further, for both networks the results were generally quite poor. In the case of Verizon Wireless, our dongle switched to EV-DO Rev A on occasion. In the case of AT&T, the operator's HSPA+ network actually performed much better than its LTE network on occasion.

Figure 46 shows the downlink throughput probability plots for Verizon Wireless and Figure 47 shows the downlink throughput probability plots for AT&T. We excluded those floors where we only had very little data due to poor / no LTE coverage, since the data does not reflect the substantial periods of time when the dongle was in search mode. In the Appendix, we provide several figures which illustrate our point. In Figure 74, the portion of the test where we used LTE is shown by the light blue line. The green line shows the portion of the test where our dongle was connected to the EV-DO Rev A network. From what we have seen, the dongle won't return back to LTE until it is in the Idle state and given our test methodology this event will never happen until we terminate the test.

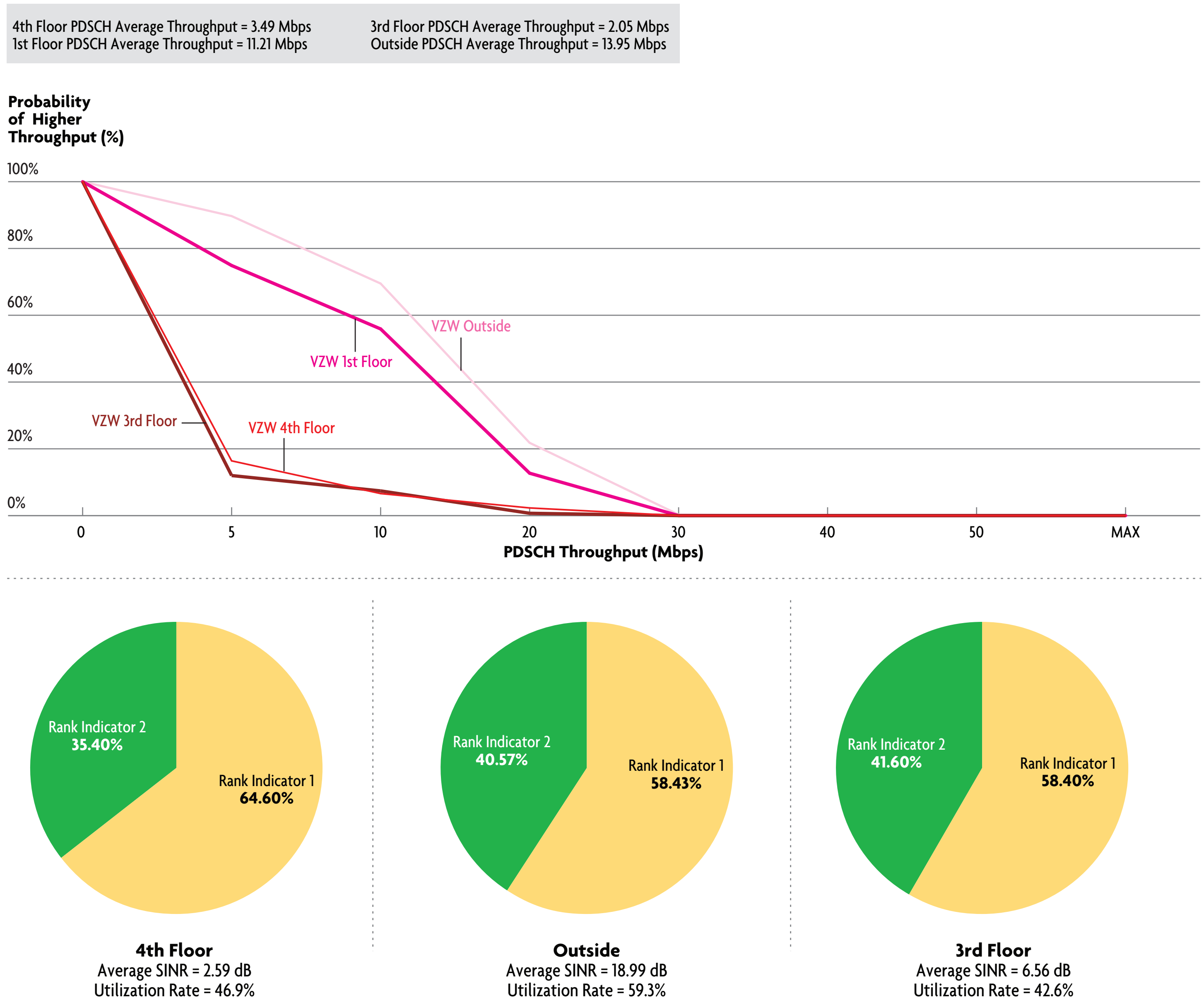
Figure 74 shows where the Pantech dongle switched to EV-DO Rev A and remained there for the duration of the test (the #2 point and the greenish line). Figure 75 (Verizon Wireless) and Figure 76 (AT&T) show spotty coverage on the Concourse Level. Figure 77 shows the substantially better performance of AT&T's HSPA+ network on the Concourse Level.

Figure 46 and Figure 47 provide a ton of information, but here are a few salient observations. On both networks there was a big difference between the outside and inside throughput with both operators having the best in-building throughput on the 1st Floor. We note that there is a BART station that connects to the shopping mall so we wouldn't rule out partial DAS coverage of the mall with LTE. In general the SINR in both networks was pretty poor inside the building.

The Westfield Mall results reflect far greater loading in the Verizon Wireless network than in the AT&T network.

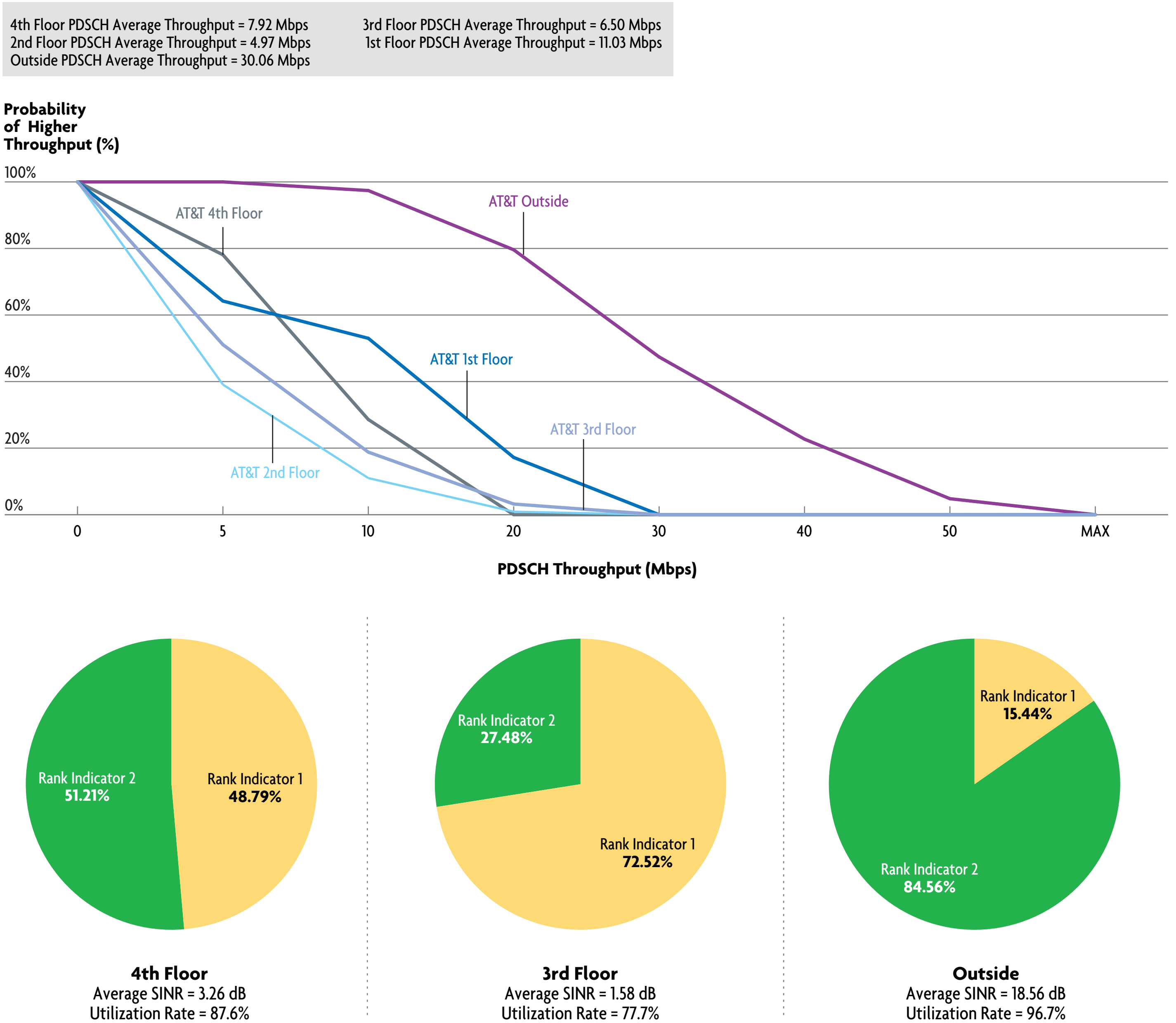
Finally, these results show a big difference in the implied loading of the two networks – note the much higher utilization rate in the AT&T network than the Verizon Wireless network. Using our methodology, this information suggests that the Verizon Wireless network had far more network traffic than in the AT&T network when we conducted these tests. In our outdoor test of the AT&T network the utilization rate was 96.7%, indicating that the network assigned virtually all of the potential sub-frames + Resource Blocks to our mobile device. Normalizing the AT&T throughput to the Verizon Wireless utilization rate, the outdoor throughput on the AT&T network would have been only 18.8 Mbps

Figure 46. Westfield Mall PDSCH Throughput – Verizon Wireless Probability Plots



Source: Signals Research Group

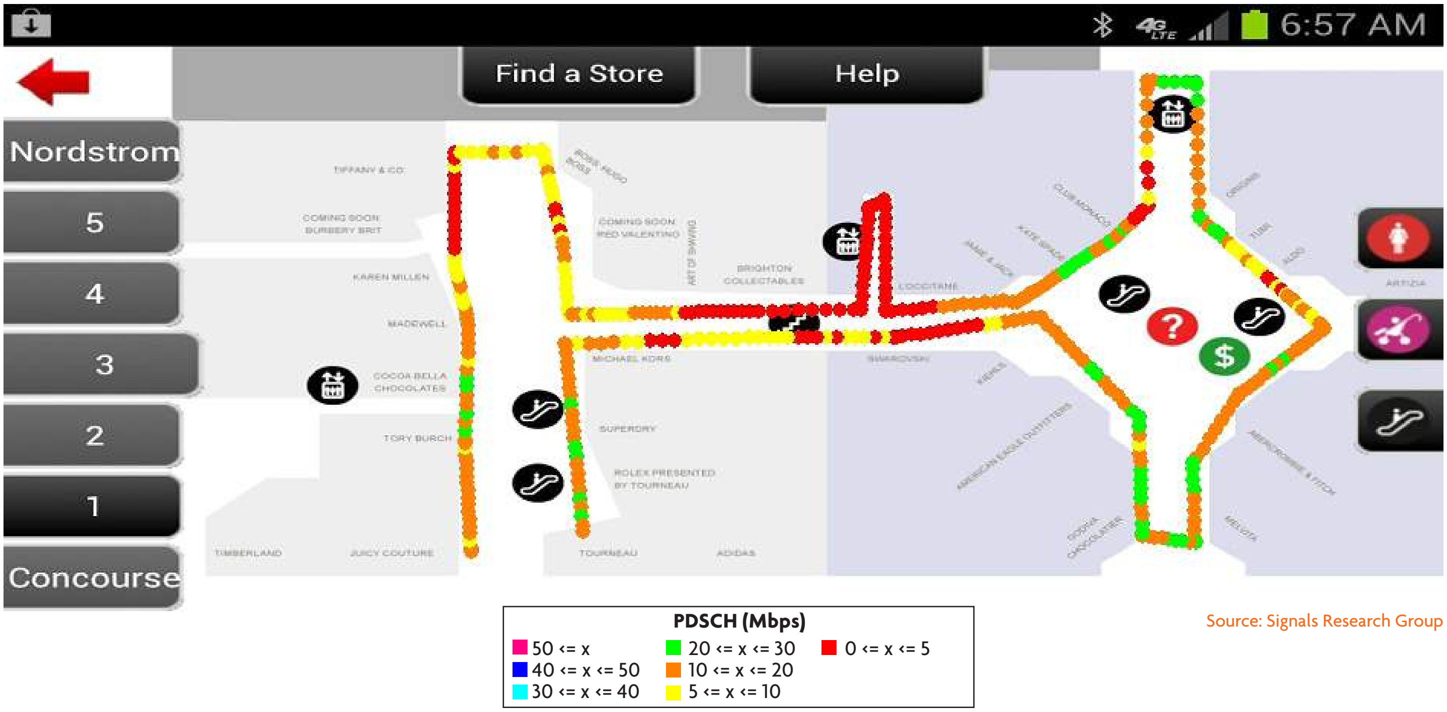
Figure 47. Westfield Mall PDSCH Throughput – AT&T Probability Plots



Source: Signals Research Group

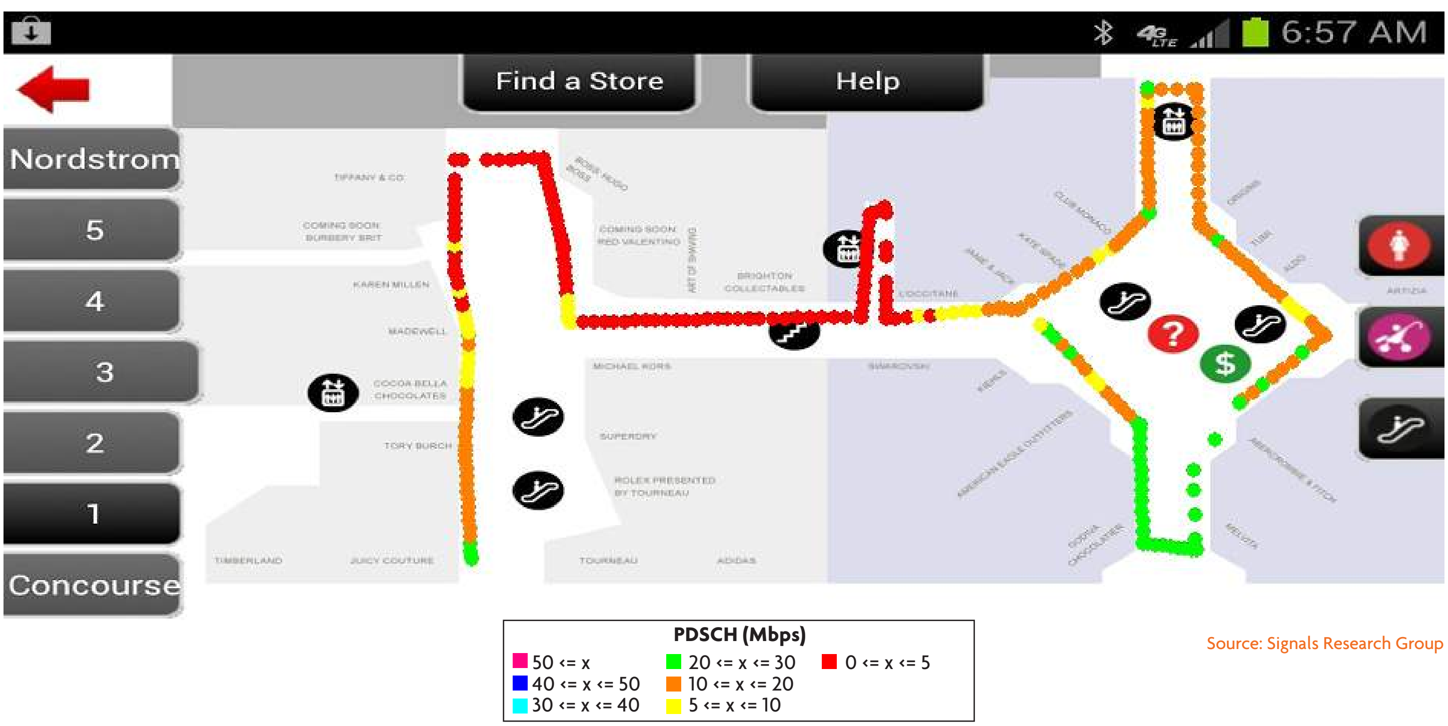
Figure 48 (Verizon Wireless) and Figure 49 (AT&T) provide plots of the throughput and how it maps to the first floor of the shopping mall.

Figure 48. Westfield Mall First Floor PDSCH Throughput – Verizon Wireless Geo Plot



Source: Signals Research Group

Figure 49. Westfield Mall Floor PDSCH Throughput – AT&T Geo Plot

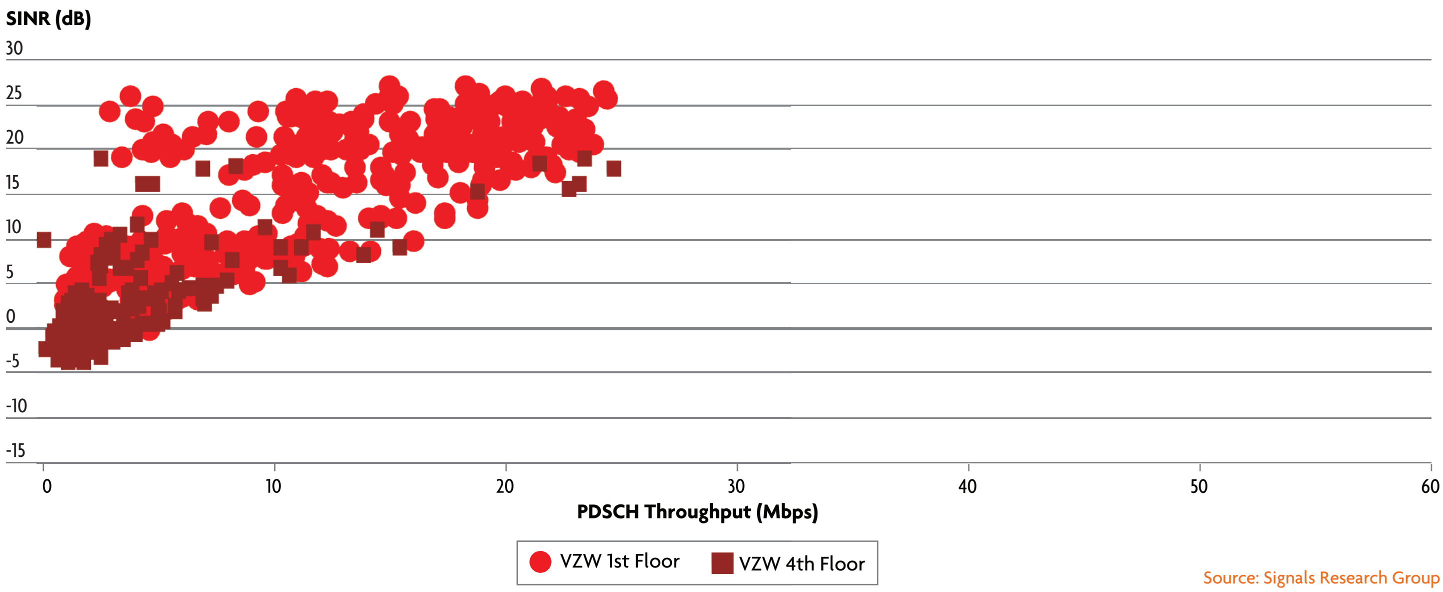


Source: Signals Research Group

The next four figures (Figure 50 through Figure 53) provide scatter plots for both operators of the PDSCH throughput as a function of the SINR. For both operators we include results from two floors within the mall and the results from testing the perimeter of the shopping mall. In general the results are consistent and they demonstrate that the low throughput was due to the low SINR. Additionally, it is evident that in the AT&T network the throughput increased more substantially when the SINR became more favorable. In the Verizon Wireless network once the SINR hit ~15-20 dB the throughput reached its peak.

Figure 50. Westfield Mall Inside SINR versus PDSCH Throughput – Verizon Wireless Scatter Plot

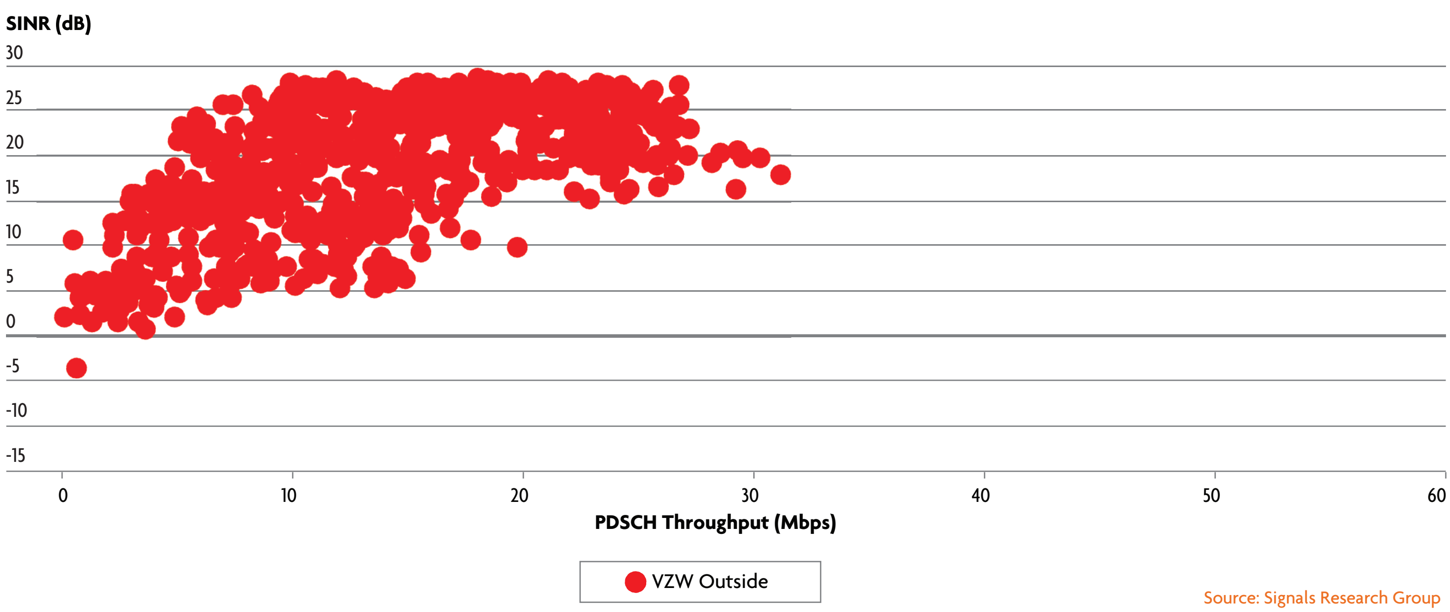
1st Floor Average PDSCH Throughput = 11.21 Mbps
1st Floor Average SINR = 15.4 dB
4th Floor Average PDSCH Throughput = 3.49 Mbps
4th Floor Average SINR = 2.59 dB



Source: Signals Research Group

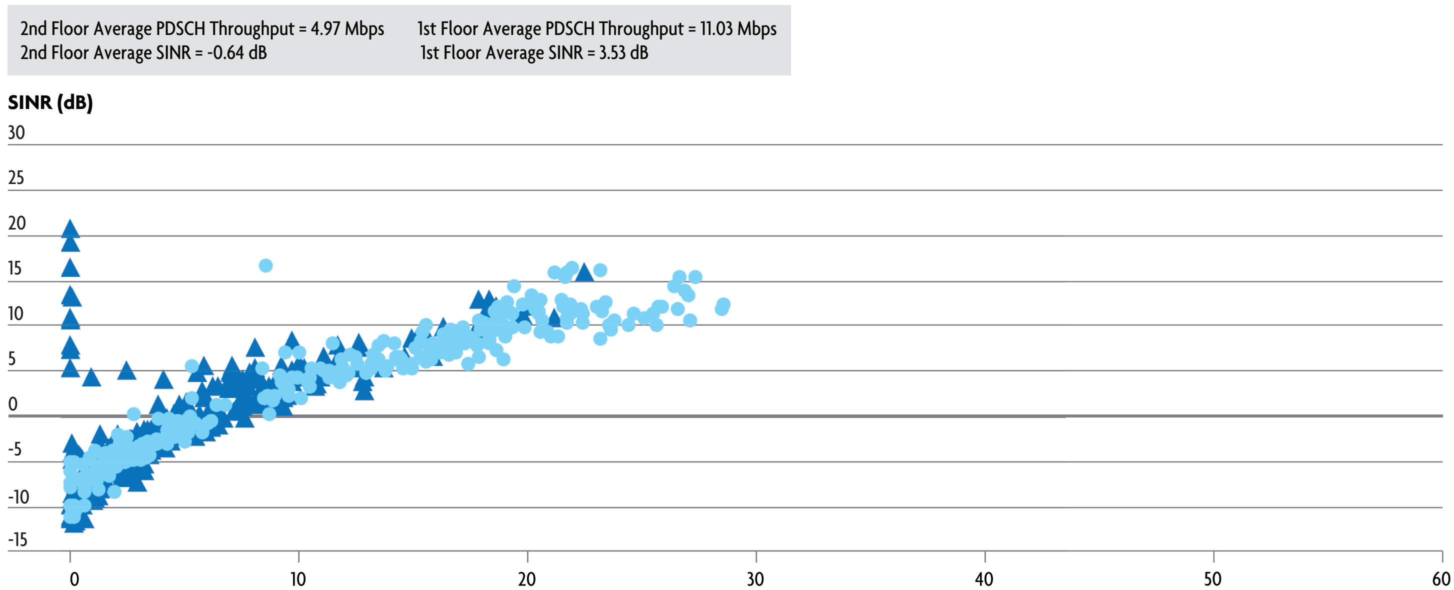
Figure 51. Westfield Mall Ouside SINR versus PDSCH Throughput – Verizon Wireless Scatter Plot

Outside Average PDSCH Throughput = 13.95 Mbps
Outside Average SINR = 18.99 dB



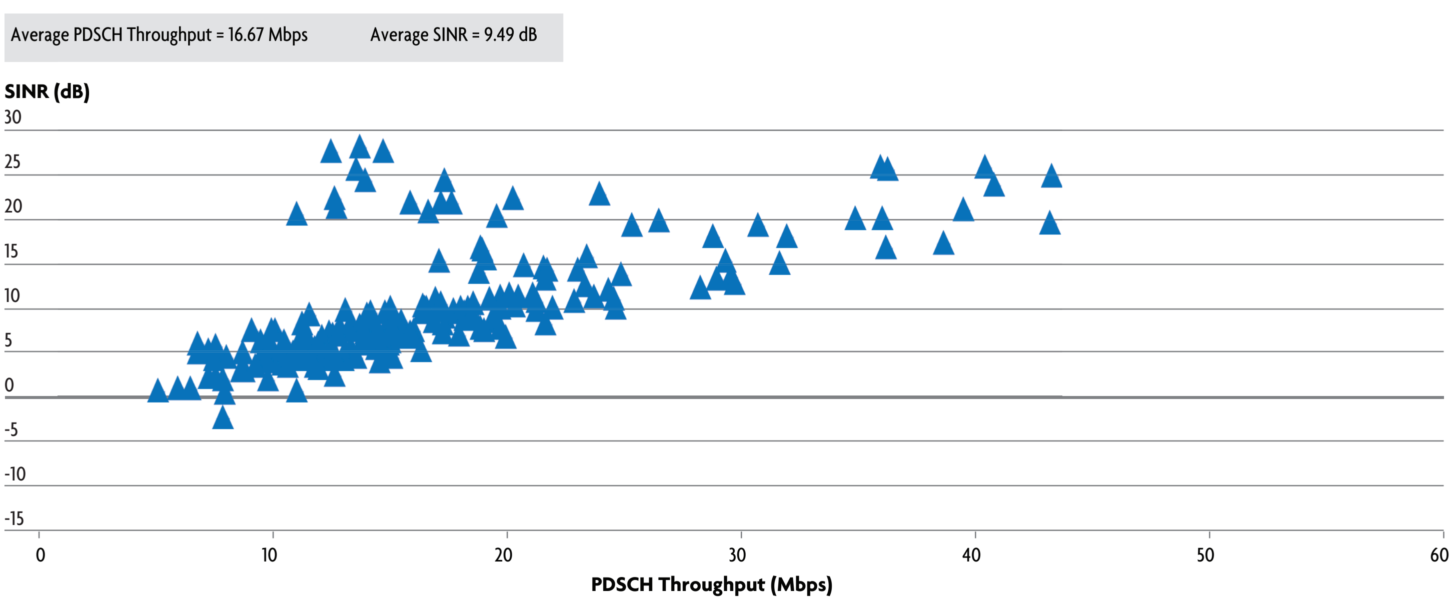
Source: Signals Research Group

Figure 52. Westfield Mall Inside SINR versus PDSCH Throughput – AT&T Scatter Plot



Source: Signals Research Group

Figure 53. Westfield Mall Outside SINR versus PDSCH Throughput – AT&T Scatter Plot

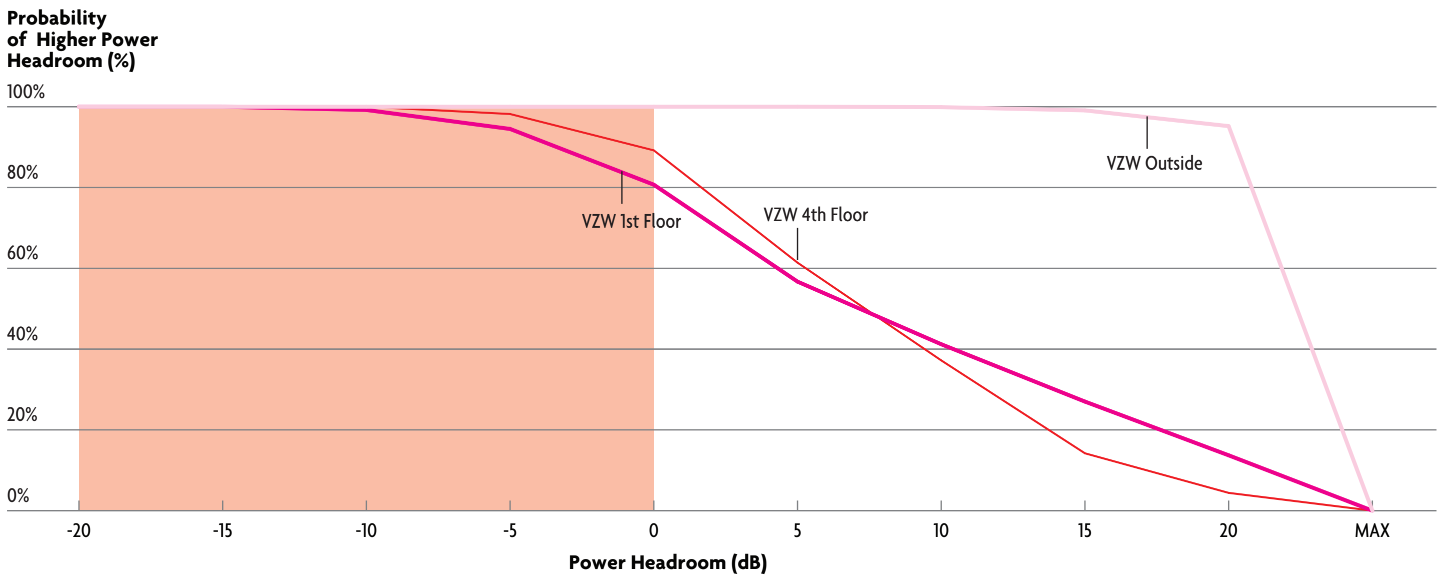


Source: Signals Research Group

Finally, the last two figures provide probability plots of the Power Headroom. Outside of the shopping mall, the Power Headroom was always positive in both networks. Within the shopping mall, the Power Headroom value was frequently negative. This situation was more likely to occur in the AT&T network.

Figure 54. Westfield Mall Power Headroom – Verizon Wireless Probability Plots

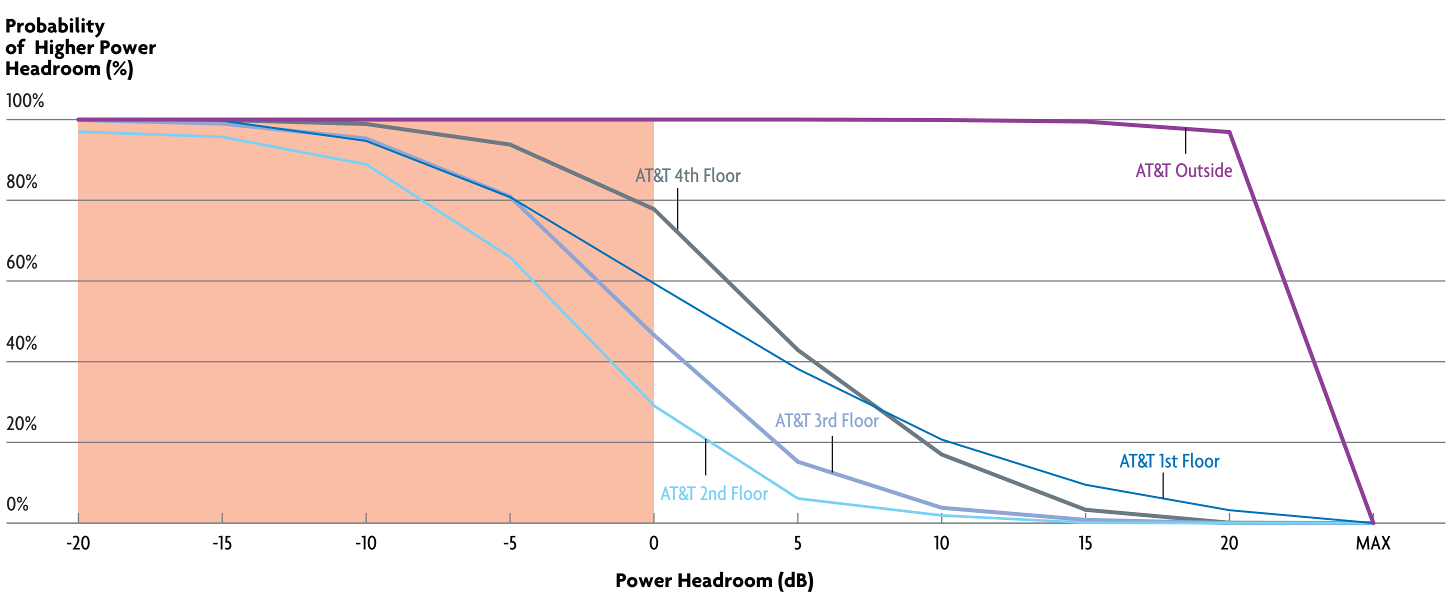
Outside Average Power Headroom= 34.69 dB   1st Floor Average Power Headroom = 8.11 dB
4th Floor Average Power Headroom = 7.35 dB



Source: Signals Research Group

Figure 55. Westfield Mall Power Headroom – AT&T Probability Plots

Outside Average Power Headroom= 32.49 dB   1st Floor Average Power Headroom = 2.33 dB
2nd Floor Average Power Headroom = -3.8 dB   3rd Floor Average Power Headroom = -0.95 dB



Source: Signals Research Group

5.0 Test Methodology

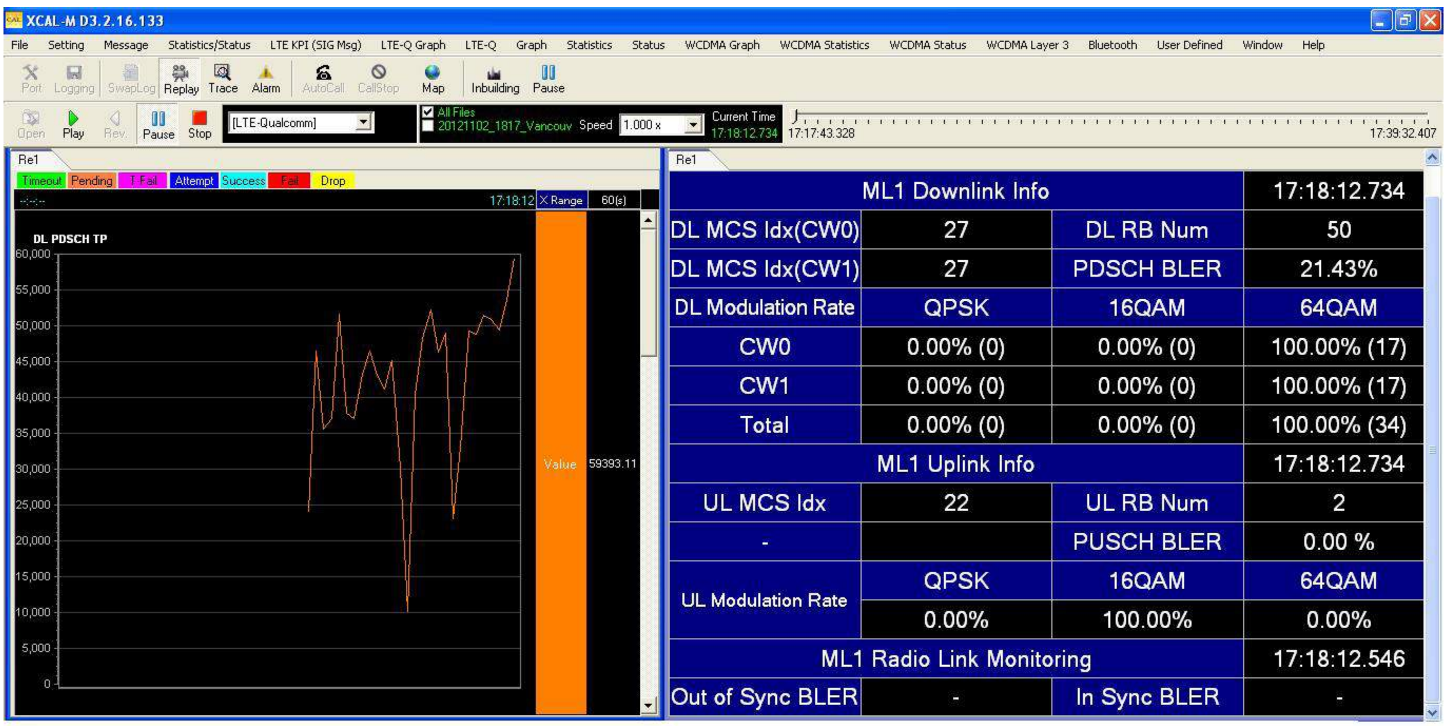
The Accuver data collection and post-processing tools support in-building testing.

For all of the drive tests we once again used the Accuver XCAL-M drive test tool to collect the underlying performance indicators and to conduct the user experience tests.

We also used the Accuver XCAP post-processing tool to analyze the data and to help us create the figures which appear in this report. Both the data collection and post-processing tools support in-building testing and these features proved to be invaluable when putting together this report and in the preliminary work that we have already done for our dedicated report on in-building performance.

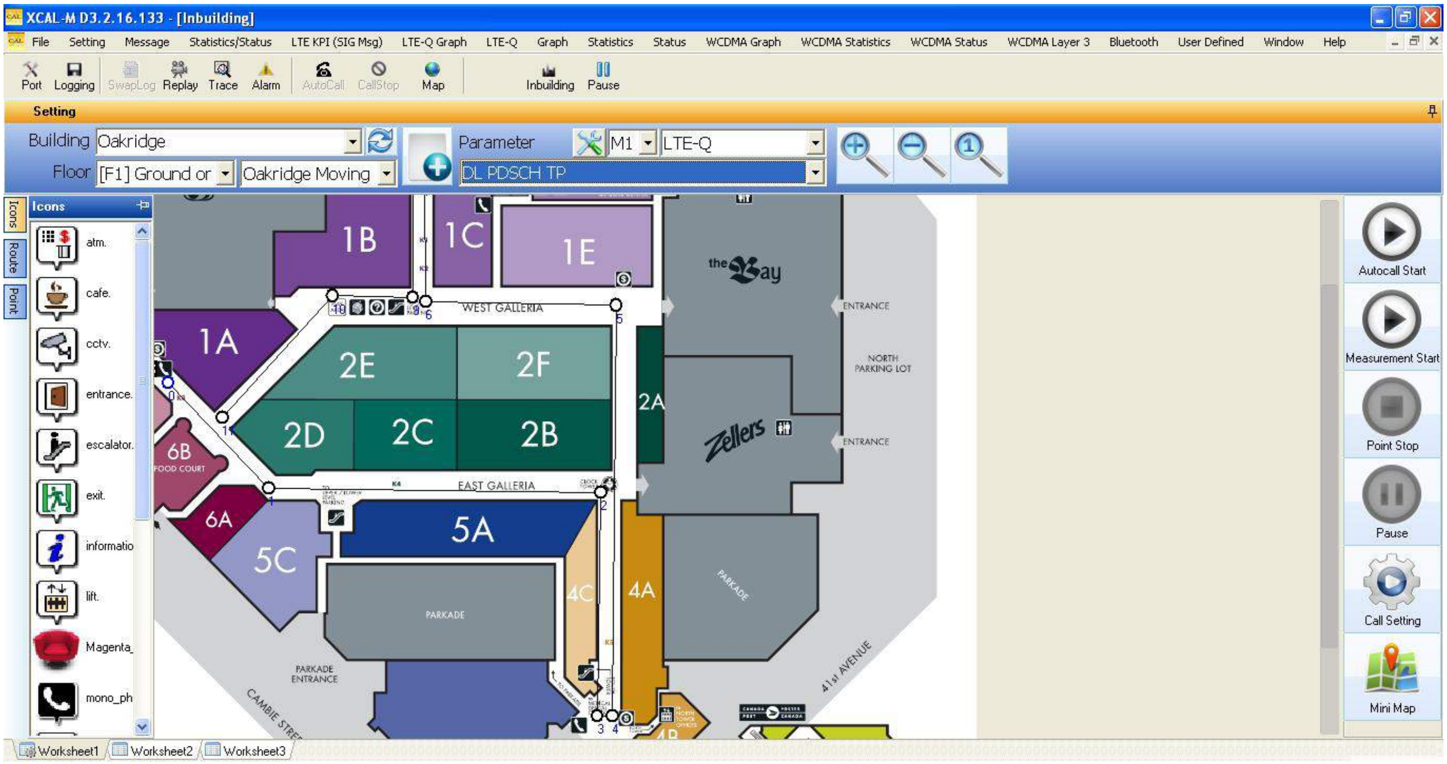
Figure 56 illustrates a typical user display that we used when collecting the data. The information in the figure stems from one of the drive tests that we did in Vancouver in the Band 4 network. The figure shows just a few of the KPIs that we collected and analyzed in this study.

Figure 56. XCAL-M Drive Test Tool in Action – DL performance



Source: Accuver XCAL and SRG

Figure 57. XCAL-M Drive Test Tool in Action – In-building



Source: Accuver XCAL and SRG

For the in-building testing we obtained facility's maps of the buildings where we wanted to conduct our tests from the Internet. For logistical reasons, we selected publicly accessible buildings. We loaded a JPG image of area within the building that we wanted to test (e.g., the first floor of a hotel) into XCAL-M and then traced out a walking route as an overlay on top of the map. In addition to the route, we marked event points at various spots along the route that we would later use during the actual data collection and in the analysis phase.

Once we started the in-building test, it was simply a matter of following the planned route and clicking a button in XCAL-M to mark the timestamp in the log file when we reached a particular event point that we identified on the map. An event point, for example, could be a stairwell or elevator, a storefront in a shopping mall (e.g., Apple), or a hallway – anything that would be easily recognizable along the route and identified on the map. It is also possible to insert landmarks on the map with the XCAL-M solution, but we felt that the maps we had obtained were already sufficient for our purposes. Once an event point was marked, the previously collected data since the last event point was spread equally between the two points, thereby negating the need for GPS, while still allowing us to link each data point in the log file to the location where it was observed. Figure 57 shows a route that we traced out in the Oakridge Mall. In addition to the route, the event points are visible as well as the feature which allows the user to add more icons/landmarks onto the map.

We were able to lock the Sierra Wireless dongles to a specific technology + band combination, but we didn't have this ability with the Pantech dongle.

Rogers Wireless provided us with two dongles and unlimited access to its network. Thanks to a prior analyst loaner program, we had the use of a SIM card with unlimited access from AT&T. However, we purchased both Sierra Wireless dongles that we used on its network and we also used our personal SIM card in many test scenarios. For Verizon Wireless, we used the Pantech dongle that we purchased along with our own SIM card. We were able to configure the Sierra Wireless dongles so that they could be locked to a specific LTE band or a single band in the case of AT&T. We didn't have this ability with the Pantech dongle so on a few cases the dongle inadvertently switched to EV-DO Rev A. We used an FTP server that Rogers Wireless provided us when we tested its network. We augmented that server with a couple of additional servers that we could access. For the US testing we relied exclusively on these additional servers since we no longer had access to the Rogers server.

Like all Signals Ahead reports, we received no sponsorship or funding from the impacted companies in this report, in order to maintain our independence.

Like all *Signals Ahead* reports, we received no sponsorship or funding from the impacted companies in this report in order to maintain our independence. As such, we foot the bill for all of our travel expenses not to mention an inordinate amount of time and effort collecting the data and writing this report. We also could not have done this report without the support of Accuver who provided us with its suite of drive test tools and post-processing software. SRG takes full responsibility for the analysis and conclusions that are documented in this report.

6.0 Conclusions

When LTE networks at 700 MHz were first being discussed the spectrum + technology combination was viewed as a panacea that would solve all of the operator's coverage and capacity problems. The reality is somewhat different.

Regardless of the frequency band, LTE can provide great outdoor coverage if it is deployed on a one-for-one grid on the operator's existing cell site grid – assuming the operator had good coverage to start. We demonstrated this point in our testing of the Rogers Wireless network when we showed that the edge of cell throughput in Band 7 was frequently as high, if not higher, than the Band 4 throughput. The wider channel allocation in Band 7 than Band 4 (20 MHz versus 10 MHz) played a huge role in the outcome, but given that most operators will be deploying the same type of network configuration the unfair comparison is still valid with the important caveat.

We observed strong evidence of higher network loading inside the various buildings that we tested than we observed in the outdoor macro network.

The problem(s) starts to develop when the subscriber moves indoors and/or when the traffic density increases and the network becomes more loaded. Based on the testing that we have done, it appears that in aggregate the outdoor networks were generally lightly loaded although there could have been errant hot spots where network congestion existed. Conversely, we observed strong evidence of higher network loading inside the various buildings that we tested than we observed in the outdoor macro network, due to the combination of more data users and/or an under-dimensioned network that lacked ample capacity. If anything, we were surprised at how quickly the network performance degraded for what we considered to be a relatively modest increase in network traffic (e.g., a lower utilization rate).

In either the outdoor or indoor scenarios, the impact of more data traffic is two-fold. First, the number of available network resources is reduced so the user throughput is limited. Second, the higher traffic levels increase the interference levels and this situation makes the remaining network resources less efficient. The network has to assign lower modulation and coding schemes and the ability to assign MIMO decreases. A double whammy if you will.

Once the outdoor / indoor networks start to experience heavier loading the sometimes hidden coverage constraints that exist today will manifest themselves into capacity constraints.

Solving the indoor coverage and capacity problem doesn't work from the outside looking in. In some cases the in-building throughput can be quite high when the in-building coverage is provided by the outdoor macro network, but it is also evident in the results that the throughput was being limited due to coverage constraints (e.g., negative Power Headroom values). Once the outdoor / indoor networks start to experience heavier loading the sometimes hidden coverage constraints that exist today will manifest themselves into capacity constraints and user throughput will suffer.

The operators' first line of attack when it comes to improving the coverage + capacity of their LTE networks will start on the inside, looking out.

Even with an in-building solution, capacity problems will still develop. We have already documented numerous instances when the throughput was very low due to a combination of high interference and limited network resources. Without knowing the specific details of what these operators have or haven't done to address in-building coverage in the buildings that we tested, it is hard to speculate on what immediate steps they should take. However, it is evident that their first line of attack when it comes to improving the coverage + capacity of their LTE networks will start on the inside, looking out. In all probability it will involve a combination of DAS-like solutions for coverage + capacity plus an additional layer of small cells to provide the necessary capacity that cannot be met by the legacy in-building solutions. The exact mix of the two solutions will depend on a combination of the operator's philosophy, the availability of solutions that meet the operator's stringent requirements, basic economics (the solution which is more cost effective in the long run), and the distribution of traffic throughout the building.

We have identified a list of pending research topics that we are currently considering or presently working on completing. The topics at the top of the list are definitive with many of them already in the works. The topics toward the bottom of the page are a bit more speculative. Obviously, this list is subject to change based on various factors and market trends. As always, we welcome suggestions from our readers.

- RCS and its impact on networks
- LTE chipset performance benchmark test results
- TD-LTE network and chipset performance benchmark results
- Multi-vendor LTE network benchmark study
- Self-Optimizing Networks (SON)
- Smartphone signaling implications across operating systems
- How network performance (throughput and latency) impacts the user experience
- Transmission Mode 3 versus Transmission Mode 4 in a Live Network and Test Lab
- The impact of Type 3i receivers on UE performance (includes chipset benchmark tests of leading solutions)
- Smartphone signaling implications and LTE
- HSPA+ (MIMO) network performance benchmark results
- The challenges of delivering video in a mobile network
- Cloud RAN and the use of a Distributed Network Architecture
- Public Safety Options with 700MHz
- LTE chipset landscape

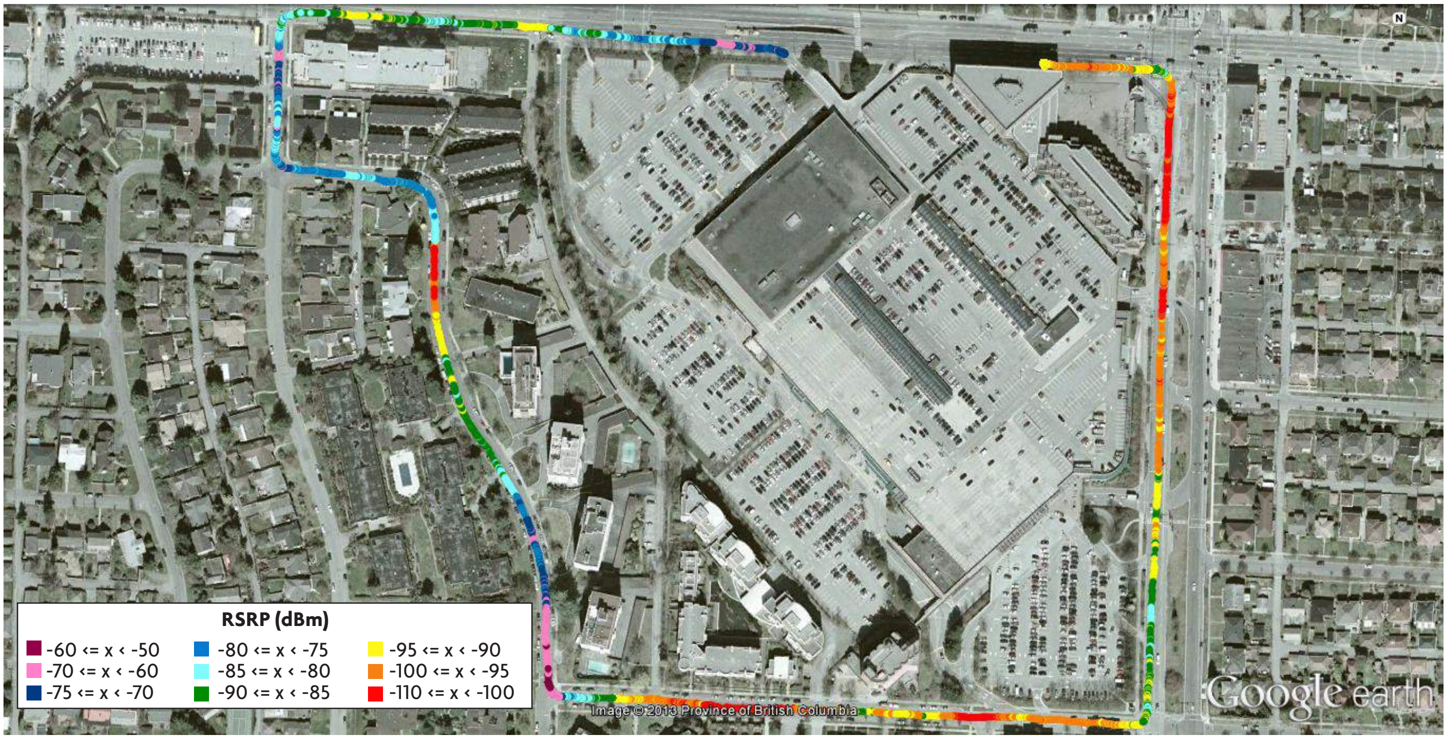
Until next time, be on the lookout for the next *Signals Ahead*….

7.0 Appendix

In the appendix we include several figures that didn't make their way into the main report. Since these figures were already referenced, we are not providing much in the way of additional commentary.

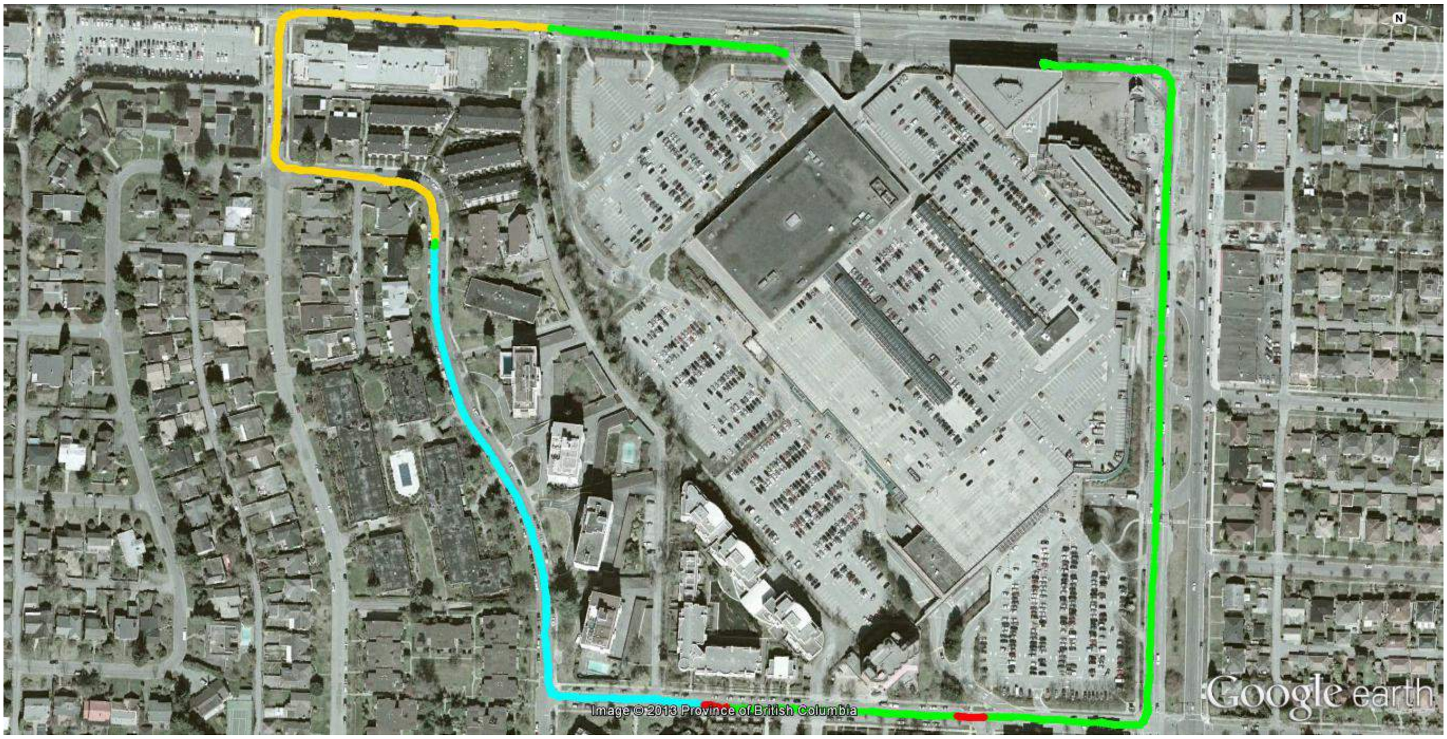
Figure 58 through Figure 64 provide results from testing in Vancouver.

Figure 58. Outside Perimeter of the Oakridge Mall RSRP Values – Band 7 Geo Plot



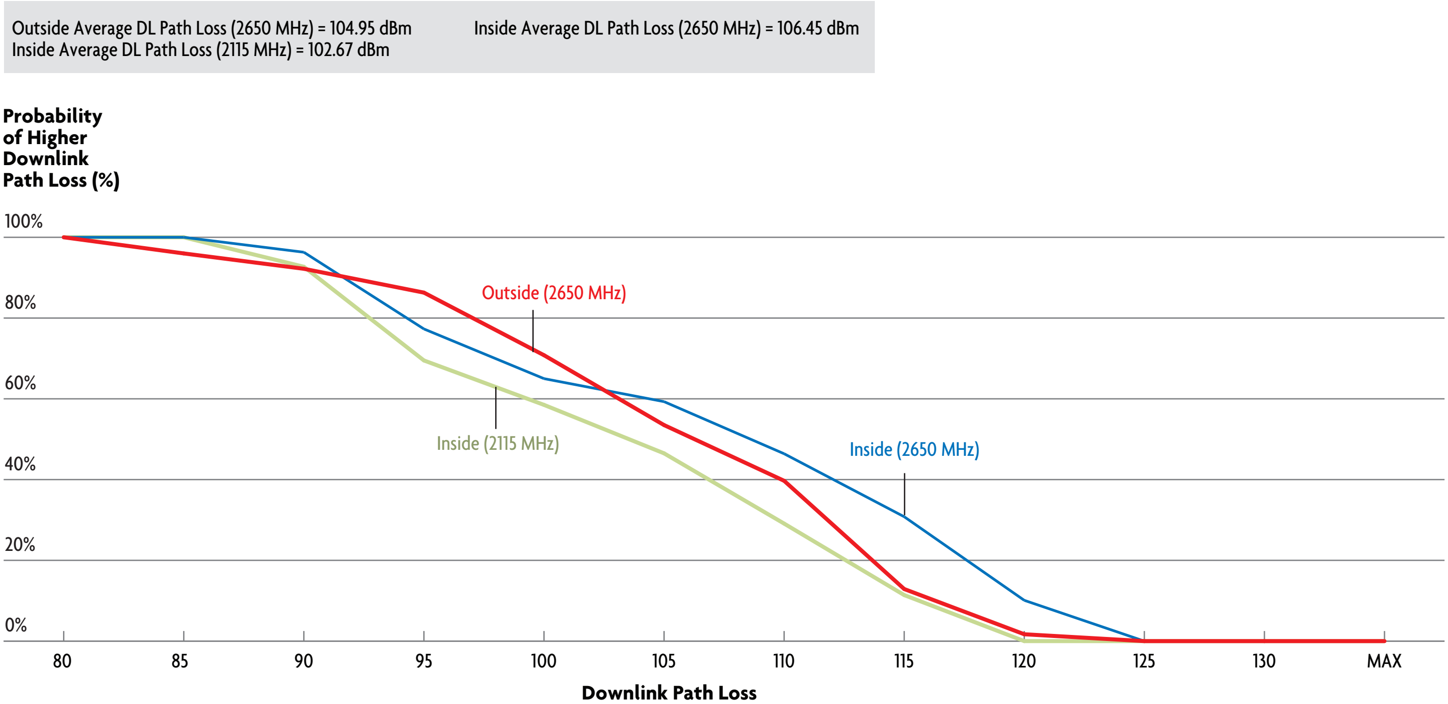
Source: Signals Research Group

Figure 59. Outside Perimeter of the Oakridge Mall Serving Cell PCI – Band 7 Geo Plot



Source: Signals Research Group

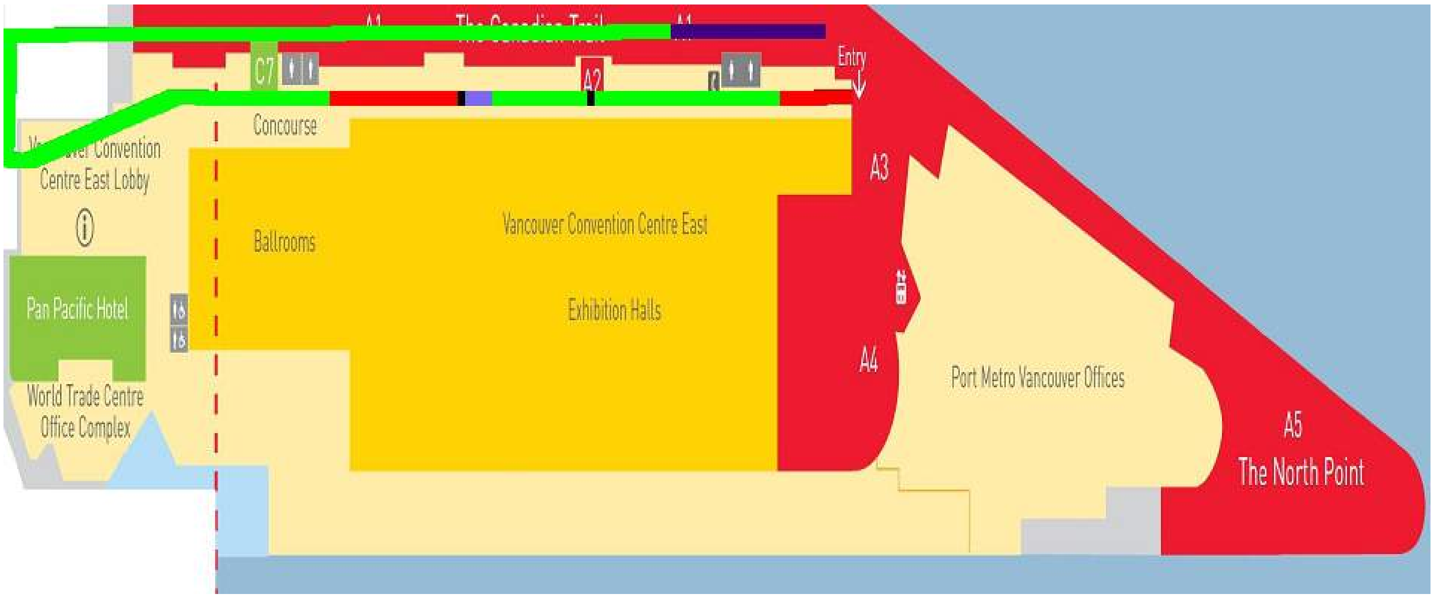
Figure 60. Oakridge Mall Downlink Path Loss – Band 7 and Band 4 Probability Plots



Source: Signals Research Group

In Figure 61, each PCI is depicted by a different color so it is possible to identify where each cell site/sector provided coverage. The figure also shows that when we finished the test our dongle was using a different cell site/sector than when we started the test.

Figure 61. Canada Place Convention Center Serving Cell PCI – Band 7 Geo Plot



Source: Signals Research Group

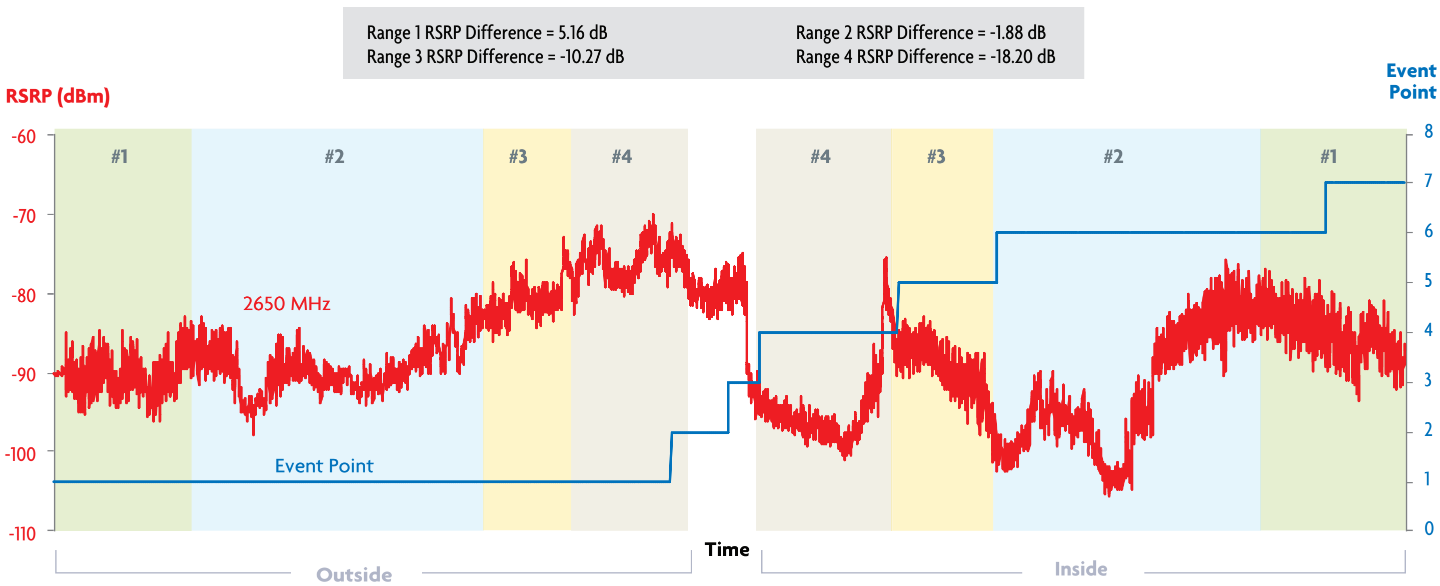
Figure 62. Canada Place Convention Center RSRP – Band 7 Geo Plot

RSRP (dBm)

-60 <= x < -50	-80 <= x < -75	-95 <= x < -90
-70 <= x < -60	-85 <= x < -80	-100 <= x < -95
-75 <= x < -70	-90 <= x < -85	-110 <= x < -100

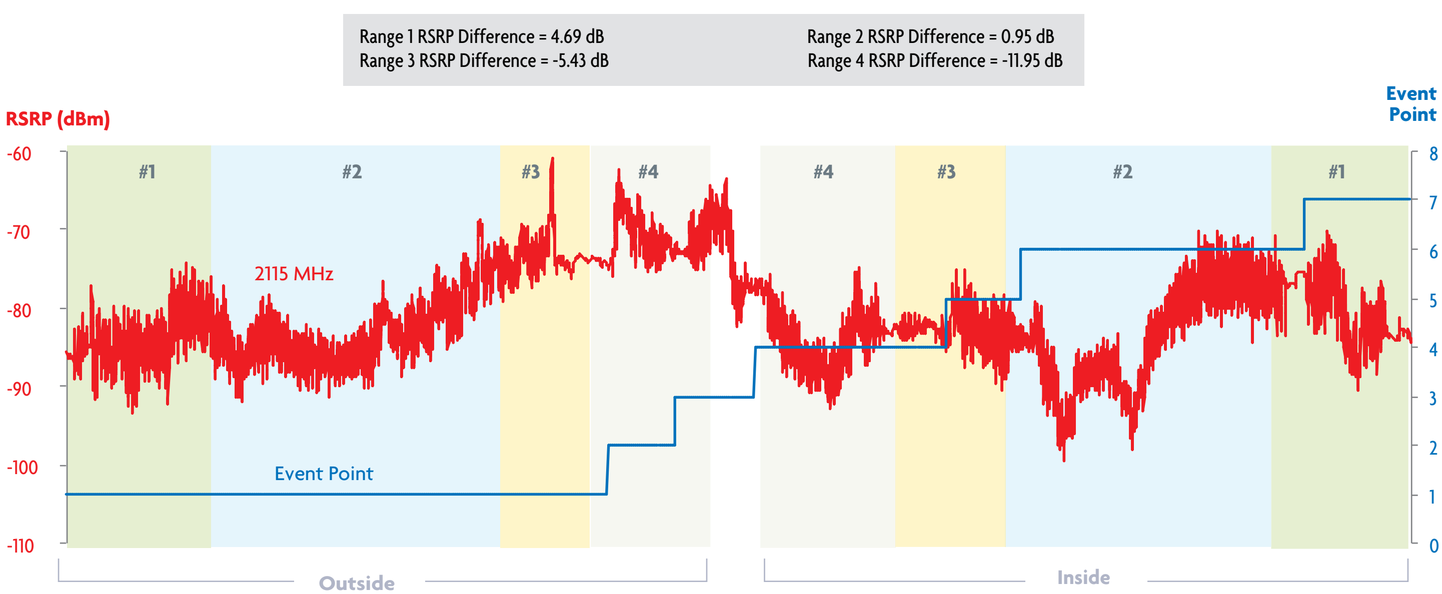
Source: Signals Research Group

Figure 63. Canada Place RSRP – Band 7 Time Series Plot with Location Tags



Source: Signals Research Group

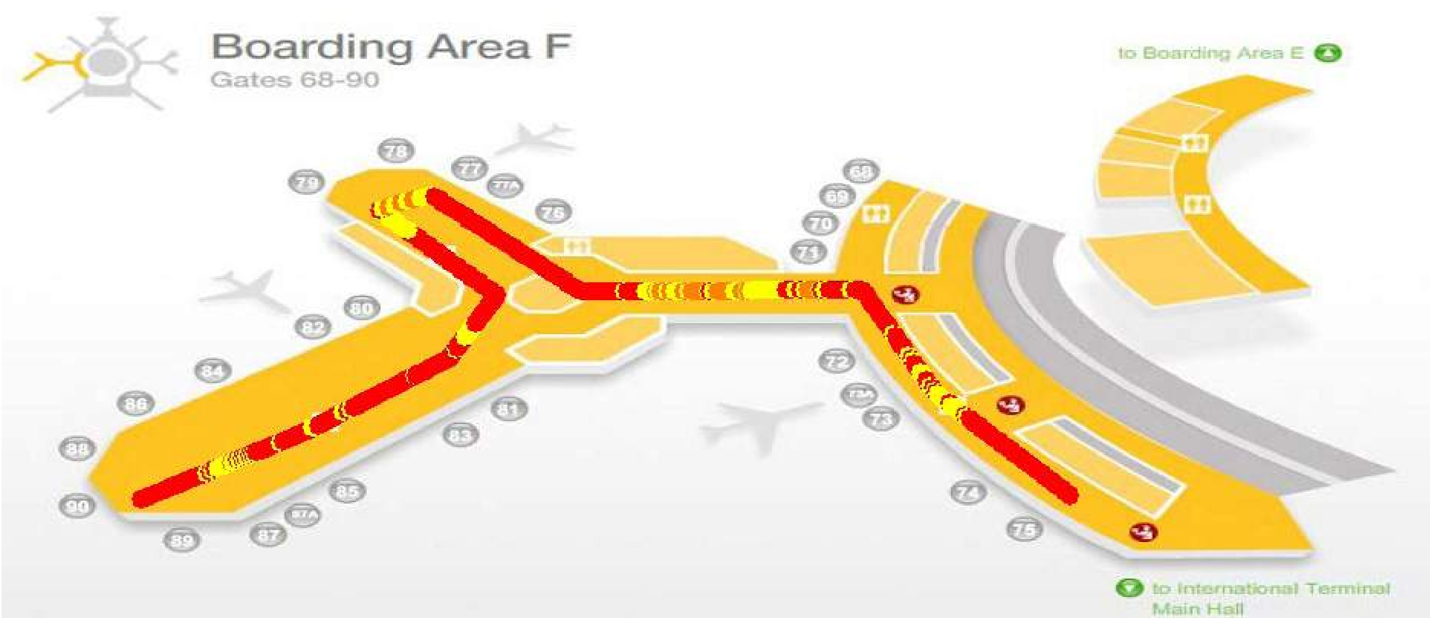
Figure 64. Canada Place RSRP – Band 4 Time Series Plot with Location Tags



Source: Signals Research Group

Figure 65 and all remaining figures stem from our testing of the Verizon Wireless and AT&T networks in the United States.

Figure 65. SFO Terminal 3 PDSCH – AT&T Geo Plot



Source: Signals Research Group

PDSCH (Mbps)

50 <= x
40 <= x <= 50
30 <= x <= 40
20 <= x <= 30
10 <= x <= 20
5 <= x <= 10
0 <= x <= 5

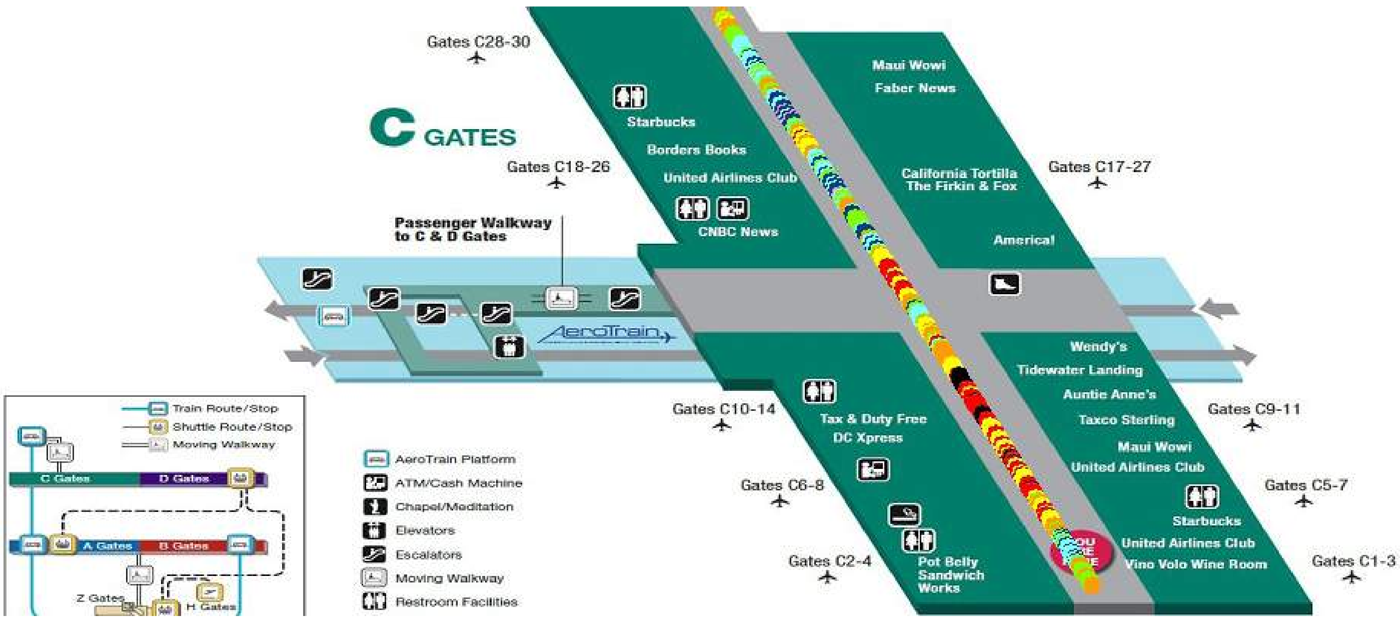
Figure 66. SFO Terminal 3 PDSCH – Verizon Wireless Geo Plot

Source: Signals Research Group

PDSCH (Mbps)

50 <= x
40 <= x <= 50
30 <= x <= 40
20 <= x <= 30
10 <= x <= 20
5 <= x <= 10
0 <= x <= 5

Figure 67. Dulles Terminal C PUSCH – AT&T Geo Plot

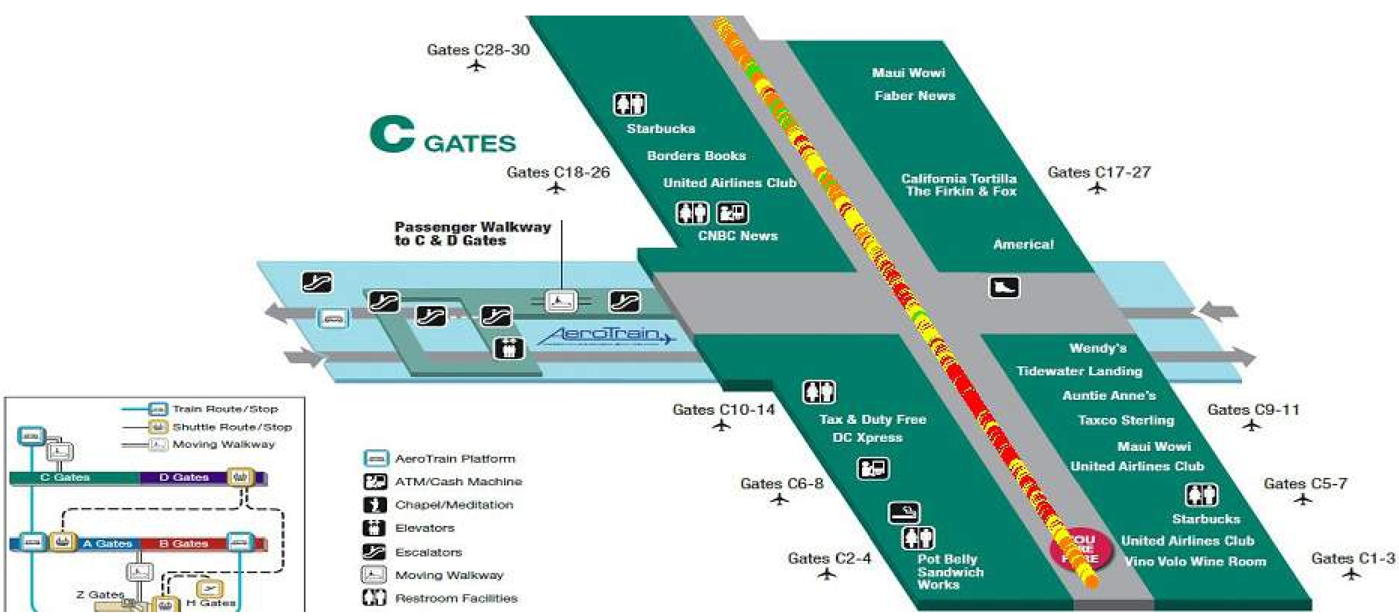


Source: Signals Research Group

PUSCH Throughput (Mbps)

- 20 <= x
- 15 <= x < 20
- 12.5 <= x < 15
- 10 <= x < 12
- 7.5 <= x < 10
- 5 <= x < 7.5
- 2.5 <= x < 5
- 1 <= x < 2.5
- 0 <= x < 1

Figure 68. Dulles Terminal C PUSCH Transmit Power – AT&T Geo Plot

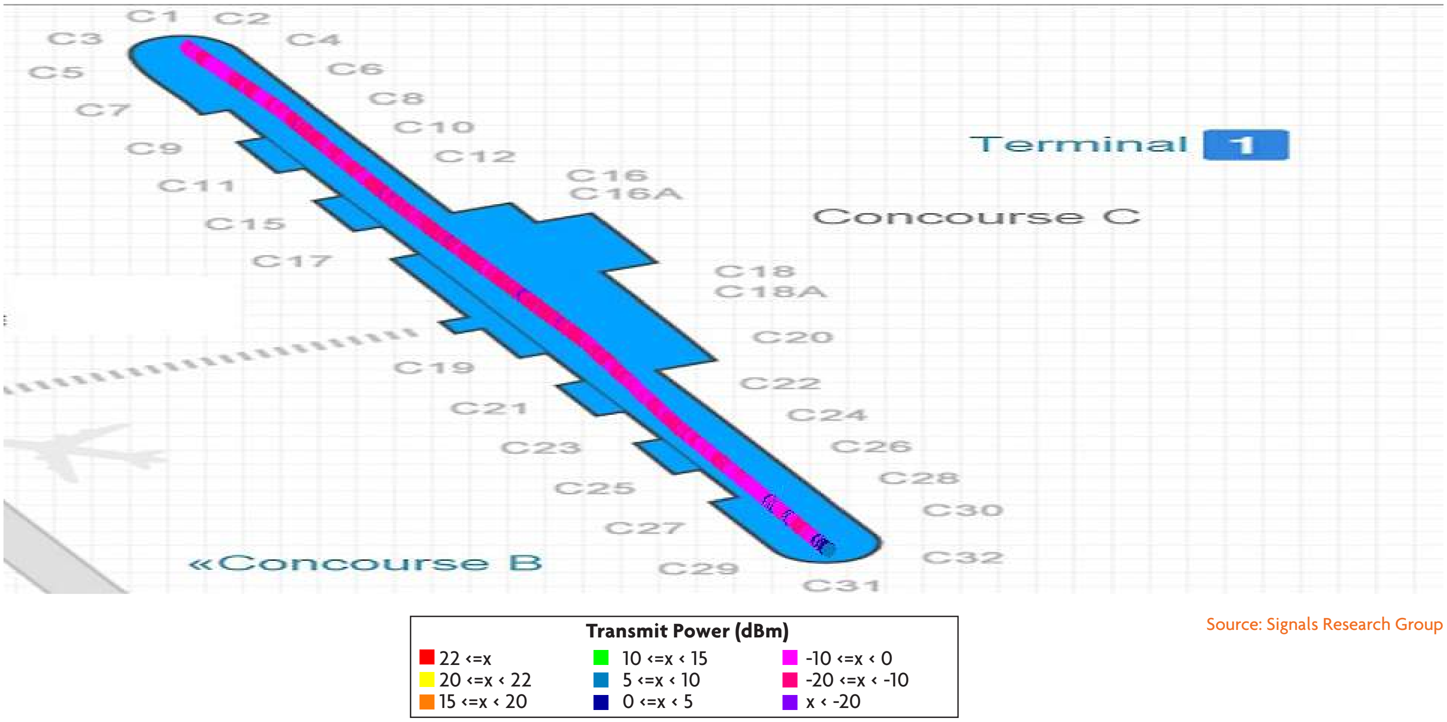


Source: Signals Research Group

Transmit Power (dBm)

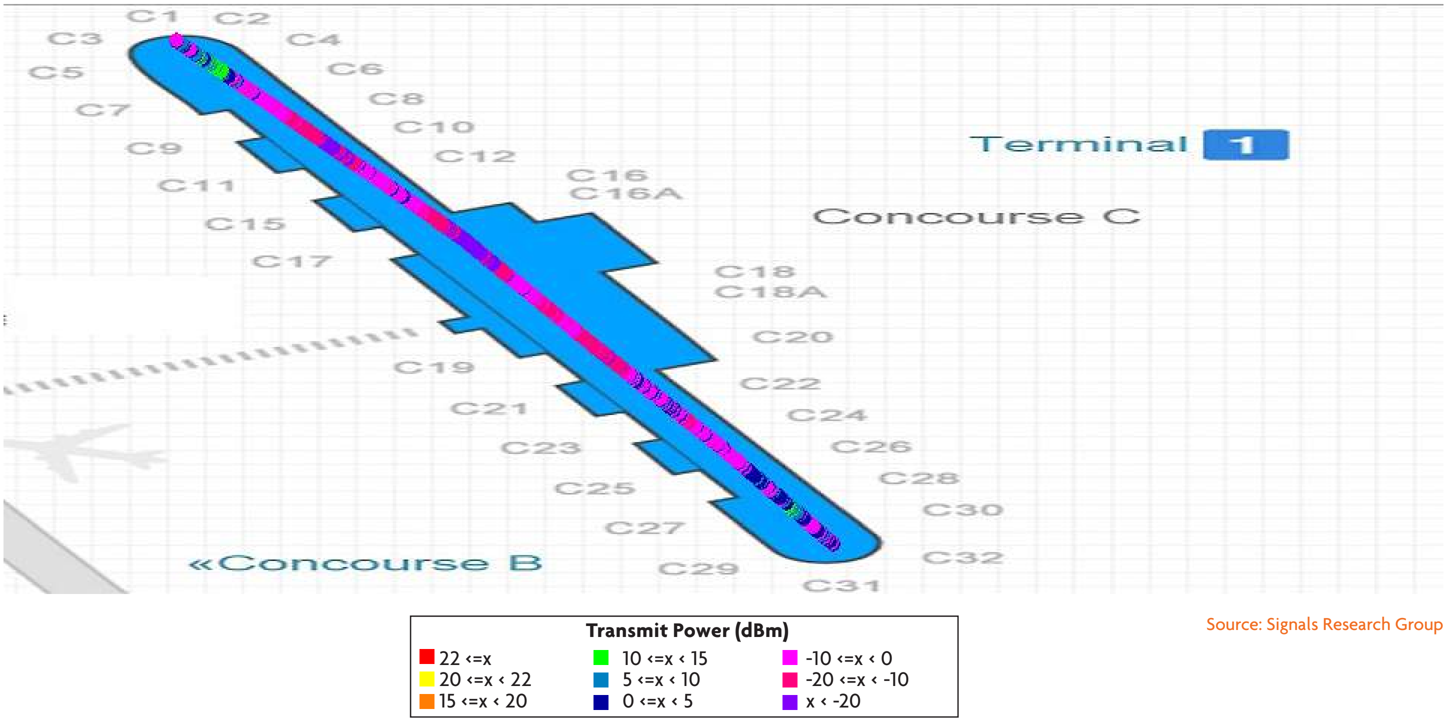
- 22 <=x
- 20 <=x < 22
- 15 <=x < 20
- 10 <=x < 15
- 5 <=x < 10
- 0 <=x < 5
- -10 <=x < 0
- -20 <=x < -10
- x < -20

Figure 69. O'Hare Terminal C PUSCH Transmit Power – AT&T Geo Plot



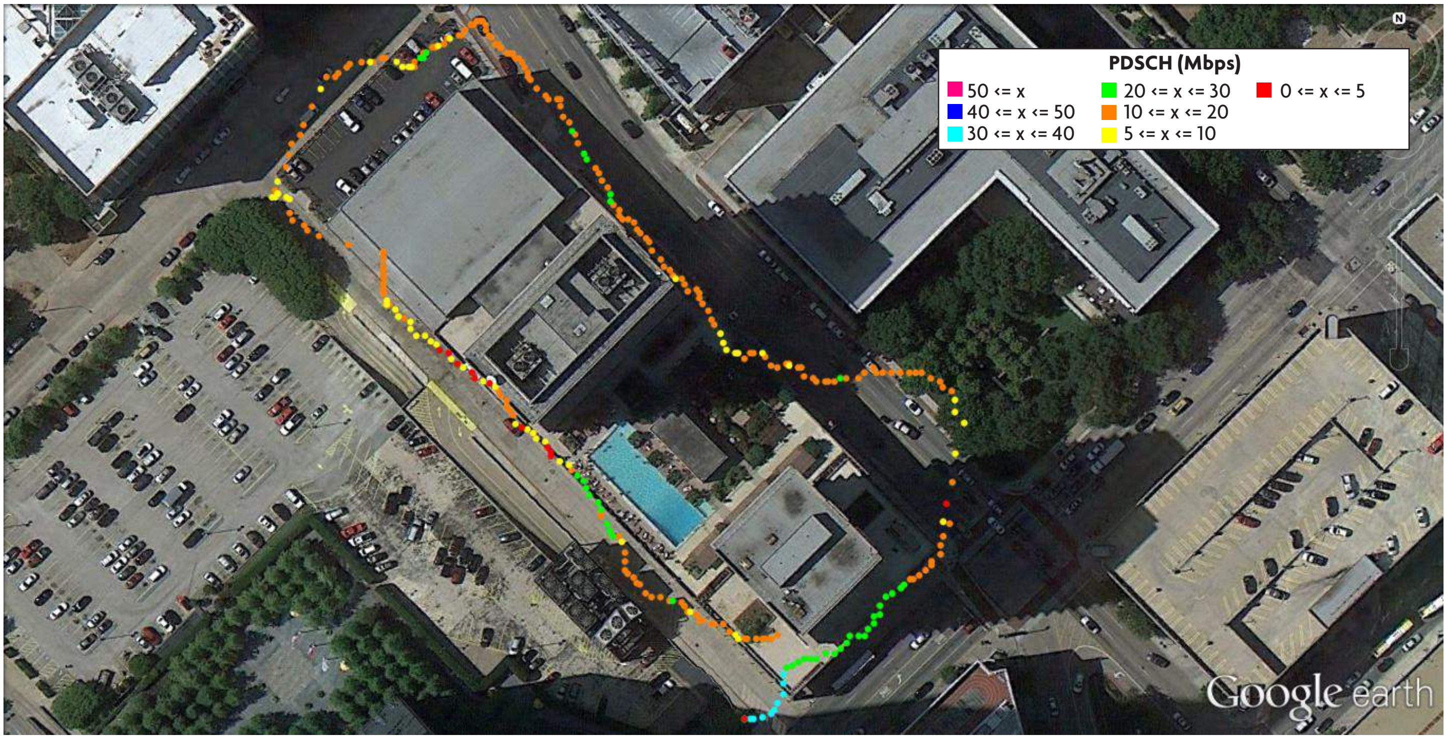
Source: Signals Research Group

Figure 70. O'Hare Terminal C PUSCH Transmit Power – Verizon Wireless Geo Plot



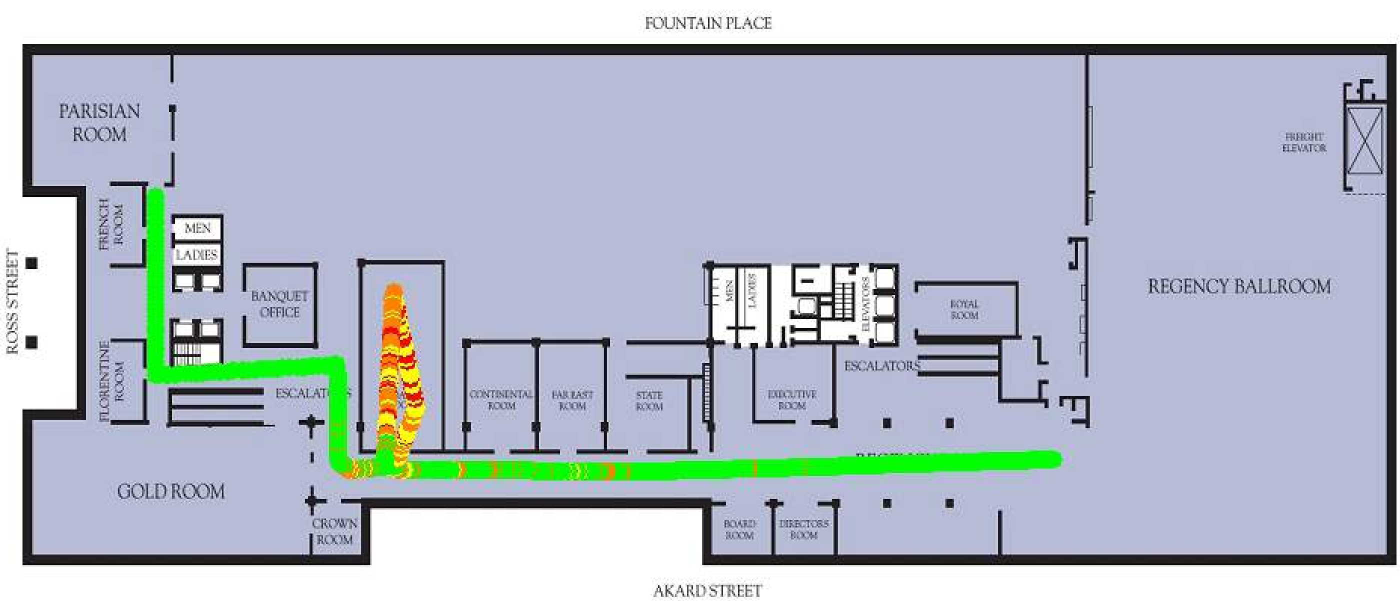
Source: Signals Research Group

Figure 71. Fairmont Hotel Outside PDSCH Throughput – AT&T Geo Plot



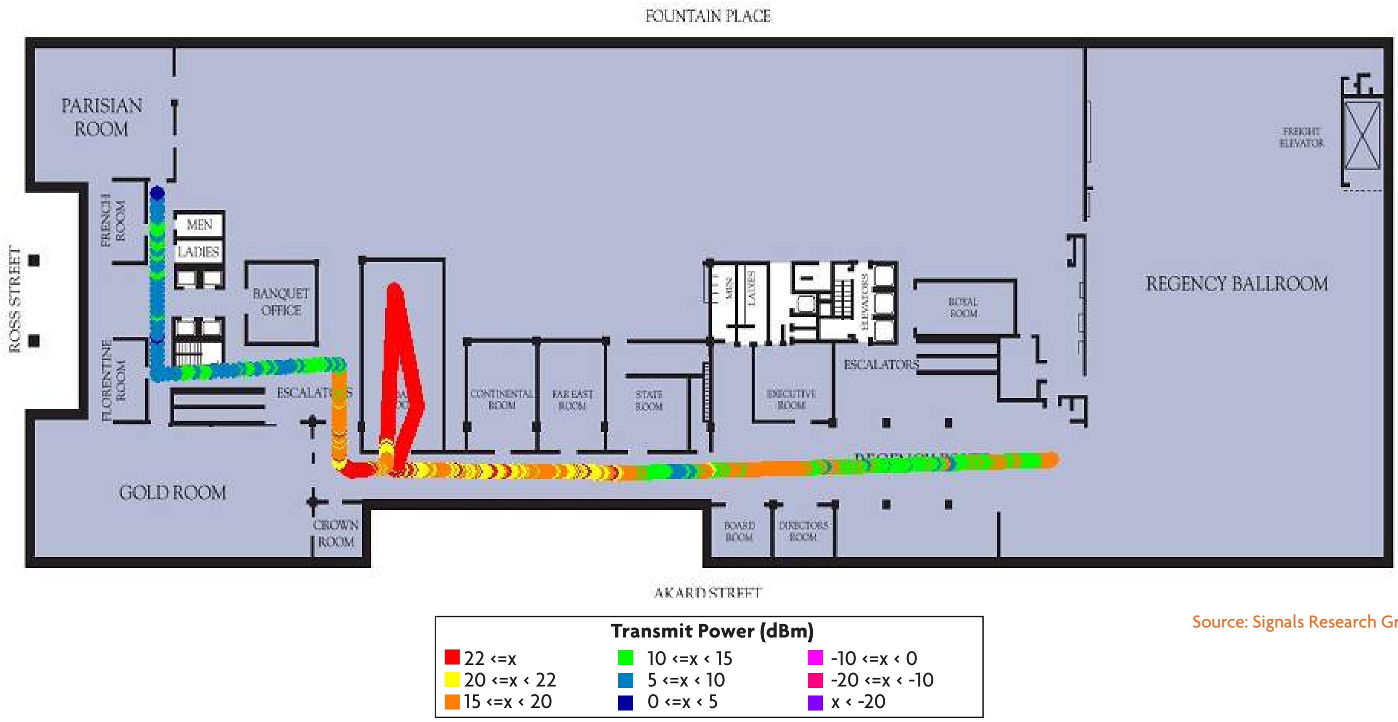
Source: Signals Research Group

Figure 72. Fairmont Hotel Oak Room Power Headroom – AT&T Geo Plot



Source: Signals Research Group

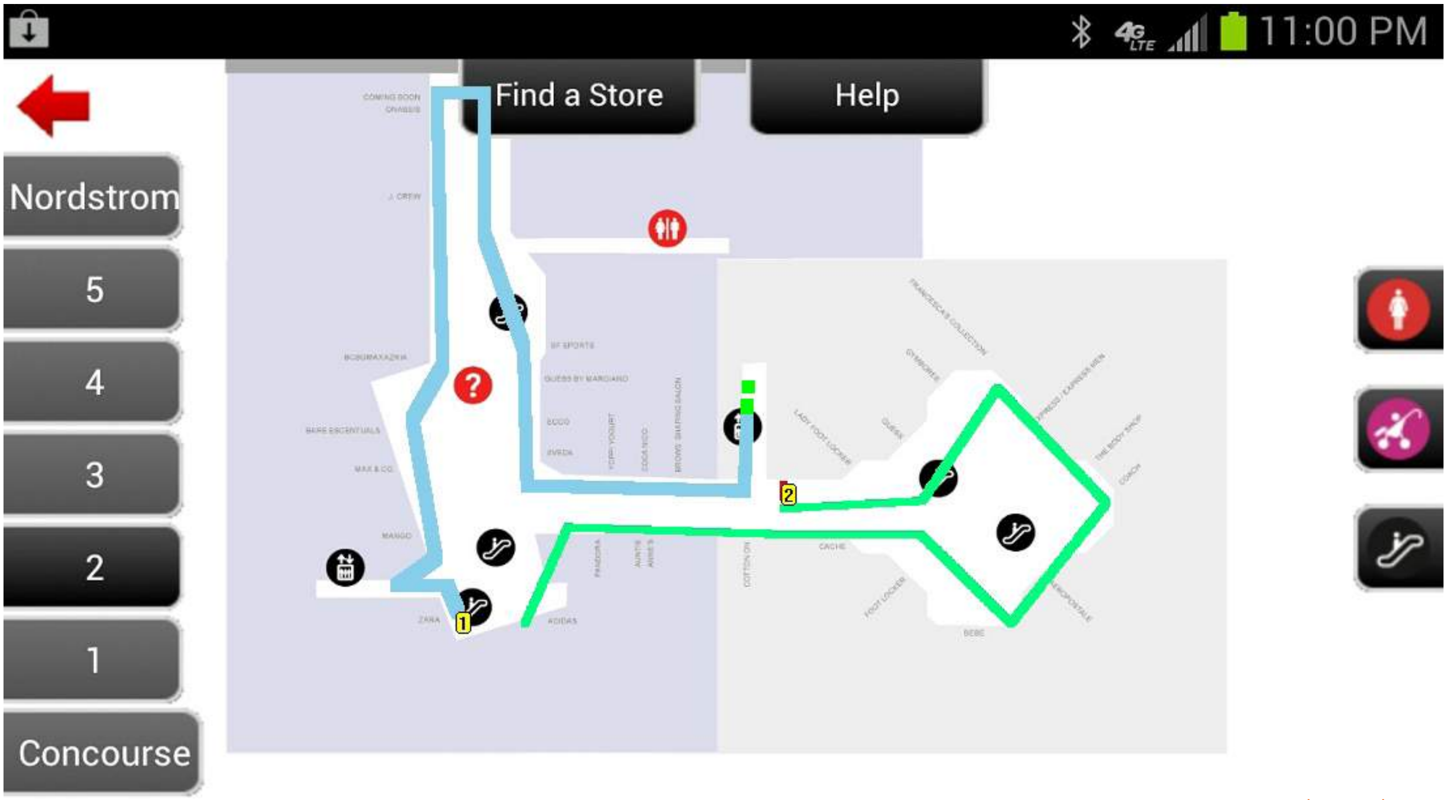
Figure 73. Fairmont Hotel Oak PUSCH Transmit Headroom – AT&T Geo Plot



Source: Signals Research Group

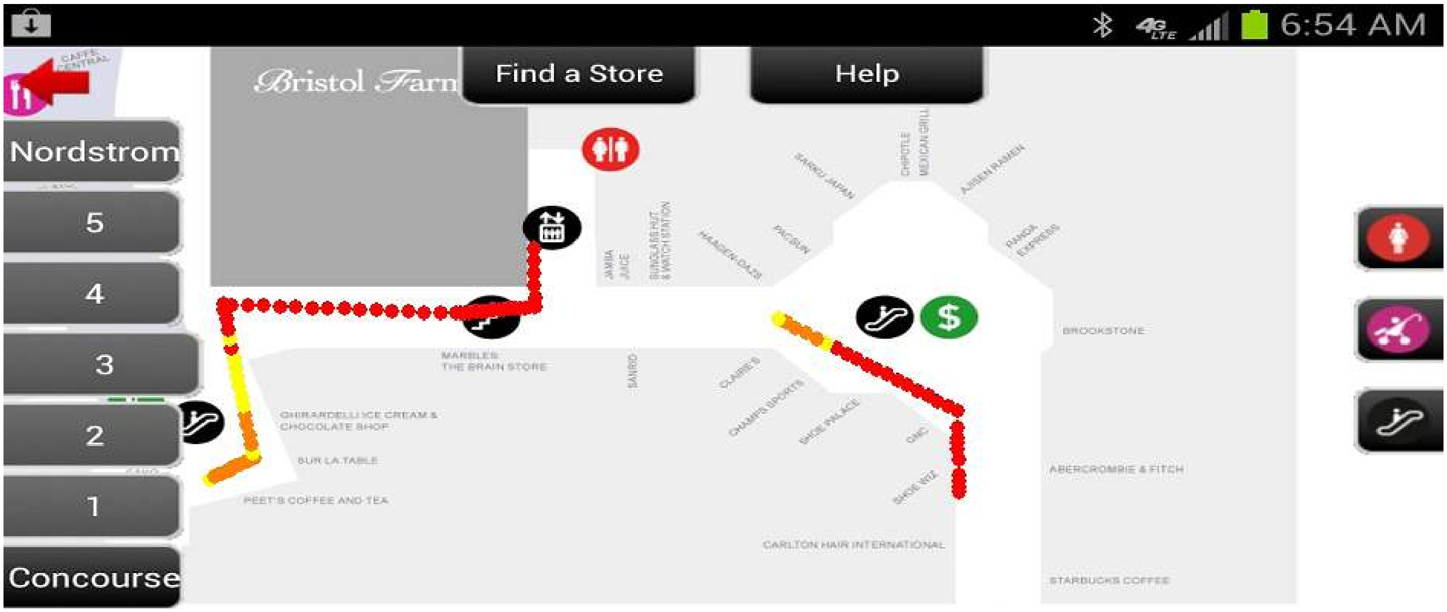
In Figure 74, the portion of the test where we used LTE is shown by the light blue line. The green line shows the portion of the test where our dongle was connected to the EV-DO Rev A network. From what we have seen, the dongle won't return back to LTE until it is in the Idle state and given our test methodology this event will never happen until we terminate the test.

Figure 74. Westfield Mall 2nd Floor LTE and EV-DO Rev A – Verizon Wireless Geo Plot



Source: Signals Research Group

Figure 75. Westfield Mall Concourse Level PDSCH Throughput – Verizon Wireless Geo Plot

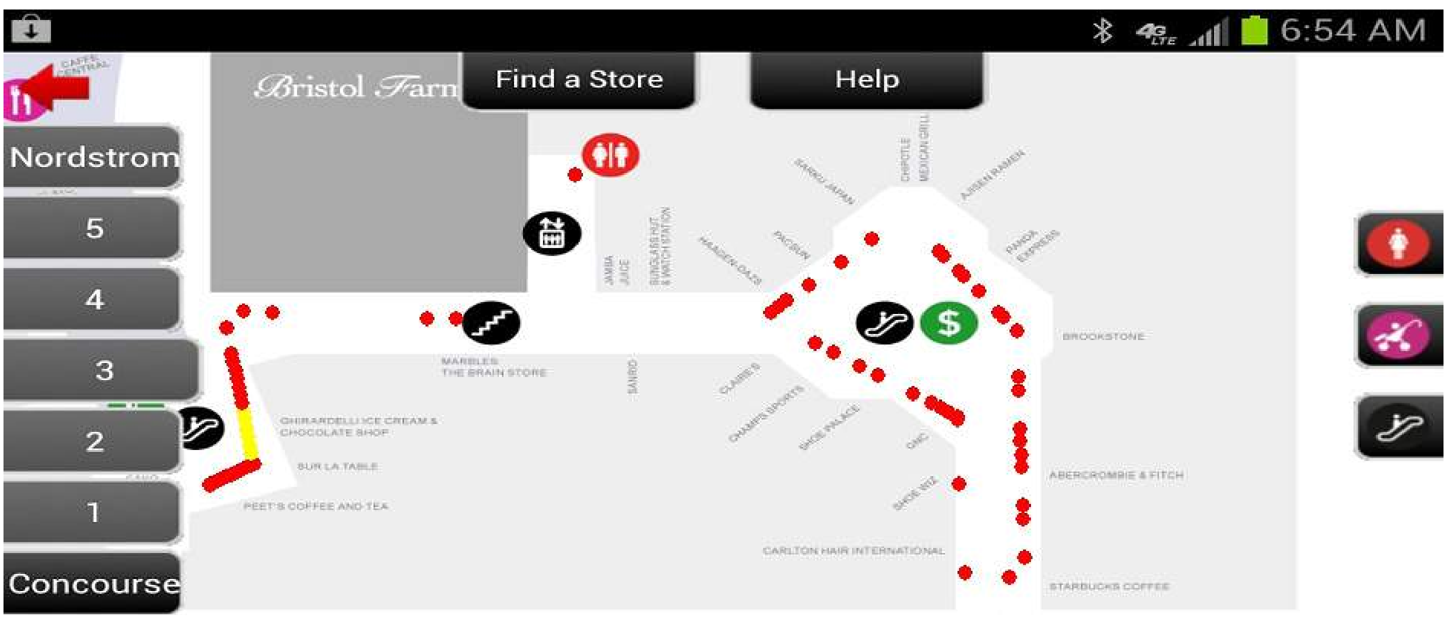


PDSCH (Mbps)

50 <= x
40 <= x <= 50
30 <= x <= 40
20 <= x <= 30
10 <= x <= 20
5 <= x <= 10
0 <= x <= 5

Source: Signals Research Group

Figure 76. Westfield Mall Concourse Level PDSCH Throughput – AT&T Geo Plot

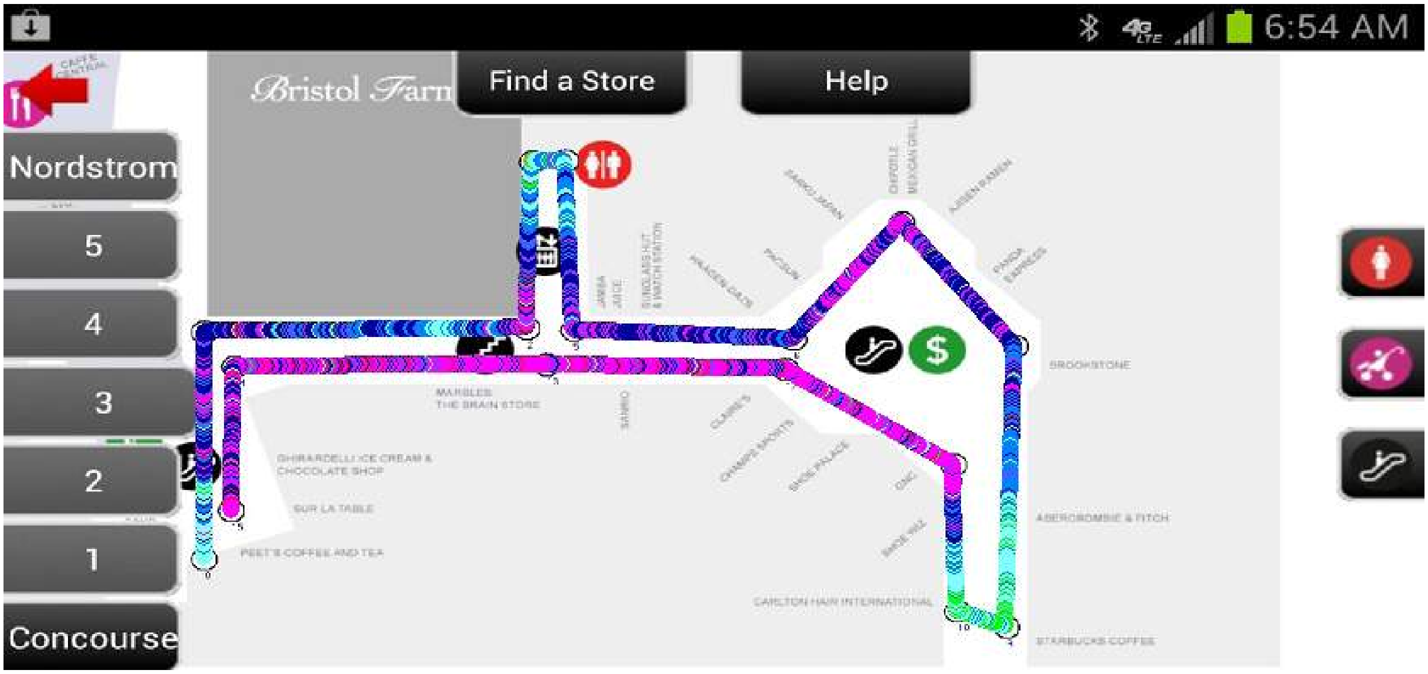


PDSCH (Mbps)

50 <= x
40 <= x <= 50
30 <= x <= 40
20 <= x <= 30
10 <= x <= 20
5 <= x <= 10
0 <= x <= 5

Source: Signals Research Group

Figure 77. Westfield Mall Concourse Level MAC Layer Throughput – AT&T Geo Plot



Downlink Throughput (Kbps)

10,000 <= x	5,000 <= x <= 7,500	1,000 <= x <= 2,500	250 <= x <= 500
7,500 <= x <= 10,000	2,500 <= x <= 5,000	500 <= x <= 1,000	0 < x <= 250

Source: Signals Research Group

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