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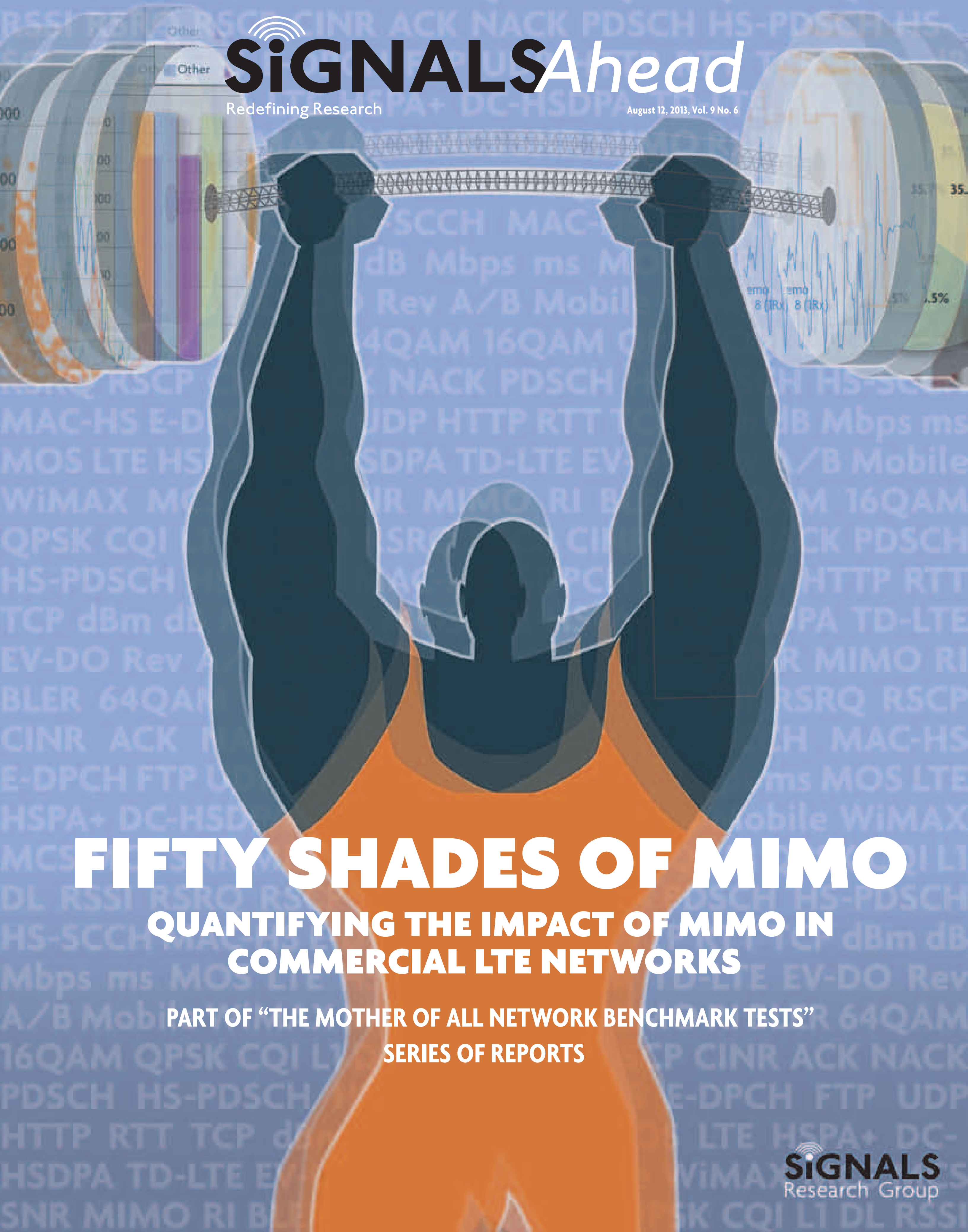

FIFTY SHADES OF MIMO

QUANTIFYING THE IMPACT OF MIMO IN COMMERCIAL LTE NETWORKS

PART OF "THE MOTHER OF ALL NETWORK BENCHMARK TESTS" SERIES OF REPORTS

SiGNALS Research Group

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1.0 Executive Summary

The various MIMO (Multiple Input, Multiple Output) antenna schemes are key technology enablers and they play a critical part of the LTE standard. In theory, 2 x 2 MIMO can double the end user throughput, but in practice the actual gains can be far more modest. Given the large number of dependencies, the most valid and interesting approach is to convince an operator [in our case two operators] to turn off MIMO and then see what happens. Easier said than done!

There are nine different transmission modes in Release 10, which is impressive but nowhere near the fifty transmission modes that we alluded to in the title of this report. Our version of the fictional story may not be as titillating as the original, but we're confident that we will still get the juices flowing with our readers as they turn the pages.

For this study, we focused exclusively on TM 3 and TM 2.

For purposes of this study we focused exclusively on Transmission Mode 3 (TM 3 – Open Loop MIMO) and Transmission Mode 2 (TM 2 – Transmit Diversity) and the relative gains associated with a network configured to support TM 3 versus a network configured to only support TM 2. We collected data during two consecutive nights in each market that we tested with TM 3 enabled during the first night and TM 3 turned off during the second night. We also tested in two different frequency bands. In downtown Knoxville, Tennessee we had access to a network that supported 2 x 5 MHz of LTE in 850 MHz (Band 5). In T-Mobile's network in Santa Clara, California, we had access to 2 x 10 MHz of LTE in 1700/2100 MHz (Band 4).

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With TM 3 enabled, we measured some of the highest average throughput that we've recorded in a commercial / pre-commercial LTE network.

With TM 3 enabled, we measured some of the highest average throughput that we've recorded in a commercial/pre-commercial LTE network. In Knoxville, the average throughput during the daytime over a geographical region that extended well beyond the test cluster was 12.81 Mbps – 21.6% of the time the throughput was higher than 20 Mbps. In T-Mobile's Santa Clara/San Jose network, the average throughput of its 2 x 10 MHz network during daytime testing was 24.71 Mbps – during the nighttime drive testing the average throughput over a 9.7 mile drive test was closer to 30 Mbps. The daytime throughput also exceeded 40 Mbps for 18.5% of the time.

In total, we transferred nearly 140 GB of data.

To provide a meaningful comparison of the data collected on the two consecutive nights, we followed identical drive routes and used the same fixed locations that we selected. We also repeated the routes numerous times to increase the sample size. In total, we transferred nearly 140 GB of data.

As we expected, we confirmed that MIMO can double the end user data rate.

As we expected, we confirmed that MIMO can double the end user data rate. In Knoxville, we tested at fixed locations where on one night the peak/average data rates hovered in the range of 30 to 31 Mbps – pretty much the theoretical limit in a 2 x 5 MHz channel. On the second night, the throughput was cut in half to only 15 Mbps. In Santa Clara, the 60 to 61 Mbps test spots became ~30 Mbps test spots on the second night.

The impact of MIMO is a function of the underlying network conditions so as the network conditions deteriorate the positive benefits of MIMO decline. We used device-reported SINR and to a lesser extent RSRP as the leading indicators for MIMO performance. We note that SINR will decline when the signal strength is low (poor coverage) or if the interference is high (likely due to higher network loading).

The availability of MIMO (TM 3) resulted in user throughput increasing by at least 20% for at least 40% of the time in the networks that we tested.

Cutting to the chase, the availability of MIMO (TM 3) resulted in user throughput increasing by 20% or more for at least 40% of the time in the networks that we tested. Conversely, at least 50% of the time the user throughput would have been at least as high, if not higher, if the network had been configured to only support TM 2. As discussed in this report, the mobile device/chipset decides if it should use TM 3 or TM 2 based on the channel conditions. The network scheduler can assign the mobile device its requested transmission mode or it can assign a different transmission mode. From our analysis of the data, the scheduler almost always assigned the mobile device its requested transmission mode. It also appears that the fairly aggressive use of TM 3 with poor channel conditions had a detrimental impact on the end user data rates.

The wired Internet can be the bottleneck of a wireless network.

We also conducted user experience testing with and without MIMO, and the results were pretty much in line with our expectations. Web pages load just as fast with TM 2 as they do with TM 3, just as a YouTube video buffers and plays just as fast with both transmission modes. The relatively small size of most web pages explains why higher throughput didn't result in a quicker web page load time. Lower latency would have helped. With other Internet content, such as YouTube videos or Google Play/iTunes applications, the capabilities of the wireless network can exceed the ability of the data source to deliver the content. Put another way, the wired Internet can be the bottleneck of a wireless network.

MIMO can increase network efficiency even when it doesn't increase end user data rates.

Separate from the impact of MIMO on end user data rates, there is still a very valid reason to use MIMO, even if it doesn't benefit the end user. MIMO can increase network efficiency since it allows the network to use fewer resources to deliver a given amount of content. We observed this phenomenon with our web page browsing tests. Although the actual web page load times were largely the same with the two network configurations, we found that roughly 50% fewer network resources (Resource Blocks) were used when TM 3 was enabled. All this and more in this issue of *Signals Ahead.*

Chapter 2 contains the key findings and observations from our study. Chapter 3 provides sample results from the drive tests and it walks readers through the multi-step process that we used to quantify the benefits of MIMO in a commercial network. Chapter 4 provides results and analysis from the stationary tests that we conducted. For this analysis, we looked at results on a per subframe basis. Chapter 5 provides results from some high-speed vehicular testing that we did along Highway 101 in Santa Clara. Chapter 6 focuses on the user experience tests, specifically web page browsing and YouTube. Chapter 7 provides our test methodology and Chapter 8 includes some closing comments. In the Appendix, we provide several tables of results from all of the drive tests and we include numerous figures which didn't find their way into the main body of the report.

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IN CASE YOU MISSED IT: SIGNALS AHEAD BACK ISSUES

- **5/28/13 "What's the PSC, Kenneth? (Quantifying the need and benefits of interference cancellation solutions in a 3G network)"** We provide insight into the amount of interference that exists in a 3G network, its potential impact on data rates and network efficiency, and how an advanced equalizer can be used to maximize performance when these challenging conditions exist. For purposes of this report, we used AT&T's HSPA+ network in San Francisco and the surrounding vicinity. This report was done in collaboration with Accuver who provided us with its XCAL and XCAP drive test solutions.

- **4/25/13 "Everything under the SON"** We discuss the background of SON, including discussions of work within NGMN, 3GPP and the SOCRATES/SEMAFOUR projects. We also cover the basics of SON including the laundry list of SON-like features, explain how they work, and what they mean for operators and vendors. We then move on to discuss the present and future requirements of SON, including what may be in store with Release 12 and beyond. Finally, we discuss the motivations and challenges of SON, including multi-vendor integration, vaguely-defined use cases, OSS limitations, 3G SON, and centralized versus decentralized architectures.

- **3/22/13 "Rich Communication Services – reinventing voice and messaging"** In this issue of *Signals Ahead* we provide a detailed analysis of RCS. In addition to providing the history of RCS since its introduction in 2008, we examine why operators have not yet fully adopted it, the capabilities by release, the inherent challenges that exist, the business relationships that exist or at least should exist, and the opportunities that could allow operators to beat the OTT providers at their own game.

- **2/25/13 "Chips and Salsa XVI: Sweet 16 and never been benchmarked"** This report provides performance benchmark analysis of 8 LTE baseband chipsets, including Altair, GCT, Intel, NVIDIA, Qualcomm, Renesas Mobile, Samsung, Sequans. This benchmark study marks the 8th time that we have collaborated with Spirent Communications to leverage its 8100 test system and engineering support. All chipsets performed well under less challenging conditions but with the more challenging conditions there was a wide variance in the results with more than a 20% difference between the top- and bottom-performing chipsets. Three chipsets vied for top honors but ultimately we had to declare one the winner.

- **01/23/13 "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, and Band 17)"** 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 at Band 4, Band 7, Band 13 and Band 17. In this report we quantify the amount of LTE network traffic that we observed in the outdoor macro network and how it compares with our in-building testing. We also demonstrate that 700 MHz isn't a panacea for in-building coverage, that potential coverage problems are being masked by ample capacity, and that some in-building networks may not scale to support future traffic demands. Finally, we compare and contrast the performance of the VZW and AT&T LTE networks.

- **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.

2.0 Key Conclusions and Observations

Signals Research Group conducted a series of drive tests to determine how MIMO impacts network performance.

Signals Research Group conducted a series of drive tests to determine how MIMO impacts network performance. In theory, MIMO can double the data rates with ideal network conditions. However, in practice the actual performance gains can be substantially different. In previous drive test reports we have always indicated how often MIMO was being used and we provided the throughput values that we observed. We didn't, however, indicate what the throughput would have been if MIMO had not been used since we had no way of knowing – until now.

With the support of two operators, we conducted MIMO ON/OFF drive tests in two different test markets, the downtown area of Knoxville, TN, and Santa Clara, CA.

With the support of two operators, we conducted MIMO ON/OFF drive tests in two different test markets, the downtown area of Knoxville, TN (Band 5 – 850 MHz), and Santa Clara, CA (Band 4 – 2100 MHz/1700 MHz). During the first night of testing in both markets, we collected network performance data with Transmission Mode 3 (TM 3), or open loop MIMO, enabled in the network. During the second night of testing, the operators turned off TM 3 so the mobile device was "forced" to use Transmission Mode 2 (TM 2), or Transmit Diversity.

For this study, we limited the size of the test area and on both nights we conducted our tests along identical drive routes and fixed locations that we selected so that we could make an apples-to-apples comparison of the data. Still, the test areas were sufficiently large with a good diversity of morphology/terrain. The Knoxville test area covered approximately 3.25 square miles and the Santa Clara market covered approximately 4.5 square miles. We also used network/device-reported parameters, in particular SINR (Signal to Noise and Interference Ratio) and RSRP (Reference Signal Received Power) to make the comparisons as accurate as possible. We repeated the drive routes numerous times in order to increase the sample size.

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We once again collaborated with Accuver, who supplied us with its XCAL drive test solution and its XCAP post-processing software. We have used their solutions since we conducted our first drive test of LTE way back in February 2010. Since that time we have taken advantage of their tool's capabilities to test an acronym soup of radio access technologies, not to mention interesting sidebar studies, including in-building performance and user experience testing. We look forward to collaborating with them in the future to provide the industry what we hope continues to be useful information. SRG takes full responsibility for the analysis and commentary presented in this report.

Based on transferring nearly 140 GB of data in the two networks, we offer the following observations, which are supported in far more detail throughout the remainder of the report.

Both LTE networks delivered outstanding end user throughput with TM 3 enabled. In addition to nighttime testing, we also tested the networks during more normal hours and over a larger geography to obtain a realistic representation of how the networks performed. We found that both networks delivered outstanding end user throughput for the allocated amount of channel bandwidth. In Knoxville, the average throughput of the 2 x 5 MHz network during the daytime tests was 12.81 Mbps with throughput of at least 20 Mbps achieved 21.6% of the time. The peak data rates, which we observed on numerous occasions, were approximately 31 Mbps, which is consistent with the peak capabilities of LTE.

In T-Mobile's Santa Clara/San Jose network, the average throughput of its 2 x 10 MHz network during daytime testing was 24.71 Mbps – during the nighttime drive testing the average throughput over a 9.7 mile drive test was closer to 30 Mbps. During the daytime testing, we observed throughput in excess of 40 Mbps for 18.5% of the time. The daytime throughput exceeded 60 Mbps for 2.7% of the time with the peak data rates reaching ~62.6 Mbps, or pretty much the theoretical limit of LTE.

Both networks were commercial but based on factors, such as the number of assigned Resource Blocks, we believe that both networks were fairly lightly-loaded during the daytime, and obviously during the nighttime testing that we conducted.

Understanding the incremental contribution of MIMO in a real-world network is important to the industry. As one can imagine, convincing an operator to turn off MIMO isn't altogether that easy, just as it isn't easy to respond to an alarm clock that rings right about the time that Letterman and Leno sign off for the evening. However, we believe that it was all worthwhile since MIMO/smart antennas will play a very important role in the future evolution of wireless technologies.

The 3GPP standards body, other associated organizations, and academia have done a lot of theoretical modeling to gauge the benefits of MIMO. Therefore, some of the results that we reach in this report shouldn't be that surprising. However, there are important nuances associated with a live network that can't be modeled and which can't be replicated in a test lab unless the network conditions and behavior of the vendor-supplied solutions are well understood in advance.

From an RF perspective, one needs to understand the likely channel conditions, including the quality of the desired signal, the amount and type of interference, the multi-path behavior, the fading propagation characteristics, and the correlation between the two data streams. There are also vendor-specific attributes that need to be considered. The algorithms used by the baseband modem chipset to request the appropriate transmission mode and by the network scheduler to assign the appropriate transmission mode may not be optimal. Further, the user equipment (smartphone, tablet, dongle etc.) may have a poor antenna design or RF layout which could negatively impact the usefulness of MIMO, except under the most ideal network conditions.

From an operator's perspective, there is a cost associated with deploying MIMO. Although it is hard to imagine an operator not deploying basic 2 x 2 MIMO, they could decide to advance or curtail their interest and investment in more advanced MIMO schemes, or they could reevaluate their cell site configurations to ensure that the full benefits of MIMO are realized.

MIMO can double the end user throughput, but the gains are generally far more modest with no benefit, and even a negative impact, possible – it all depends on the network conditions. It didn't take long for us to confirm that MIMO can double the end user throughput with fairly ideal conditions. We pretty much confirmed it a few seconds after the operator turned off MIMO in Knoxville since we were logging data at the time from our hotel room (note the XCAL figures in Chapter 7). However, our primary goal was to determine the behavior of MIMO performance so that we could predict how MIMO influences throughput for a given set of channel conditions. Then, by knowing the distribution of channel conditions for a given operator's network we could determine the typical impact of MIMO and how the impact changes as the underlying network conditions change.

Thankfully, the results that we obtained were very consistent in each drive test and between the two markets. Figure 1 illustrates how we believe MIMO performs based on the results that we collected in the two markets. Each slice of the pie depicts a throughput gain in percentage terms due to MIMO – specifically TM 3. The size of each slice corresponds to the probability that the network conditions required to support the MIMO-related throughput gain exist in the network. The sizes of the pie slices are different between the two markets, largely due to differences in the network conditions that we observed. Chapter 3, in particular Chapter 3.4, explains the multi-step process that we took to reach the conclusions portrayed in the figure.

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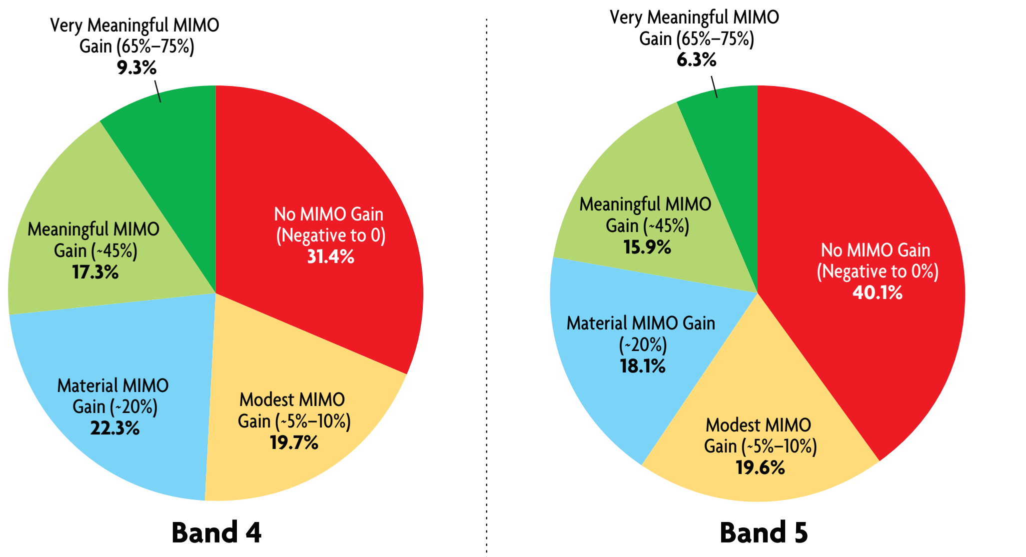
Figure 1. The Impact of MIMO in a Commercial LTE Network – Band 4 and Band 5



Source: Signals Research Group

The impact of MIMO is directly related to the underlying channel conditions.

Without going into a lot of detail in this chapter, the impact of MIMO is directly related to the underlying channel conditions. We focused on the device-reported SINR and RSRP values and found a high degree of success. The results in the figure can be interpreted with a glass is half-full mentality or with a glass is half-empty perspective. The optimist (half-full) would observe that at least 40% of the time the availability of TM 3 can increase the end user throughput by at least 20%. The exact percentages that we observed are 40.3% (Knoxville) and 48.9% (Santa Clara). The pessimist would observe that at least 50% of the time, the availability of TM 3 would only have a modest impact on throughput (~5%-10%), at best, and that 30-40% of the time the availability of TM 3 could actually degrade end user throughput, or at least have no positive influence. As network conditions deteriorate due to increased loading, the benefits of MIMO will decrease.

The potentially negative performance gains associated with MIMO occur in regions with low SINR.

The potentially negative performance gains associated with MIMO occur in regions with low SINR when the mobile device/chipset requests TM 3, even though it would have achieved higher throughput with TM 2. In theory, the network scheduler can intervene and assign the mobile device a different transmission mode but from the analysis that we conducted this action seldom, if ever, took place when we were doing max throughput testing. With user application testing, in particular web page browsing, the scheduler in the Knoxville network frequently assigned Rank Indicator 1 (Transmit Diversity) even through the mobile device always requested Rank Indicator 2 (Open Loop MIMO). We assume this action was taken for efficiency reasons due to the small amount of data transferred when loading a web page. The network conditions at this location were ideal and during the max throughput testing the network always used TM 3, as requested by the modem.

In a somewhat loaded LTE network, MIMO is more likely to have no impact or even degrade the end user throughput than it is to have a measurable benefit on the end user throughput.

Based on the data we collected and the analysis that we performed, MIMO can have a tremendous impact on end user throughput. In numerous cases during our stationary testing, we observed a doubling in the end user throughput – consistent with the full capabilities of MIMO and our expectations. However, MIMO isn't a panacea and ideal conditions are seldom present in a commercial LTE network. Instead, the contribution of MIMO to end user throughput varies as a function of SINR with lower SINR (more network loading) resulting in lower gain. Another factor is the multipath behavior and the correlation between the two signals – uncorrelated signals are preferable. Taking into consideration all of the data that we analyzed and which we present in this report, in a somewhat loaded LTE network (average reported SINR < 10 dB), MIMO is more likely to have no impact or even degrade the end user throughput than it is to have a measurable benefit on the end user throughput.

In our view, it is probably in the interest of the industry to pursue and understand how the various transmission modes are allocated and under what conditions. We've only tackled two transmission modes, but there are other transmission modes available today (e.g., TM 4 – Closed Loop MIMO) with other transmission modes coming on the horizon (e.g., TM 5 – Multi-User MIMO).

The benefits of MIMO on the individual user experience are highly dependent on the application. We also conducted a series of tests to evaluate the impact of MIMO while using typical smartphone applications. We focused primarily on web page browsing and viewing a video on YouTube. Not surprisingly, we found that MIMO didn't load the web pages any faster and it didn't cause the YouTube video to download and play in a shorter amount of time. The data actually suggests that the web pages loaded faster when the networks were configured to only support TM 2, but we believe this result stems from the relatively small sample size.

The network latency can never be too low.

When we conducted user experience testing back in 2011, we reached a similar conclusion. With that study we found that once the throughput reaches a certain rate the user experience doesn't improve with incrementally higher data rates. Instead, latency is immensely important, meaning that the network latency can never be too low. For applications, such as web browsing, the optimal data rate is ~ 5 Mbps so naturally web pages will not load faster at 60 Mbps then they do at 30 Mbps. With other applications, such as iTunes or Google Play, the optimal data rates are considerably higher but it is still frequently the case that the host server is the bottleneck and not the wireless network.

MIMO doesn't have any influence on the user experience while web browsing.

In this study, we looked at the transport block size (TBS) allocations on a per 1 ms sub-frame basis, thanks to the capabilities of the XCAP post-processing software. While loading a typical web page, the maximum TBS is used, but overwhelming the data is sent using smaller TBS allocations. For example, we conducted a web page browsing test from several ideal locations where the average/median TBS was higher than 15,000 bits, yet the average/median TBS allocation while loading a web page was barely 6,000 bits. We also observed that the average TBS allocation with TM 2 was roughly equivalent to the sum of the TBS allocations from the two orthogonal data streams with TM 3 enabled. This observation also supports our conclusion that MIMO doesn't have any influence on the user experience while web browsing.

With respect to YouTube, we found that while the maximum TBS allocations were used, the network scheduler didn't schedule a large number of concurrent sub-frames so the average TBS assignments were well below the maximum value that could have been assigned. Even when the video was buffering during the initial download of data, smaller TBS allocations were frequently used and several sub-frames were not assigned. We believe that the YouTube server was not able to send the data fast enough to support the full capabilities of the air interface with TM 3 enabled. Interestingly, the peak Physical Layer data rate during the entire viewing of the YouTube video was only slightly more than 8 Mbps – the network was capable of achieving at least 30 Mbps from this location.

Even when the end user doesn't directly benefit from MIMO, the operator can still benefit. In addition to increasing end user data rates, MIMO can increase network efficiency. Sometimes the efficiency gains are achieved even when there isn't an increase in user throughput. In the case of web browsing, we already mentioned that the web pages loaded just as fast with TM 2 as they did with TM 3. So, from an end user perspective MIMO didn't help improve the user experience. However, the end user still indirectly benefited from MIMO while the operator directly benefited.

We analyzed the amount of network resources, specifically resource blocks, required to load the web pages with TM 3 enabled and with the network configured to only support TM 2. We found that approximately twice as many resource blocks were used to load the web pages when only TM 2 was available versus when TM 3 was used. By using fewer resource blocks to perform a user interaction with the network, the resources can be assigned elsewhere to benefit another mobile data user. Multi-User MIMO (MU-MIMO) is based on this principle. Instead of assigning both orthogonal data streams to a single user and doubling the data rate, each data stream is assigned to a unique mobile data user. From the end user's perspective, the network behaves as if it is only offering transmit diversity, but from the operator's point of view, the benefits of MIMO are being delivered. A given number of network resources (sub-frames + Resource Blocks) support two mobile data users instead of a single mobile data user.

3.0 Detailed Results – low-speed mobility

In this chapter we provide the results from our low-speed mobility drive tests. By our definition, low-speed mobility involves the likely vehicular speeds that are observed in an urban/suburban market, or an average speed of roughly 20 mph to 30 mph. Section 3.1 provides some high-level throughput results that we collected during the daytime with TM 3 enabled. The subsequent sections focus exclusively on the nighttime testing, culminating in Section 3.4 which explains how we quantified the impact of MIMO. Section 3.5 looks exclusively at edge-of-cell performance.

3.1 Overall Daytime PDSCH and SINR Results

SRG conducted separate drive tests of Transmission Mode 3 (TM 3) versus Transmission Mode 2 (TM 2) in two separate networks. Most of the testing occurred during the nighttime hours for hopefully obvious reasons. Since network performance (and the benefits of MIMO) is a function of network loading, we thought it would be only appropriate to show the performance of the two networks during more reasonable hours of the day. The results in the subsequent figures include data collected within the test clusters that we used for the MIMO testing but we also included areas outside of the clusters in order to obtain network performance that may be more representative of a wider cross-section of the markets where we tested.

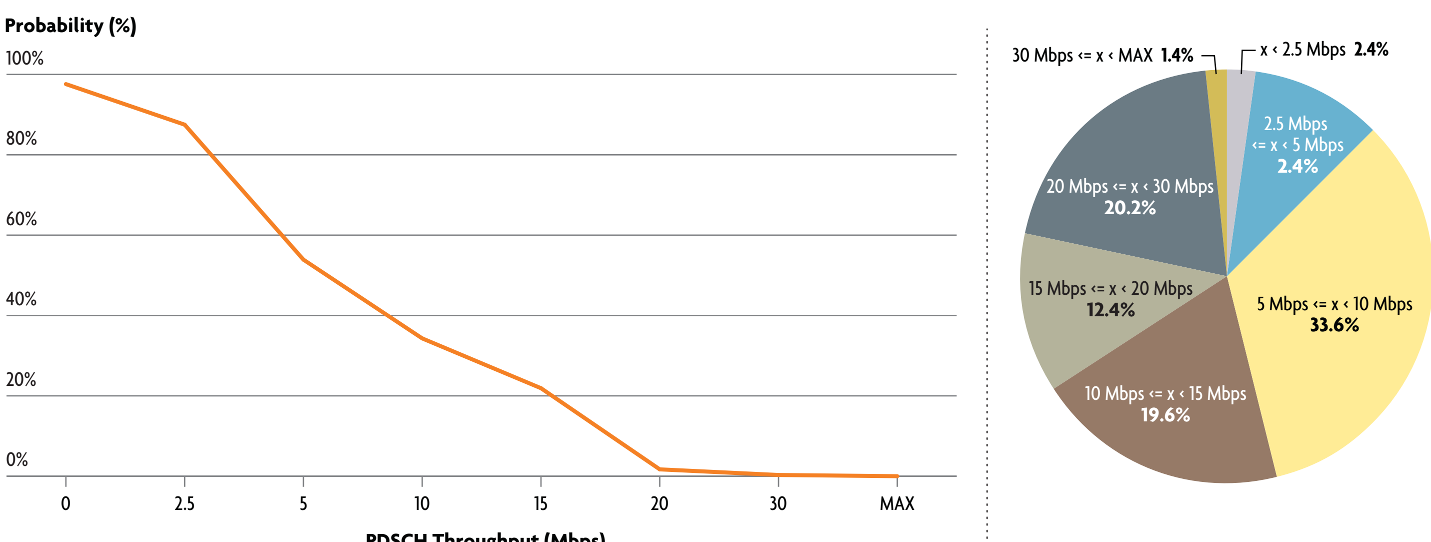
In T-Mobile's network in Santa Clara the Physical Layer throughput exceeded 40 Mbps for 18.5% of the time during the daytime testing.

Figure 2 and Figure 3 provide the distributions of Physical Layer throughput for the two networks. Figure 2 is for the 2 x 5 MHz Band 5 network in Knoxville, Tennessee. T-Mobile gave us access to its 2 x 10 MHz Band 4 network in Santa Clara, California. Figure 3 provides the Physical Layer throughput distribution – worth noting, 18.5% of the time the throughput exceeded 40 Mbps. Figure 4 and Figure 5 provide geo plots for the Physical Layer throughput in the two markets. The Knoxville results include a lengthy drive to the airport and the Santa Clara results include testing in downtown San Jose and the surrounding area. The results in all figures stem from daytime testing. The throughput/network performance during the nighttime testing was at least as good, if not considerably better than the results shown here.

As shown in Figure 2, the average throughput in the 2 x 5 MHz network in Knoxville was 12.81 Mbps and the average throughput in the 2 x 10 MHz network in Santa Clara was 24.71 Mbps. Both results are higher than what we have observed in previous testing involving comparable

Figure 2. Probability Distribution of Daytime Physical Layer Throughput – Knoxville Band 5 Network

PDSCH Throughput (Median) = 10.64 Mbps PDSCH Throughput (Average) = 12.81 Mbps
Total Data Transfer = 30.2 GB

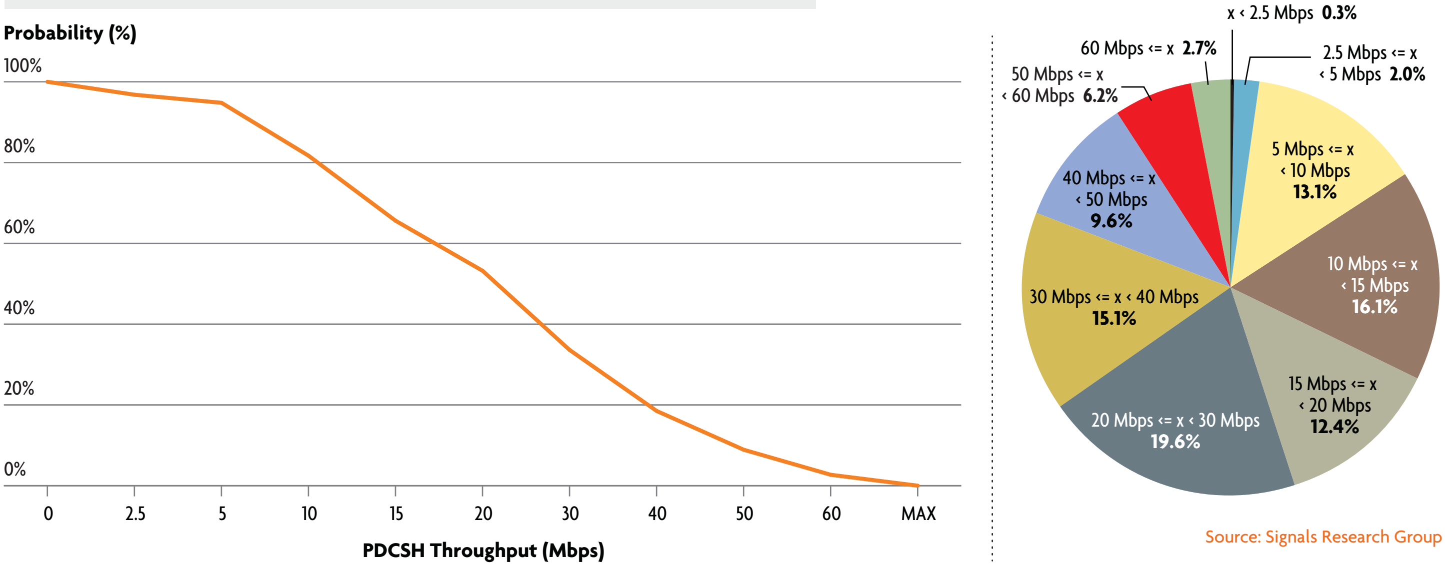


Source: Signals Research Group

channel bandwidths. For comparison purposes, the average throughput from the testing of AT&T's pre-commercial network in Houston was 23.6 Mbps, which until now was the best performance that we have observed. One could infer that both networks were fairly lightly-loaded, even during daytime hours.

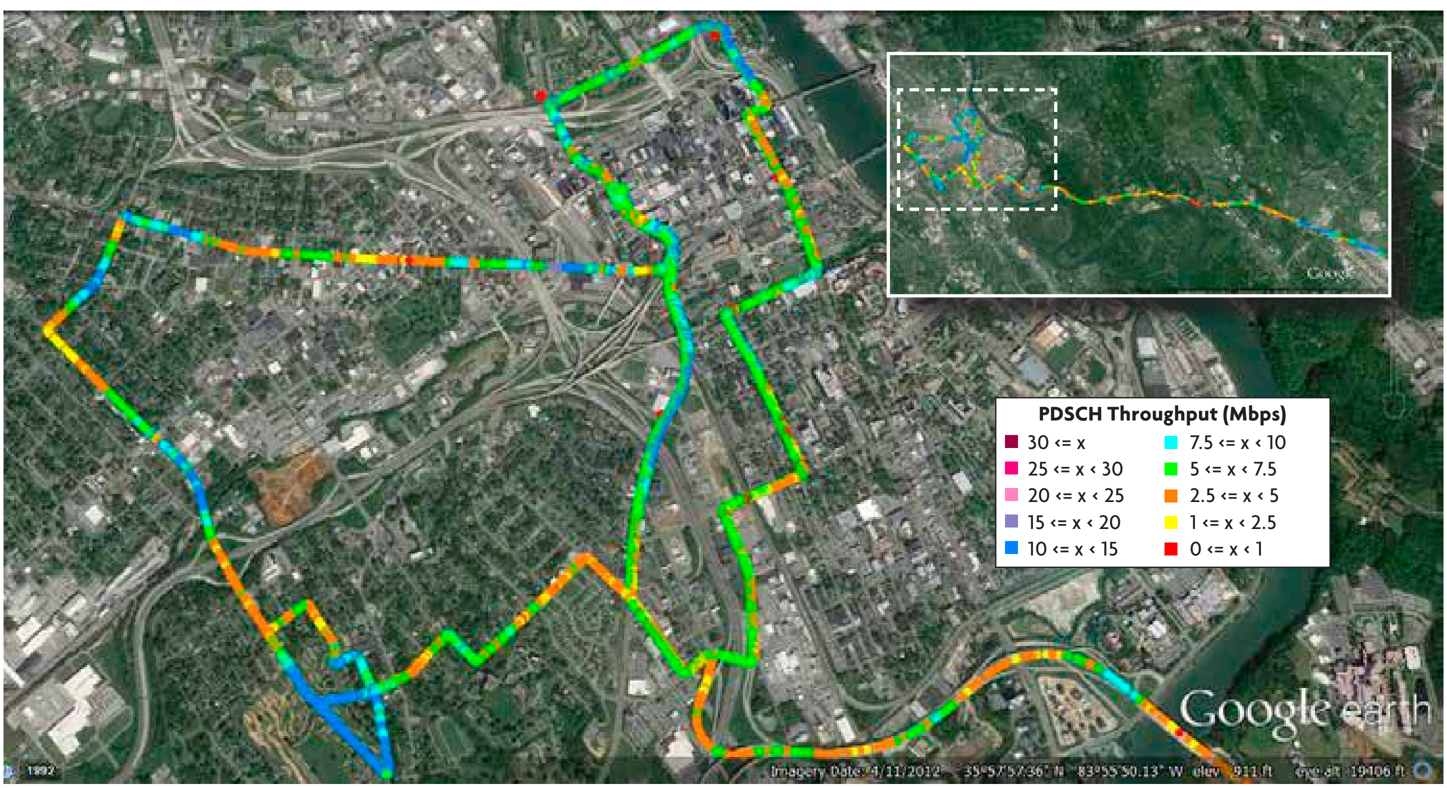
Figure 3. Probability Distribution of Daytime Physical Layer Throughput – Santa Clara Band 4 Network

PDSCH Throughput (Median) = 21.71 Mbps
PDSCH Throughput (Average) = 24.71 Mbps
Total Data Transfer = 108.7 GB



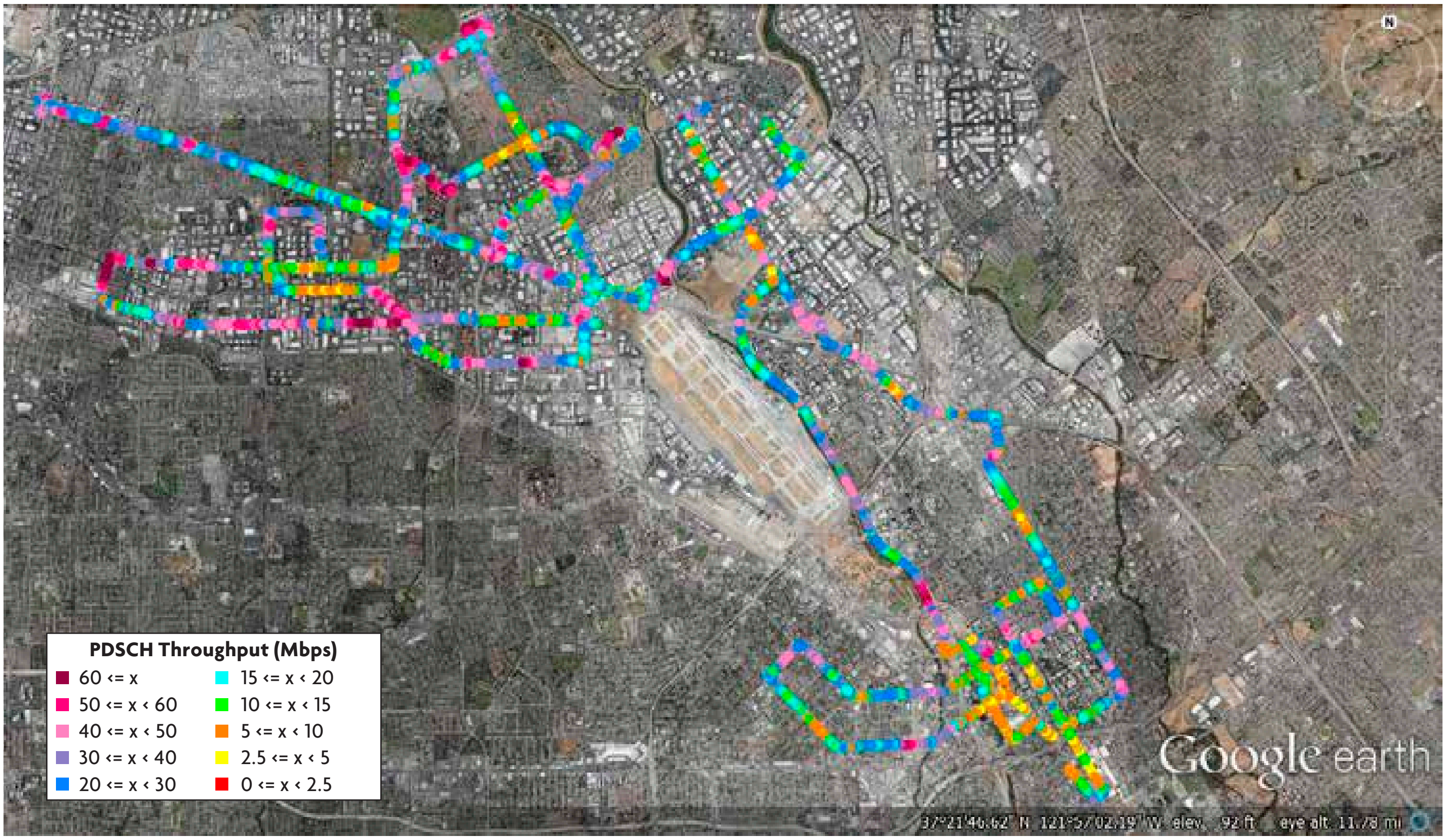
Source: Signals Research Group

Figure 4. Daytime Physical Layer Throughput – Knoxville Band 5 Network (geo plot)



Source: Signals Research Group

Figure 5. Distribution of Daytime Physical Layer Throughput – Santa Clara Band 4 Network (geo plot)



Source: Signals Research Group

As networks experience higher degrees of network loading the measured SINR will decline.

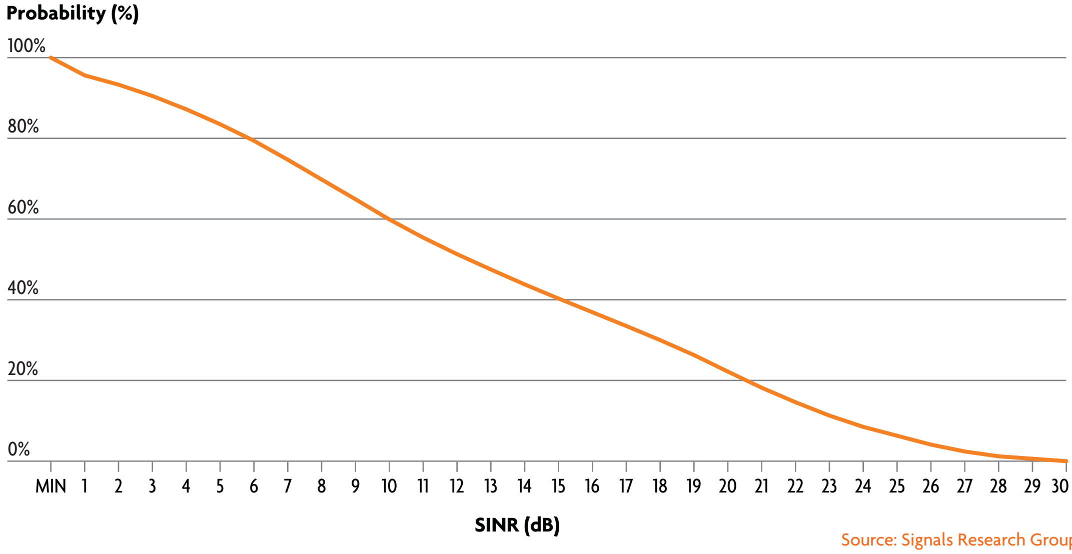
When it comes to determining the likely benefits of MIMO, one needs to look no further than the measured SINR, as reported by the mobile device. Within the 3GPP community, SINR isn't well defined other than its basic definition that it quantifies the quality of the desired signal relative to the noise level. Further, the reported SINR is a function of how the chipset measures and reports the value. In our case we used the same device/chipset for the TM 3 and TM 2 testing in each market, although a different device in each network, so the comparisons between the two transmission mode configurations are valid.

As we indicted in the previous chapter and demonstrate later in this report, the impact of MIMO is directly related to the SINR, in particular, the higher the reported SINR the higher the gain associated with MIMO. With this in mind, Figure 6 provides a probability distribution plot for the reported SINR in the Knoxville network and Figure 7 provides comparable information for the Santa Clara /San Jose market. These results are based on daytime testing so the SINR values are consistent with the typical characteristics of the network at this time. When the network is lightly-loaded the SINR should be at their best. Conversely, as networks experience higher degrees of network loading the measured SINR will decline. Poor coverage can also degrade the SINR and this situation can be verified with an analysis of the RSRP. The behavior of SINR as a function of network loading is an extremely important consideration that we will revisit in a moment. Both figures, and other parameters that we analyzed, suggest the networks were fairly lightly-loaded when we conducted our tests.

We will return to the SINR-related information presented in these two figures later in this chapter since we use the information to help quantify the likely benefits of MIMO in a commercial LTE network.

Figure 6. Probability Distribution of Daytime Reported SINR Values– Knoxville Band 5 Network

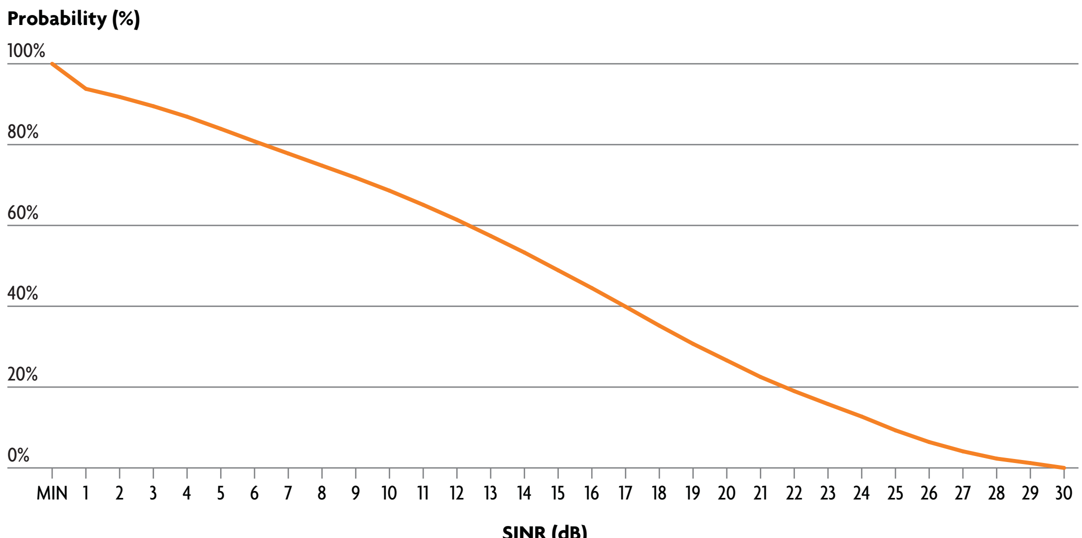
SINR (Median) = 12.3 dB	SINR (Average) = 12.9 dB



Source: Signals Research Group

Figure 7. Probability Distribution of Daytime Reported SINR Values – Santa Clara Band 4 Network

SINR (Median) = 14.7 dB	SINR (Average) = 14.1 dB



Source: Signals Research Group

3.2 Sample Nighttime Drive Test Results – Physical Layer Throughput versus SINR

We have included some sample results for Knoxville and Santa Clara in this section. Additional results are included in the appendix. For comparison purposes, and as previously stated in this report, the network in Knoxville used a 2 x 5 MHz channel and operated in Band 5 (850 MHz). The network in Santa Clara used a 2 x 10 MHz channel and operated in Band 4 ((DL ~ 2100 MHz, UL ~1700 MHz).

In both markets we selected random drive routes within the 27 to 45 cell sector test clusters that the two operators provided us for our testing.

In both markets we selected random drive routes within the 27 to 45 cell sector test clusters that the two operators provided us for our testing. In a few isolated regions the drive route took us outside of the clusters. Since the percentage of time was so low we generally left the results from these regions in the analysis that we conducted since we felt it wouldn't have any measureable impact on our analysis. In one case (Highway 101 in Santa Clara), we did remove the data from the non-cluster regions.

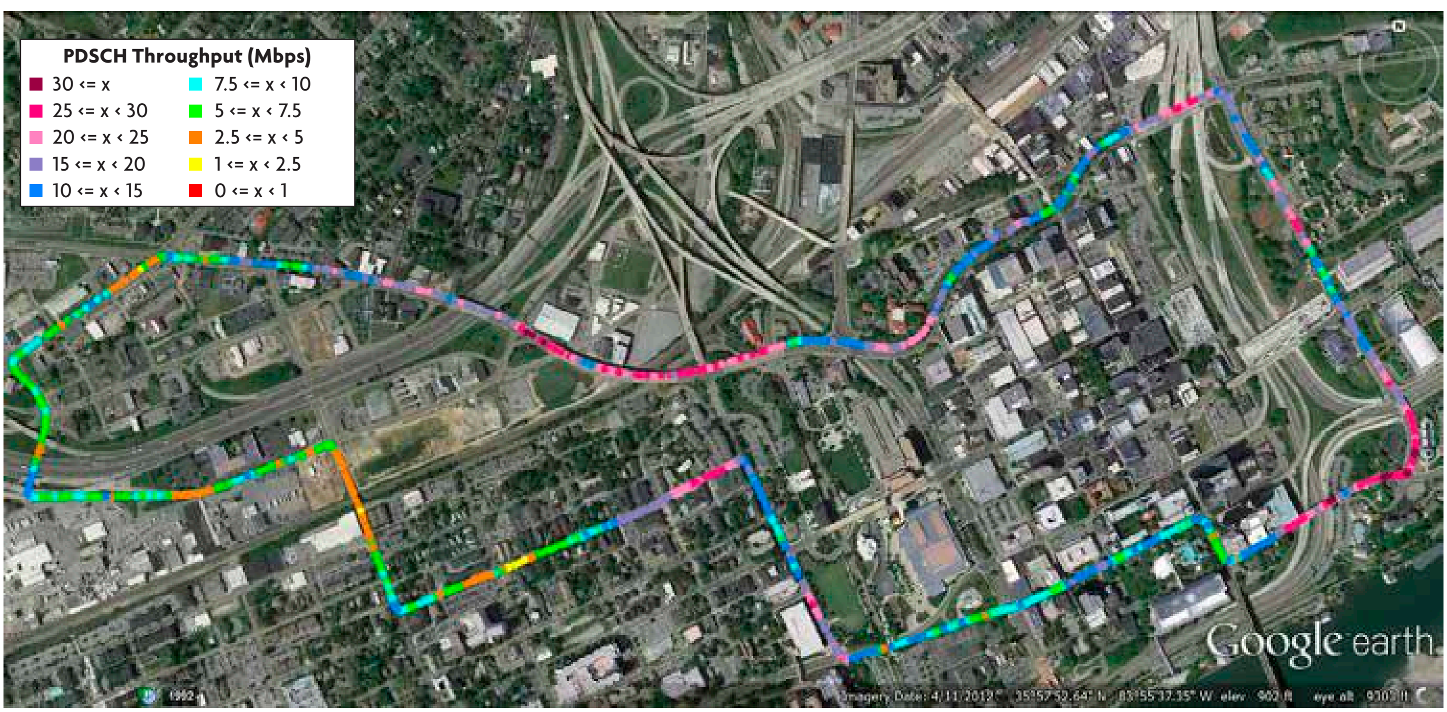
3.2.1 Sample Nighttime Drive Test Results – Knoxville Band 5 Network

The primary drive route was 4.7 miles, which took us approximately 18-19 minutes to drive.

The tests in Knoxville, Tennessee occurred on June 18th and June 19th. On June 18th we conducted the tests with TM 3 enabled and on June 19th we conducted the tests with TM 2 only. Figure 8 provides a geo plot of the Physical Layer throughput over the drive test route. The length of the primary drive route was nearly 4.7 miles and each test lasted approximately 18-19 minutes.

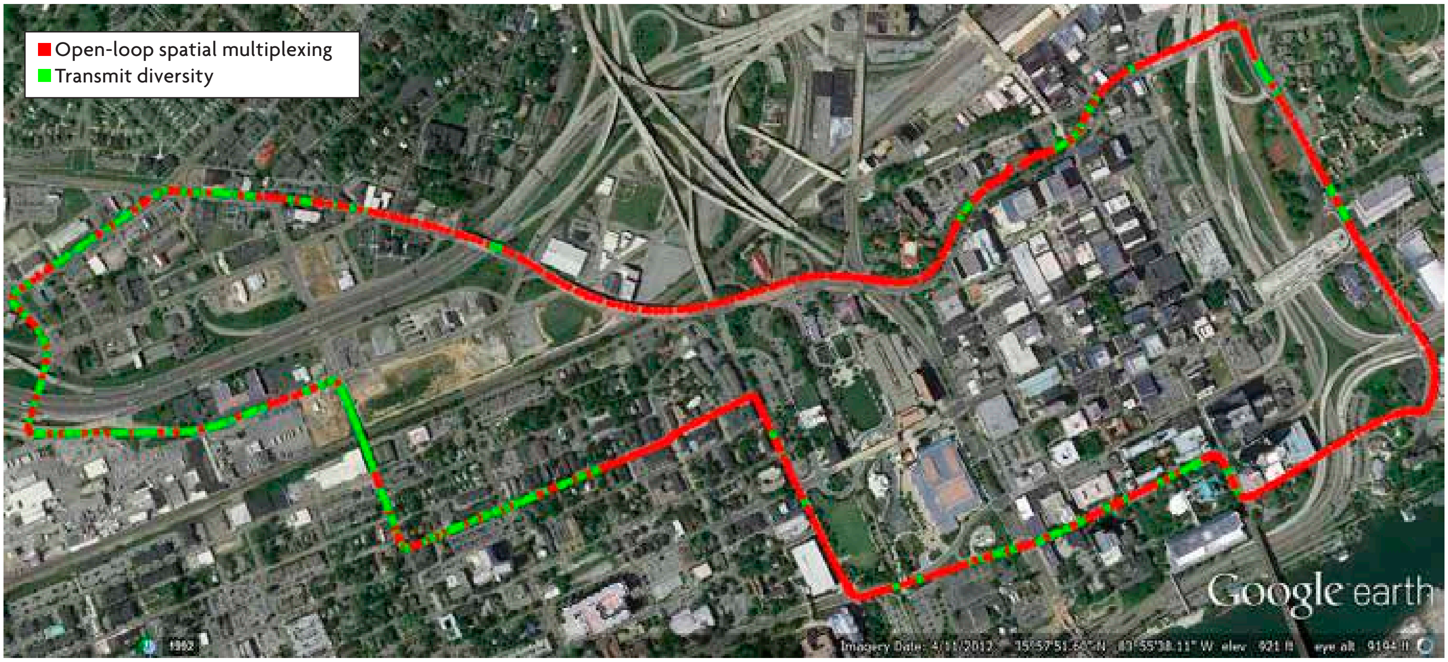
Figure 9 illustrates the usage of TM 3 and TM 2. As evident in the figure, just because TM 3 was available, doesn't mean that it was always used. For example, with lower SINR conditions a mobile device is more likely to request TM 2 than TM 3. Further, the network scheduler may assign the mobile device TM 2 when it requests TM 3, if, for example, the scheduler believes that the mobile device is over-estimating its ability to handle TM 3. However, from our analysis of the data, we observed that the network schedulers from the two infrastructure suppliers pretty much assigned the mobile device the transmission mode that it requested. We re-examine this observation in Section 3.4.

Figure 8. Physical Layer Throughput with TM 3 Enabled, June 18th, 0148 hours – Knoxville Band 5 Network (geo plot)



Source: Signals Research Group

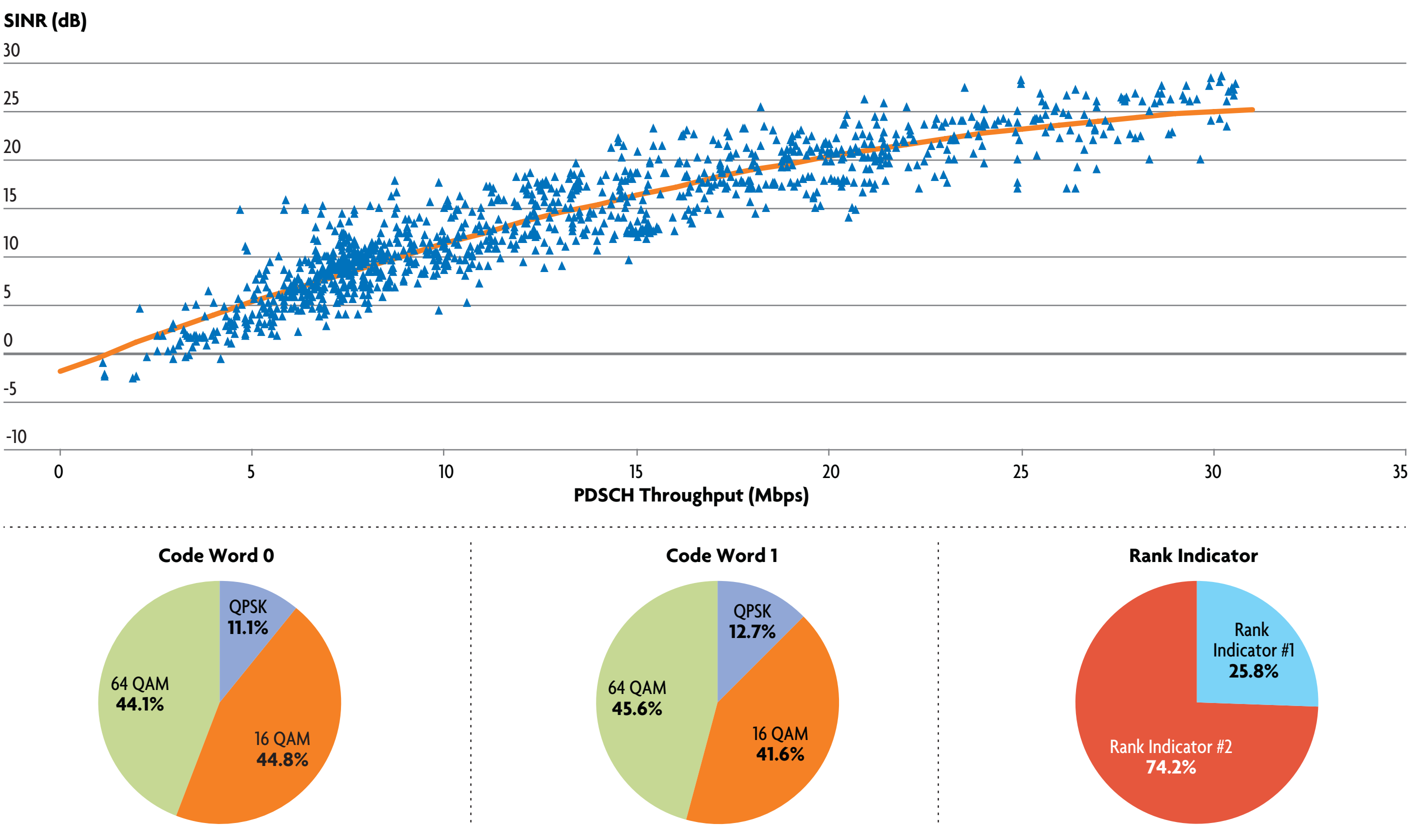
Figure 9. Transmission Mode Assignments with TM3 Enabled, June 18th, 0148 hours – Knoxville Band 5 Network (geo plot)



Source: Signals Research Group

Figure 10. Physical Layer Throughput Versus SINR Scatterplot Plus Assorted KPIs with TM 3 Enabled, June 18th 0148 hours – Knoxville Band 5 Network

PDSCH Throughput (Median) = 11.28 Mbps	PDSCH Throughput (Average) = 13.01 Mbps	SINR (Average) = 13.37 dB	CQI (Average) = 10.73
MCS #0 (Median) = 15.56	MCS #1 (Median) = 15.52	Num of RB (Average) = 23.55	



Source: Signals Research Group

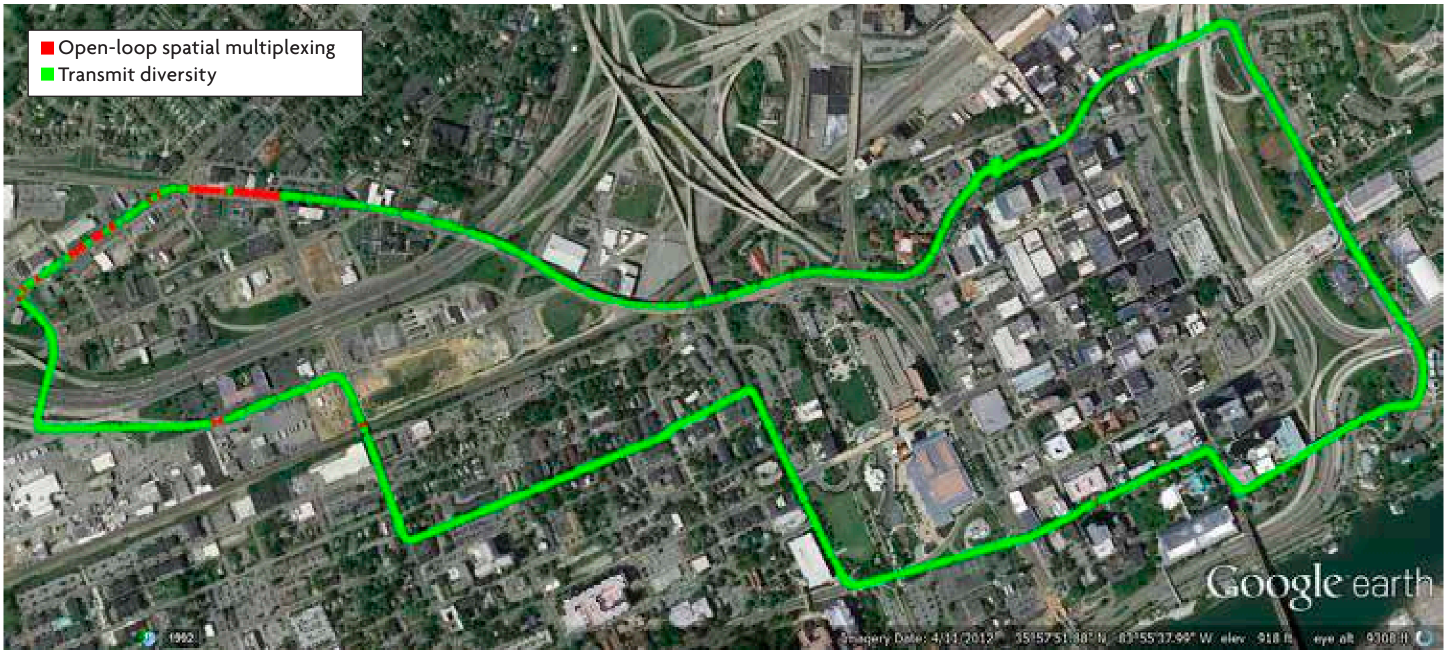
Figure 10 provides a wealth of information. The scatterplot shows the relationship between the Physical Layer throughput and the reported SINR. The plotted line shows the "best fit" relationship between the two KPIs – generally we used a 2nd order polynomial fit. The text above the scatterplot identifies other relevant KPIs, including the average and median throughput, the reported SINR and CQI, the average number of assigned resource blocks (RBs) and the median Modulation and Coding Scheme (MCS) for each code word, or orthogonal data streams with MIMO. There are three pie charts below the scatterplot. Two of the pie charts show the distribution of modulation schemes (QPSK, 16 QAM and 64 QAM) for each code word. Finally, the Rank Indicator pie chart shows the distribution of the two transmission modes. In this drive test, Rank Indicator 2 (MIMO or TM 3) was requested/assigned 74.2% of the time and Rank Indicator 1 (no MIMO or TM 2) was requested/assigned 25.8% of the time.

The next set of figures show the results from the second night when TM 3 was disabled, meaning that TM 2 was the only available transmission mode. Figure 11 provides a geo plot of the throughput and Figure 12 illustrates the usage of transmission modes. As previously indicated, our drive route unintentionally took us briefly outside of the test cluster. In these situations, the mobile device could receive TM 3 – note the brief appearances of the "red dots" in the figure. Since this situation happened only very briefly, we elected to include the data when we conducted the analysis.

Figure 11. Physical Layer Throughput with TM 2 Only, July 19th, 0117 hours – Knoxville Band 5 Network (geo plot)

Source: Signals Research Group

Figure 12. Transmission Mode Assignments with TM2 Only, June 19th, 0117 hours – Knoxville Band 5 Network (geo plot)

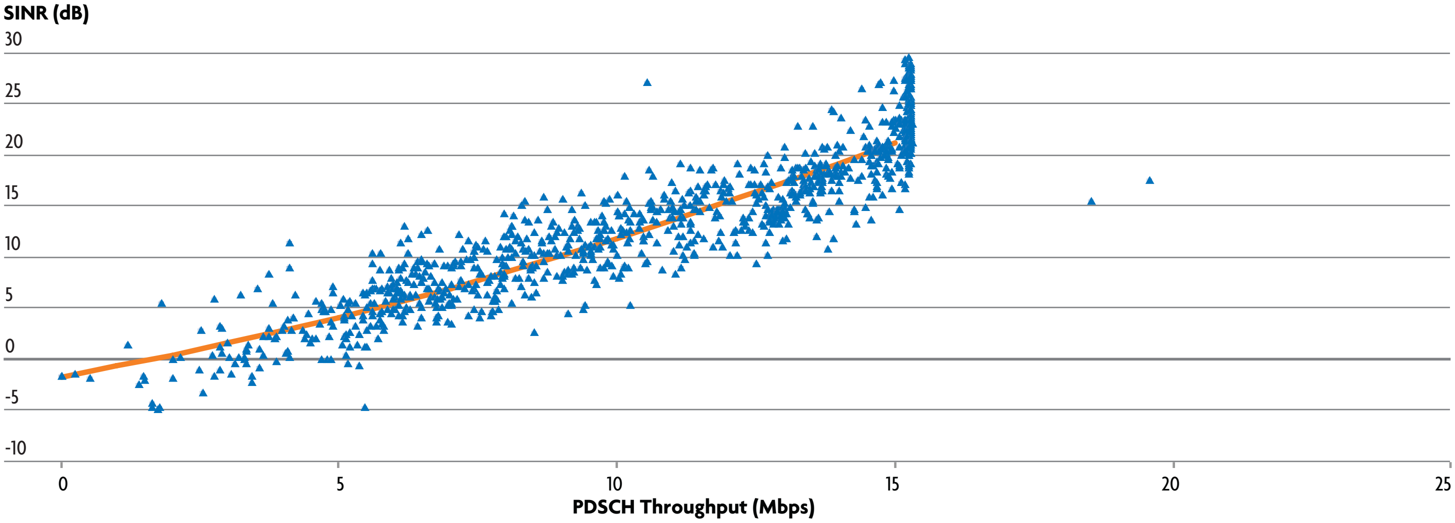


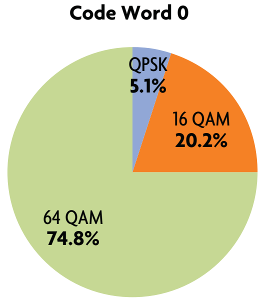
Source: Signals Research Group

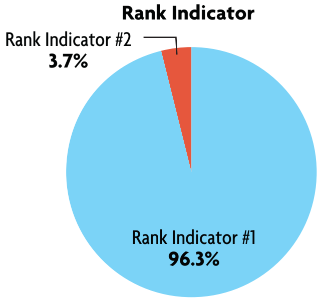
Figure 13. Physical Layer Throughput Versus SINR Scatterplot Plus Assorted KPIs with TM 2 Only, June 19th 0117 hours – Knoxville Band 5 Network

PDSCH Throughput (Median) = 11.58 Mbps
SINR (Average) = 13.72 dB
MCS #0 (Median) = 20.76
Num of RBs (Average) = 23.26

PDSCH Throughput (Average) = 10.78 Mbps
CQI (Average) = 12.9
MCS #1 (Median) = NM







Source: Signals Research Group

The MCS values and subsequently the availability of 64 QAM favored the TM 2 only results.

Figure 13 provides the same information that was provided in Figure 10. As shown in the scatter-plot, the throughput is limited to roughly 15 Mbps without Transmission Mode 3. The two dots near 20 Mbps were reported when we were outside the test cluster. In fact, it is evident that the maximum TM 2 throughput can be reached with a relatively low SINR value (~20 dB) and that higher SINR values have no incremental benefit on the delivered throughput. Comparing the two figures, the average throughput is ~20% higher with TM 3 enabled but the median throughput is actually higher with TM 2 only. It is also interesting to point out that the MCS values and subsequently the availability of 64 QAM favored the TM 2 only results. This outcome is expected since without the second data stream the quality of the signal for the single data stream should be higher. The Rank Indicator pie chart shows the use of TM 3 when we unintentionally drove outside of the test cluster.

3.2.2 Sample Nighttime Drive Test Results – Santa Clara Band 4 Network

With TM 3 enabled, the average Physical Layer throughput was an impressive 31.1 Mbps.

The testing in Santa Clara occurred on July 18th (TM 3) and July 19th (TM 2 only). The primary drive route was 9.7 miles, which took us roughly 20 minutes to complete. Figure 14 shows a geo plot of the Physical Layer throughput with TM 3 enabled and Figure 15 illustrates the usage of TM 3 and TM 2.

Figure 16 provides important information regarding the performance of the network with TM 3 enabled. With TM 3 enabled, the average Physical Layer throughput was an impressive 31.1 Mbps, thanks in part to a very favorable distribution of reported SINR values. We downloaded slightly more than 3.7 GB during this particular test.

Figure 14. Physical Layer Throughput with TM 3 Enabled, July 18th, 0232 hours – Santa Clara Band 4 Network (geo plot)

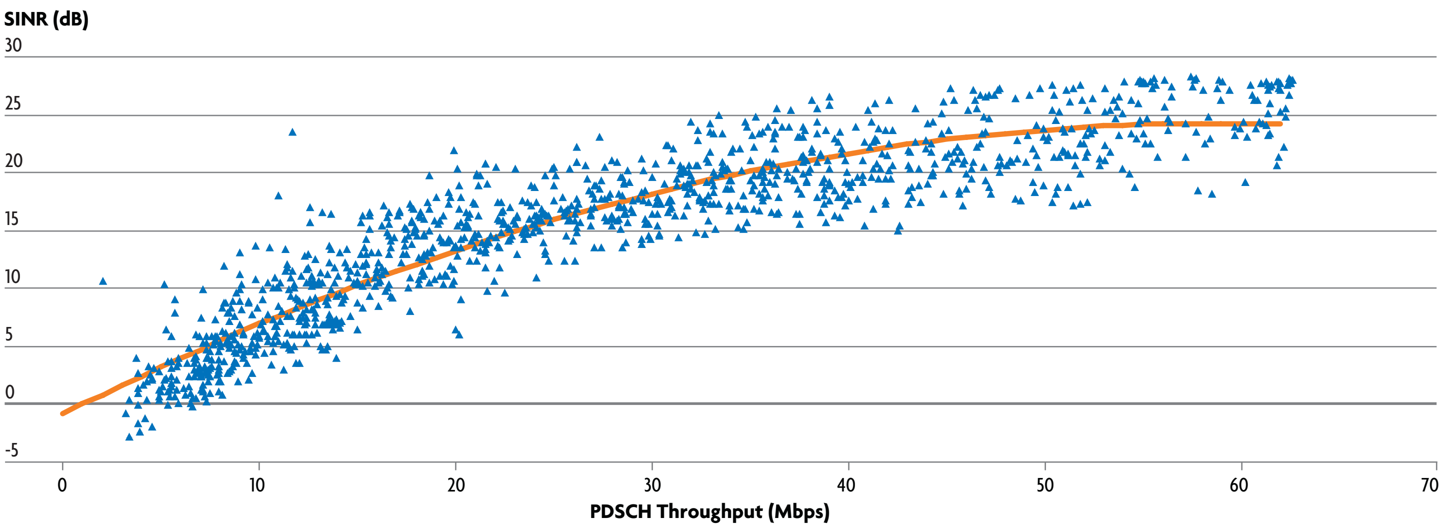
Source: Signals Research Group

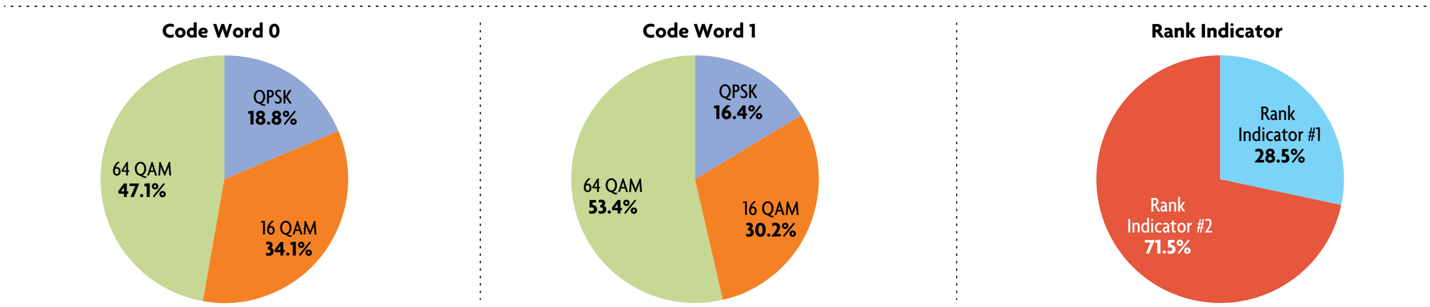
Figure 15. Transmission Mode Assignments with TM3 Enabled, July 18th, 0232 hours – Santa Clara Band 4 Network (geo plot)

Source: Signals Research Group

Figure 16. Physical Layer Throughput Versus SINR Scatterplot Plus Assorted KPIs with TM 3 Enabled, July 18th 0232 hours – Santa Clara Band 4 Network

PDSCH Throughput (Median) = 28.61 Mbps	PDSCH Throughput (Average) = 31.1 Mbps	SINR (Average) = 15.2 dB	CQI (Average) = 10.42
MCS #0 (Median) = 15.87	MCS #1 (Median) = 17.33	Num of RB (Average) = 46.7	





Source: Signals Research Group

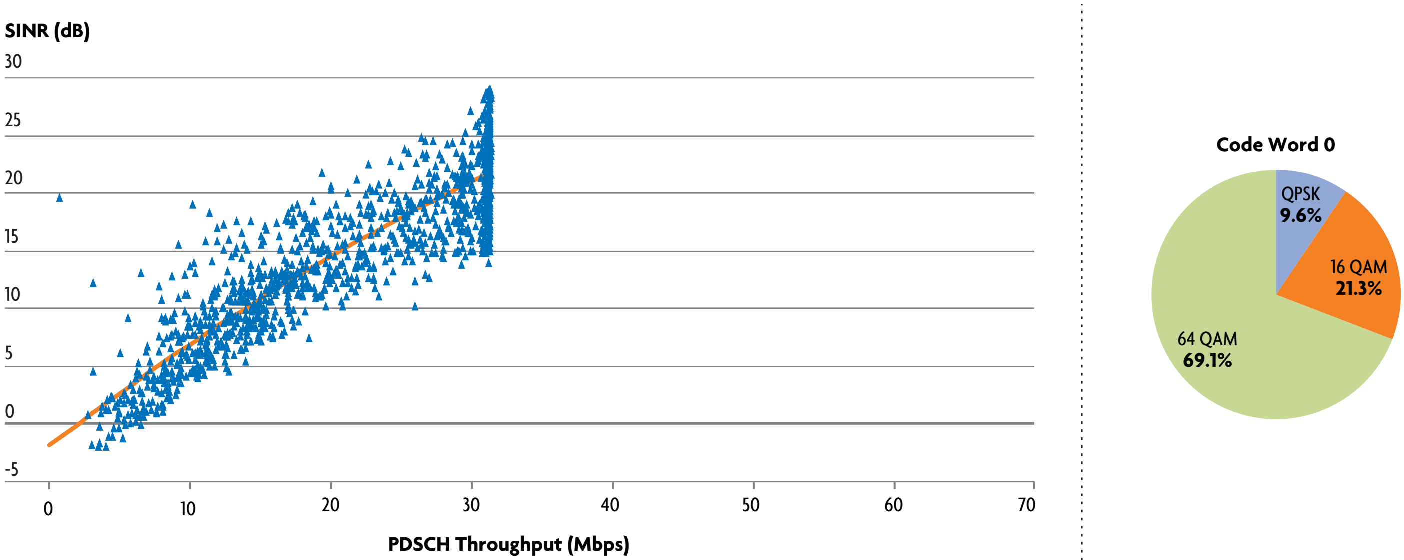
The next set of figures pertains to the network configured to only support TM 2. Figure 17 provides a geo plot of the throughput and Figure 18 provides a similar set of information that we provided in Figure 16. We are not showing a geo plot of the transmission modes since it would have shown that TM 2 was used 100% of the time.

Figure 17. Physical Layer Throughput with TM 2 Only, July 19th, 0105 hours – Santa Clara Band 4 Network (geo plot)

Source: Signals Research Group

Figure 18. Physical Layer Throughput Versus SINR Scatterplot Plus Assorted KPIs with TM 2 Only, July 19th 0105 hours – Santa Clara Band 4 Network

PDSCH Throughput (Median) = 21.37 Mbps	PDSCH Throughput (Average) = 20.98 Mbps
SINR (Average) = 14.77 dB	CQI (Average) = 12.33
MCS #0 (Median) = 21.60	MCS #1 (Median) = N.M.
Num of RB (Average) = 46.8	



Source: Signals Research Group

Comparing Figure 16 and Figure 18, the average throughput over the entire drive test route was 44.3% higher with TM 3 enabled and the median throughput was 33.8% higher. The primary reason for the much higher throughput with TM 3 enabled was the favorable SINR values. Consistent with the Knoxville results, it is clearly evident that the throughput is limited with TM 2 only since the maximum throughput of ~31 Mbps was achieved with a SINR of only 15 dB, meaning that higher SINR values didn't result in higher throughput.

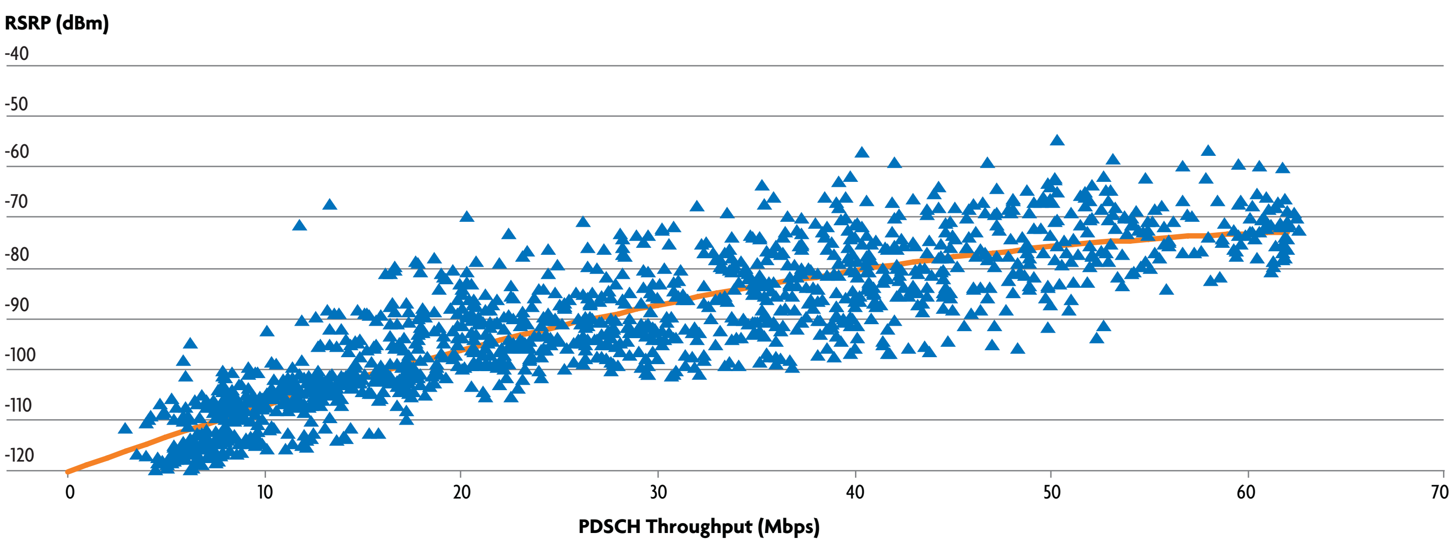
3.3 Sample Nighttime Drive Test Results – Physical Layer versus RSRP

In this section we briefly compare the relationship between Physical Layer throughput and RSRP (Reference Signal Received Power). Figure 19 provides a scatterplot of the Physical Layer throughput and the associated RSRP values along with a line of fitted values.

At or below an RSRP of approximately -100 dBm there is no benefit in end user throughput associated with the availability of TM 3.

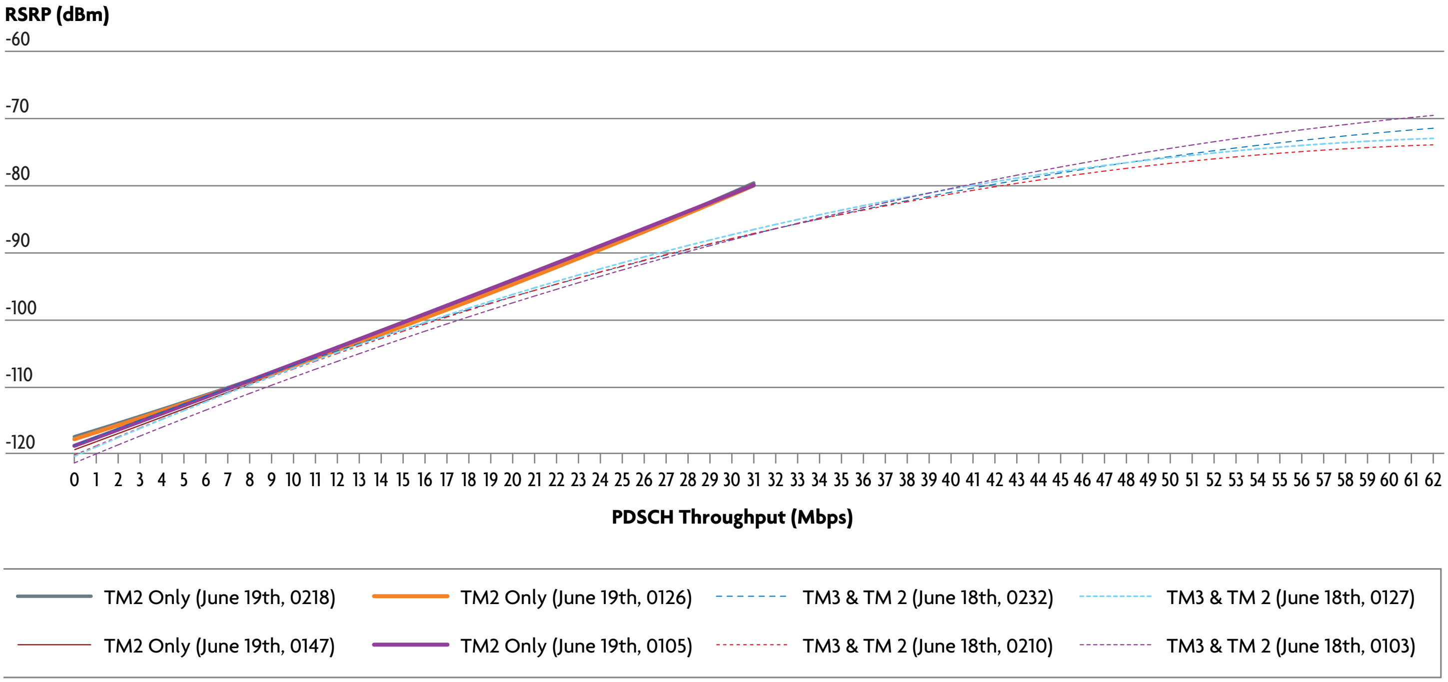
For each Santa Clara drive test we created a Physical Layer throughput versus RSRP scatterplot and the corresponding line of fitted values. Figure 20 shows the line of fitted values for each drive test. Note that there is what we consider to be a fairly high degree of consistency for the grouping of TM 3 Enabled and TM 2 Only lines. We then averaged the values for each grouping of fitted value lines. This information is shown in Figure 21. From this figure we can conclude that at or below an RSRP of approximately -100 dBm there is no benefit in end user throughput associated with the availability of TM 3. In fact, the data suggests that at very low RSRP values the availability/use of TM 3 actually results in lower throughput. In this case, we believe that this result could stem from some inaccuracies of the fitted lines at both ends of the range. Further, just because TM 3 was available with the lower RSRP values doesn't necessarily mean that it was used. That being the case, we demonstrate in the next section that TM 3 was used fairly aggressively and that it appeared to have a slightly negative impact on the end user throughput.

Figure 19. Physical Layer Throughput Versus RSRP Scatterplot with TM 3 Enabled, July 18th 0127 hours – Santa Clara Band 4 Network



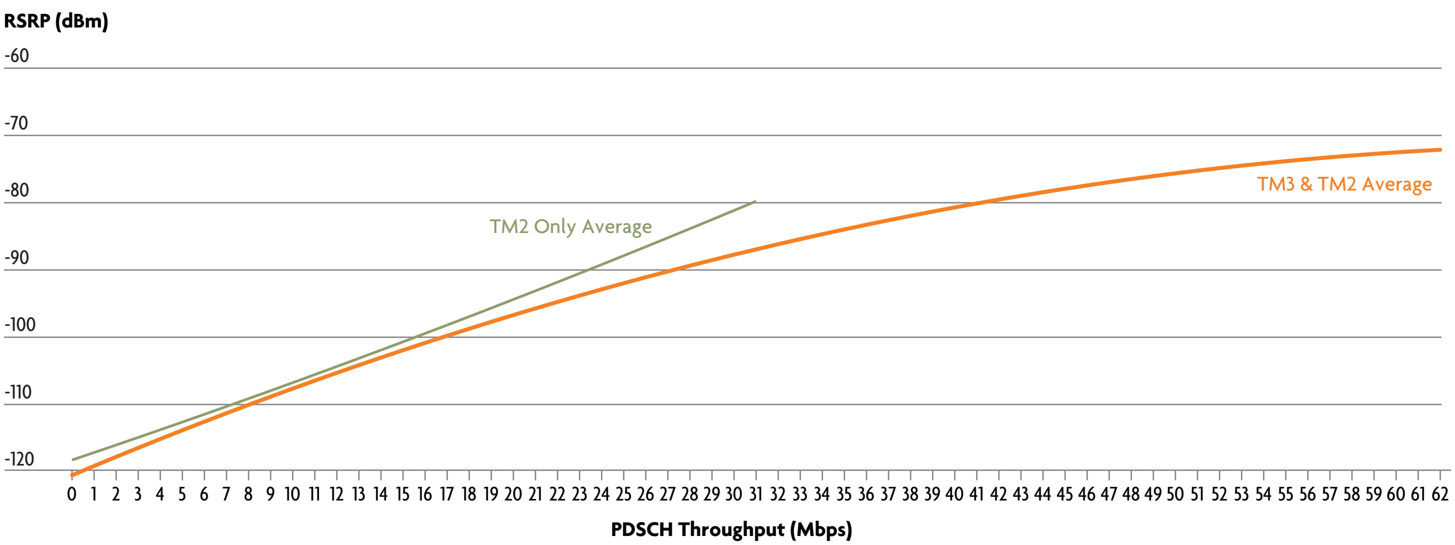
Source: Signals Research Group

Figure 20. Physical Layer Throughput Versus RSRP for all Drive Tests – Santa Clara Band 4 Network



Source: Signals Research Group

Figure 21. Consolidated Physical Layer Throughput Versus RSRP for TM 3 Enabled Versus TM 2 Only – Santa Clara Band 4 Network



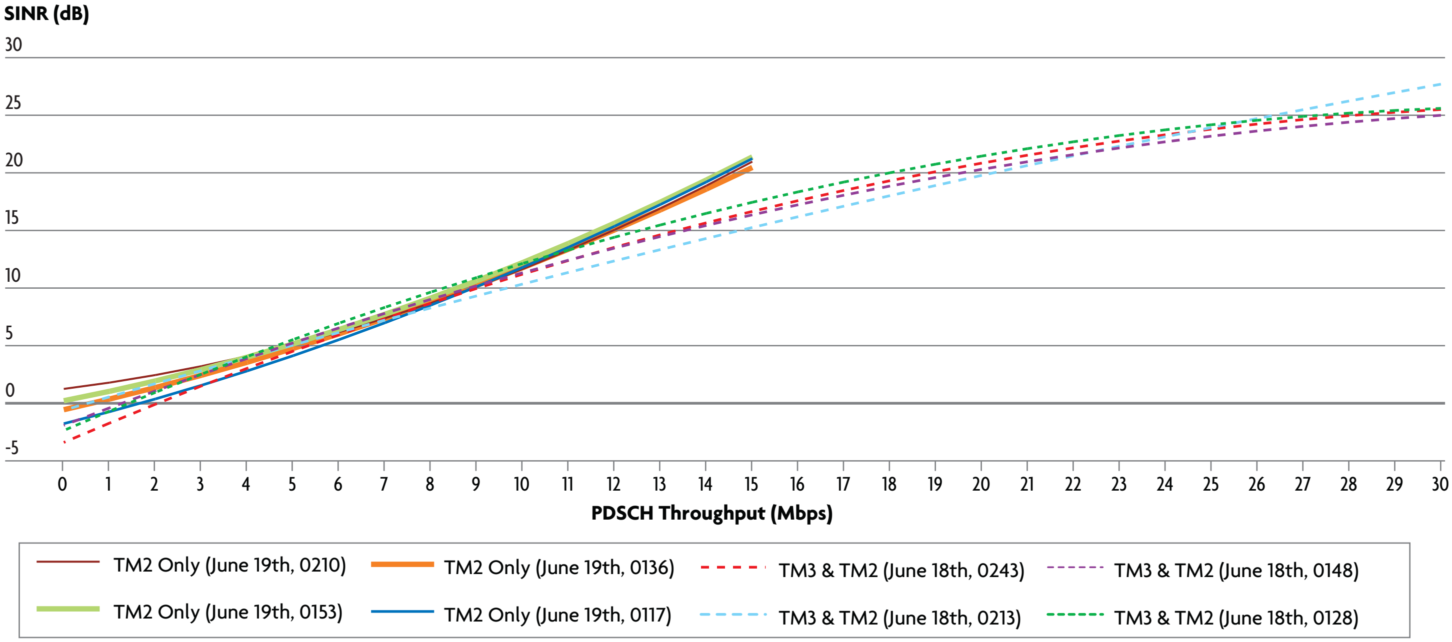
Source: Signals Research Group

3.4 Mapping MIMO Performance Impacts as a Function of SINR

In this section we tie everything together to quantify the impact of MIMO in a commercial LTE network. For each drive test, we created a scatterplot of the throughput versus the reported SINR, and then for each scatterplot we inserted a line of fitted values that shows the best correlation between the throughput and the corresponding SINR values. This approach is identical to the approach we used for the RSRP plots in the previous section.

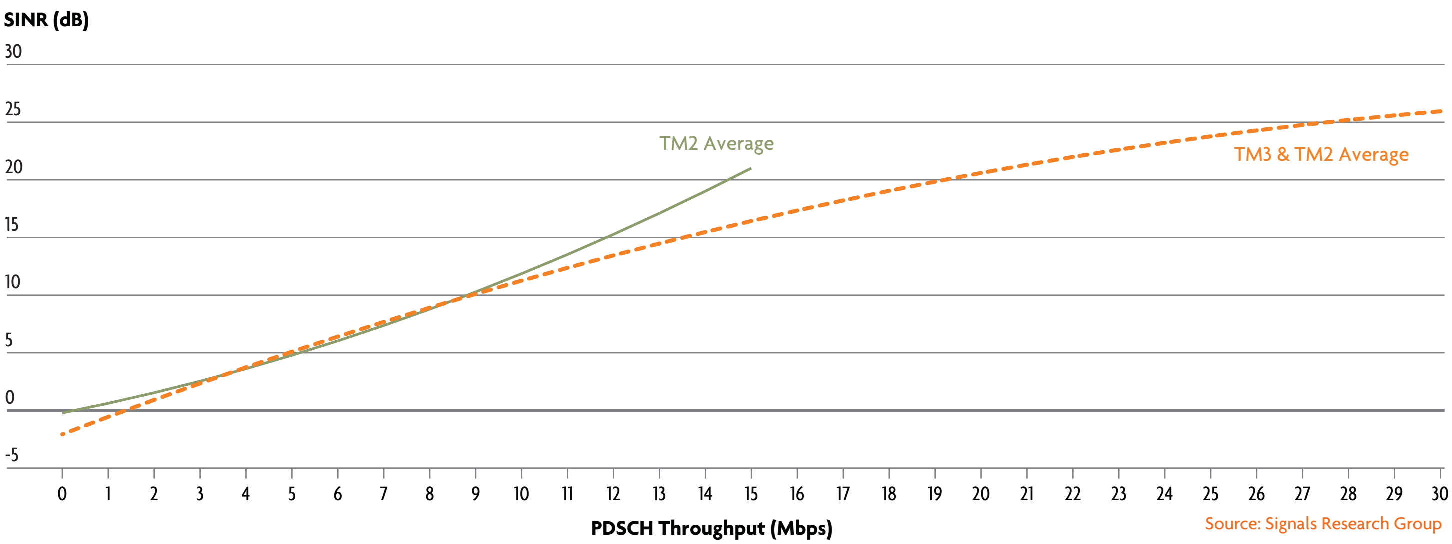
Figure 22 shows each line of fitted values from the Knoxville network. Figure 23 shows the average values within each grouping of lines – one line shows TM 3 Enabled and one line shows TM 2 Only. As shown in Figure 22, the results are fairly consistent across all drive tests. Among other findings, Figure 23 shows that with a SINR of less than 10 dB, there isn't much, if any, benefit in

Figure 22. Physical Layer Throughput Versus SINR for all Drive Tests – Knoxville Band 5 Network



Source: Signals Research Group

Figure 23. Consolidated Physical Layer Throughput Versus SINR for TM 3 Enabled Versus TM 2 Only – Knoxville Band 5 Network

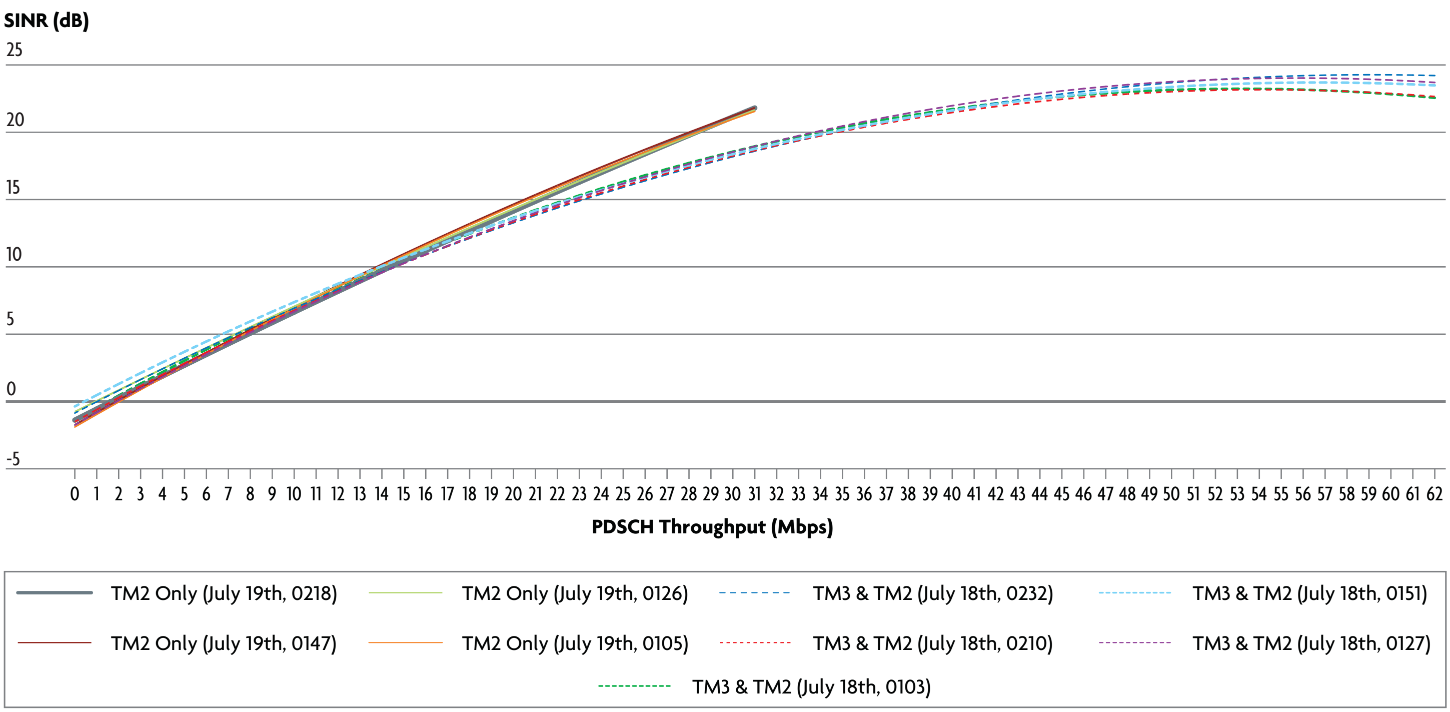


Source: Signals Research Group

end user data rates due to the availability of TM 3. It is also evident that TM 3 can deliver significant gains with higher SINR values.

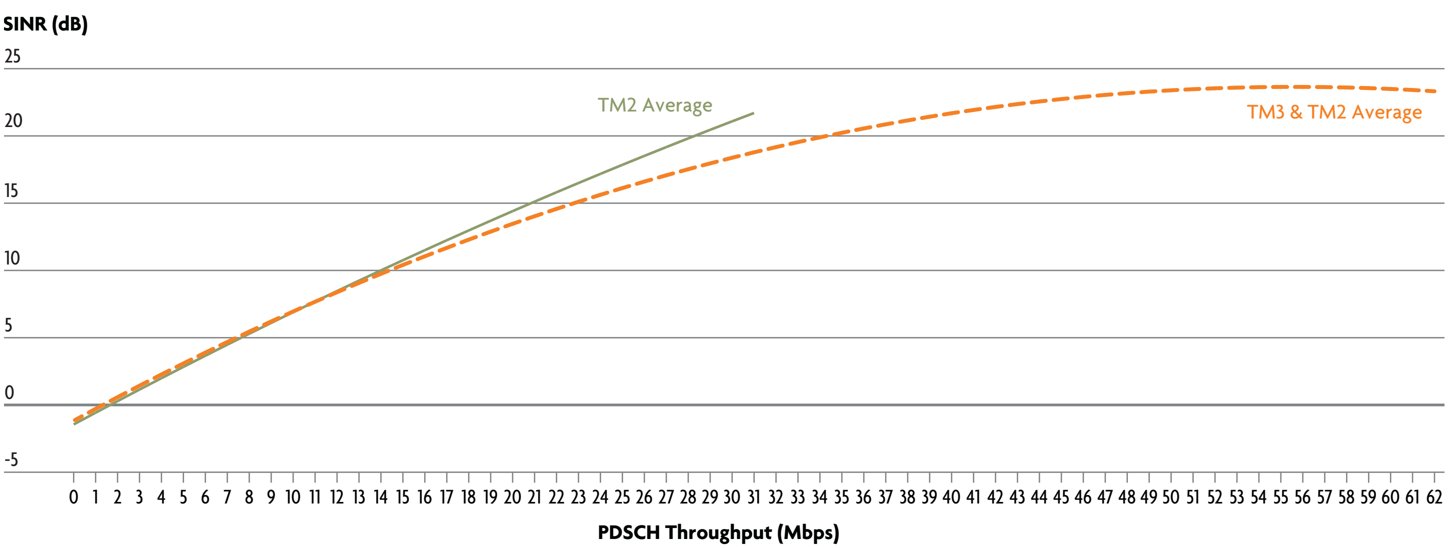
Figure 24 and Figure 25 provide comparable results for the Santa Clara network. Setting aside the differences in channel bandwidth, which led to much higher overall data rates, the results between the two networks are fairly similar.

Figure 24. Physical Layer Throughput Versus SINR for all Drive Tests – Santa Clara Band 4 Network



Source: Signals Research Group

Figure 25. Consolidated Physical Layer Throughput Versus SINR for TM 3 Enabled Versus TM 2 Only – Santa Clara Band 4 Network



Source: Signals Research Group

We grouped the results into buckets of SINR values for the two network configurations.

In addition to calculating fitted values, we also grouped the results into buckets of SINR values for the two network configurations. Specifically, we grouped the Physical Layer throughput results into five buckets: Reported SINR > 25 dB, 20 dB < Reported SINR < 25 dB; 15 dB < Reported SINR < 20 dB; 10 dB < Reported SINR < 15 dB; and Reported SINR < 10 dB. Within each bucket, we averaged all measured throughput values for the two network configurations. Note that this approach is different than the methodology that we used to create the information shown in previous figures, such as Figure 25. Table 1 shows the results of this effort for the Knoxville network. Figure 26 shows the same results in bar format with the inset showing the relative performance differences between TM 3 Enabled and TM 2 Only.

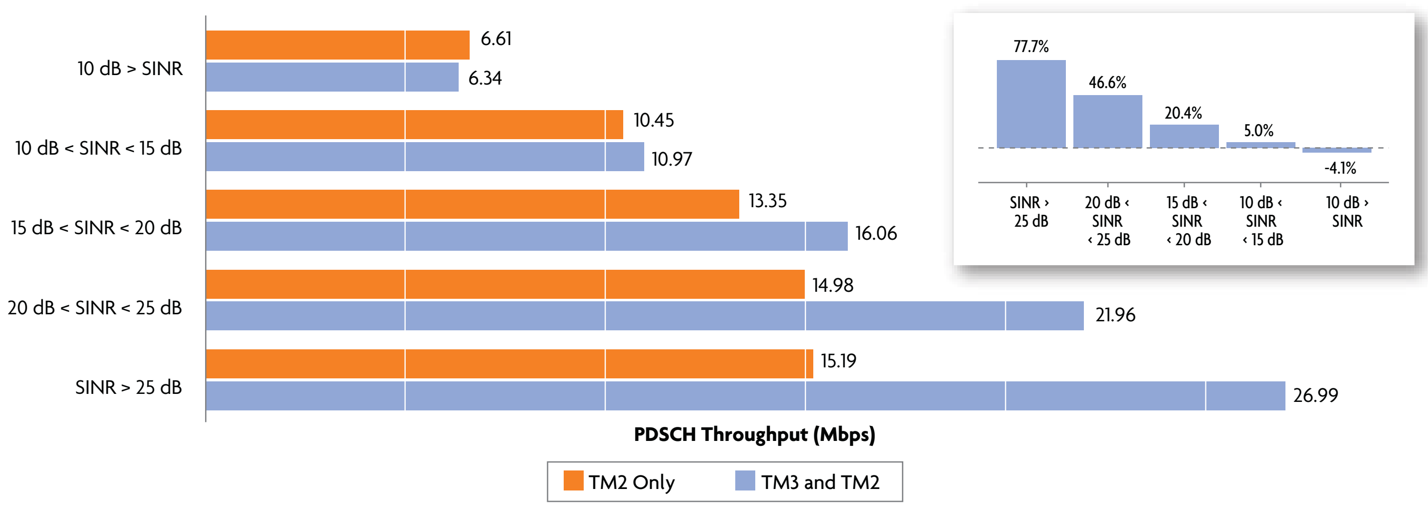
Table 1. Physical Layer Throughput Gains with TM 3 Enabled Versus TM 2 Only as a Function of SINR – Knoxville Band 5 Network

	PDSCH Throughput - Average (Mbps)				
	SINR > 25 dB	20 dB < SINR < 25 dB	15 dB < SINR < 20 dB	10 dB < SINR < 15 dB	10 dB > SINR
TM3 and TM2	**26.99**	**21.96**	**16.06**	**10.97**	**6.34**
June 18th 0128	25.57	22.89	15.46	10.15	5.39
June 18th 0148	27.42	21.76	16.28	11.10	6.74
June 18th 0213	28.51	22.36	16.19	13.26 **	6.71
June 18th 0243	26.48	20.82	16.32	11.26	6.52
TM2 Only	**15.19**	**14.98**	**13.35**	**10.45**	**6.61**
June 19th 0117	15.12	15.00	13.27	10.74	6.20
June 19th 0136	15.24	14.99	13.79	10.77	6.53
June 19th 0153	15.26	15.06	12.87	10.41	6.52
June 19th 0210	15.13	14.87	13.45	9.90	7.18

** PDSCH Throughput excluding 0 mph = 11.39 Mbps.

Source: Signals Research Group

Figure 26. Physical Layer Throughput Gains with TM 3 Enabled Versus TM 2 Only as a Function of SINR – Knoxville Band 5 Network



Source: Signals Research Group

When the reported SINR was below 10 dB, the TM 3 Enabled throughput was lower than the TM 2 Only throughput.

Table 2 and Figure 27 provide comparable results for the Santa Clara network. Setting aside the differences in channel bandwidth, the results between the two networks are fairly consistent. When the SINR was higher than 25 dB, the throughput was up to 77.7% higher with TM 3 enabled in the Knoxville network. The gain was 64.3% in the Santa Clara network. When the SINR was between 10 dB and 15 dB the performance gain with TM 3 enabled was a modest 5-6%. Interestingly, when the reported SINR was below 10 dB, the TM 3 Enabled throughput was lower than the TM 2 Only throughput in both markets.

We recognize that there is a fairly large spread between the minimum reported SINR value and 10 dB. However, even in the range of 10 dB to 15 dB, the benefits of MIMO were only single digit values.

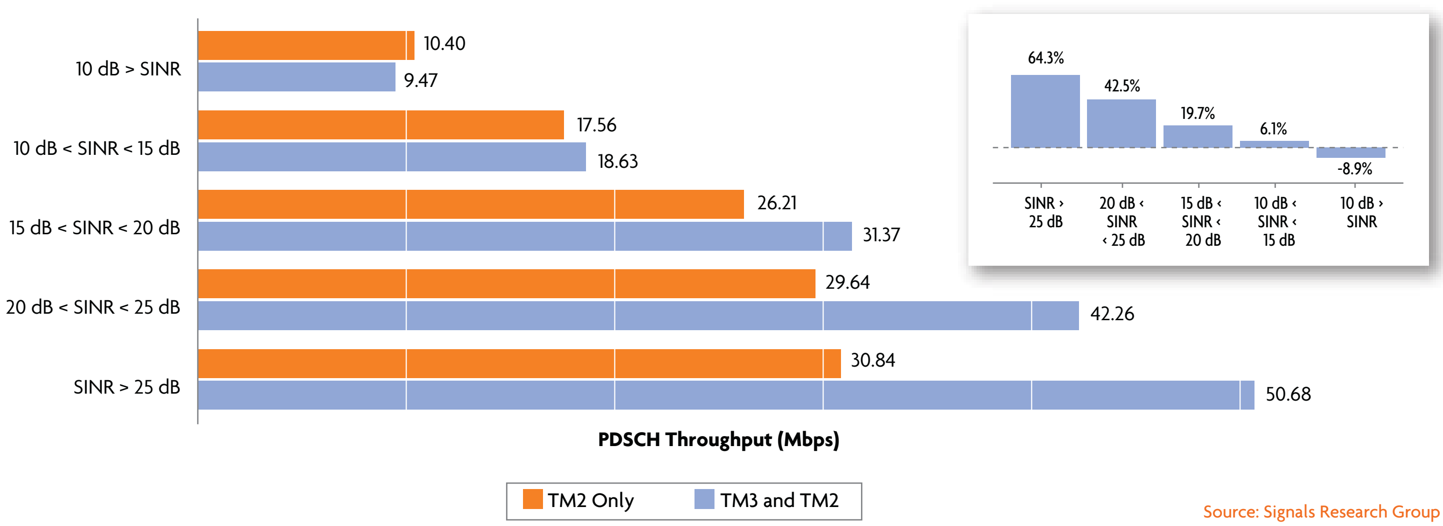
With one exception the results from each drive test were fairly consistent with each other. The one exception was during the June 18th 0213 drive test in Knoxville, when the throughput within the SINR range of 10 dB to 15 dB was measurably higher than the throughput during the other three drive tests within the same range. Upon reflection, we recalled one drive test when we were "stuck" at a traffic light for an unordinary amount of time. Therefore, we went back to the data file and excluded all results when the vehicular speed was 0 mph and recalculated the throughput within each grouping of SINR values for this drive test. Only one throughput value changed – the one in

Table 2. Physical Layer Throughput Gains with TM 3 Enabled Versus TM 2 Only as a Function of SINR – Santa Clara Band 4 Network

	PDSCH Throughput - Average (Mbps)				
	SINR › 25 dB	20 dB ‹ SINR ‹ 25 dB	15 dB ‹ SINR ‹ 20 dB	10 dB ‹ SINR ‹ 15 dB	SINR ‹ 10 dB
TM 3 and TM 2	**50.68**	**42.26**	**31.37**	**18.63**	**9.47**
July 18th, 0103	51.86	43.63	32.68	17.85	8.27
July 18th, 0127	50.01	41.31	31.34	19.12	9.31
July 18th, 0151	46.68	41.13	31.27	19.68	10.56
July 18th, 0210	51.06	42.65	30.85	18.38	9.61
July 18th, 0232	53.79	42.57	30.70	18.11	9.63
TM 2 Only	**30.84**	**29.64**	**26.21**	**17.56**	**10.40**
July 18th, 0105	31.16	29.71	25.63	17.90	10.16
July 18th, 0126	30.90	29.77	26.33	17.05	9.96
July 18th, 0147	30.31	29.33	26.59	17.08	11.66
July 18th, 0218	30.96	29.77	26.28	18.20	9.79

Source: Signals Research Group

Figure 27. Physical Layer Throughput Gains with TM 3 Enabled Versus TM 2 Only as a Function of SINR – Santa Clara Band 4 Network



Source: Signals Research Group

question – and the new value (11.39 Mbps) is consistent with the other values. We used this new value when calculating the average.

Figure 28, which we previously showed in Chapter 2, ties everything together. The two pie charts, one for each network/band, show the end user throughput gains associated with the availability of TM 3 relative to an LTE network configured to only support TM 2. Each slice of the pie corresponds to one of the buckets of SINR values that we previously identified (e.g., reported SINR > 25 dB, 20 dB < reported SINR < 25 dB, etc.). The size of each slice of the pie, or the probability that the pertinent throughput gain is achieved stems from the SINR probability plots that we showed in Figure 6 (Knoxville) and Figure 7 (Santa Clara). For example, in the Knoxville network the reported SINR was higher than 25 dB for 6.3% of the time so the figure indicates that "Very Meaningful MIMO Gain" should occur 6.3% of the time, based on the data from the Knoxville network.

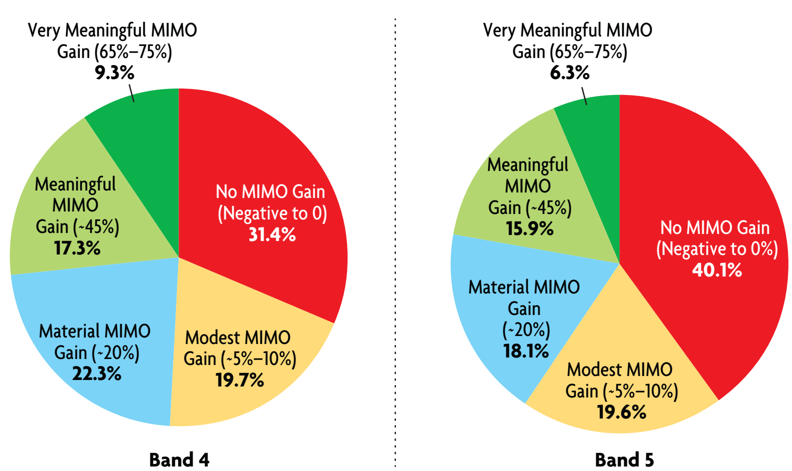
To make comparisons between the two figures easier, we have used the same ranges for each grouping of values. The data actually suggests that the throughput gain with TM 3 was higher in Knoxville (77.7% gain) with SINR > 25 dB than it was in Santa Clara (64.3% gain) and that the throughput degradation with TM 3 was lower in Knoxville (-4.1% gain) than it was in Santa Clara (-8.9% gain). The actual results, which suggest some measurable differences between the two networks, could be due to vendor-specific implementations or they could be due to the distribution of SINR within each grouping. Another distinct possibility is vehicular speed, since we needed to drive a bit faster along the Santa Clara routes that we selected. For purposes of this study, we didn't feel that resolving these minor differences was worth pursuing.

Setting aside this observation, the results from the two networks are fairly consistent. To the extent that there are differences, they are largely due to different distributions in the reported SINR values – the Santa Clara network had slightly better SINR.

One can look at the results and conclude that the glass is half-full or conclude that the glass is half-empty.

One can look at the results and conclude that the glass is half-full or conclude that the glass is half-empty. The optimist (half-full) would observe that at least 40% of the time the availability of TM 3 can increase the end user throughput by at least 20%, subject to the distribution of reported SINR values. The exact percentages that we observed are 40.3% (Knoxville) and 48.9% (Santa Clara). The pessimist would observe that at least 50% of the time, the availability of TM 3 would only have a modest impact on throughput (~5%-10%), at best, and that 30-40% of the time the availability of TM 3 could actually degrade end user throughput, or at least have no positive influence.

Figure 28. The Impact of MIMO in a Commercial LTE Network – Band 4 and Band 5



Source: Signals Research Group

A studious pessimist would also refer back to our in-building LTE drive test study (*SA* 01/22/13: "On the Inside, Looking Out") and observe that the typical SINR values in more loaded, but by no means fully-loaded, outdoor macro LTE networks are lower than what we are showing in this report. Specifically, during a Sunday afternoon drive test of downtown San Francisco (lots of Christmas shoppers, holiday bowl game, etc., but very few people at work) the average reported SINR on the AT&T LTE network was 12.92 dB and only 10.84 dB on the Verizon Wireless LTE network. Further, the distribution of reported SINR indicated that the SINR was 15 dB or lower for ~70% of the time on the Verizon Wireless LTE network and ~60% of the time on the AT&T LTE network – a SINR range where the benefits of MIMO are at best only 10%.

Just because TM 3 is available, doesn't mean that it was necessarily used.

Just because TM 3 is available, doesn't mean that it was necessarily used. Instead, the mobile device/chipset makes its measurements and then it informs the network scheduler of its channel conditions and whether or not it can handle two spatial data streams. The channel quality indicator (CQI) is used to determine the appropriate transport block size (TBS), which specifies the size of the block of data that can be transferred without exceeding the target BLER (Block Error Rate) – larger block sizes require a higher modulation and coding scheme (MCS).

For a given [non-ideal] channel condition, if TM 2 (Rank Indicator 1) is used, the mobile device should be able to support a higher MCS in a single data stream than if TM 3 is used.

Note that with a higher MCS value there are fewer redundancy/error correction bits in the transferred data so it becomes more difficult to decode the data in more challenging radio conditions. Further, it becomes more difficult to handle two orthogonal data streams. Therefore, the frequency of using TM 3 declines, as does the TBS/MCS values. Another very important observation is that if TM 2 (Rank Indicator 1) is used, the mobile device should be able to support a higher MCS in a single data stream unless the channel conditions are ideal. This phenomenon is evident in the results that we present in this report and in the median MCS values that are provided in the results tables in the appendix – the median values are always higher in the drive tests when only TM 2 was available.

The network assignments of transmission modes were almost identical, if not completely identical, with what the mobile device requested.

Table 3 (Knoxville) and Table 4 (Santa Clara) show the requested transmission mode as a function of reported SINR – please refer to our test methodology section for some important points regarding how we made some of these, and other, calculations. As expected, the usage of TM 3 dropped with lower SINR values, yet its usage below 10 dB was still fairly high – it was probably much higher at 10 dB than it was at 5 dB. In this table, we are showing the transmission mode that the mobile device requested and not what the network assigned. In theory, the network could assign the mobile device TM 2 even though the mobile device requested TM 3. We did, however, analyze the actual TM assignments and compared them with what the mobile device requested. We found that the network assignments of transmission modes were almost identical, if not completely identical, with what the mobile device requested. Since the infrastructure vendors and Qualcomm do a lot of integration testing together, this observation is not surprising. It would be interesting to see how the requested transmission modes and the assigned transmission modes compare and contrast with another supplier's chipset.

Table 3. Rank 2 Indicator Usage as a Function of SINR – Knoxville Band 5 Network

	June 18th, 0128		June 18th, 0148		June 18th, 0213		June 18th, 0243	
	RI = 1 (Average)	RI = 2 (Average)	RI = 1 (Average)	RI = 2 (Average)	RI = 1 (Average)	RI = 2 (Average)	RI = 1 (Average)	RI = 2 (Average)
SINR >= 25	0.2%	99.8%	0.3%	99.7%	0.0%	100.0%	0.2%	99.8%
20 <= SINR < 25	0.8%	99.2%	0.9%	99.1%	0.2%	99.8%	2.2%	97.8%
15 <= SINR < 20	9.0%	91.0%	4.5%	95.5%	4.2%	95.8%	6.8%	93.2%
10 <= SINR < 15	26.3%	73.7%	22.9%	77.1%	11.4%	88.6%	23.9%	76.1%
MIN < SINR < 10	66.6%	33.4%	54.7%	45.3%	52.2%	47.8%	47.7%	52.3%

Source: Signals Research Group

Table 4. Rank 2 Indicator Usage as a Function of SINR – Santa Clara Band 4 Network

	July 18th, 0103		July 18th, 0127		July 18th, 0151		July 18th, 0210		July 18th, 0232	
	RI = 1 (Avg)	RI = 2 (Avg)	RI = 1 (Avg)	RI = 2 (Avg)	RI = 1 (Avg)	RI = 2 (Avg)	RI = 1 (Avg)	RI = 2 (Avg)	RI = 1 (Avg)	RI = 2 (Avg)
SINR >= 25	0.2%	99.8%	0.7%	99.3%	0.9%	99.1%	1.4%	98.6%	0.3%	99.7%
20 <= SINR < 25	1.7%	98.3%	4.3%	95.7%	1.4%	98.6%	1.8%	98.2%	2.7%	97.3%
15 <= SINR < 20	7.7%	92.3%	9.4%	90.6%	5.3%	94.7%	4.3%	95.7%	5.7%	94.3%
10 <= SINR < 15	36.7%	63.3%	24.9%	75.1%	36.7%	63.3%	29.3%	70.7%	32.2%	67.8%
MIN < SINR < 10	79.9%	20.1%	76.9%	23.1%	79.8%	20.2%	76.1%	23.9%	81.6%	18.4%

Source: Signals Research Group

In a somewhat loaded LTE network, MIMO is more likely to have no impact or even degrade the end user throughput than it is to have a measurable benefit on the end user throughput.

So what does this all mean? Based on the data we collected and the analysis that we performed, MIMO can have a tremendous impact on end user throughput. In numerous cases during our stationary testing (next chapter), we observed a doubling in the end user throughput – consistent with the full capabilities of MIMO and our expectations. However, MIMO isn't a panacea and ideal conditions are seldom present in a commercial LTE network. Instead, the contribution of MIMO to end user throughput varies as a function of SINR with lower SINR (more network loading) resulting in lower gain. Another factor is the multipath behavior and the correlation between the two signals – uncorrelated signals are preferable. Taking into consideration all data points, in a somewhat loaded LTE network (average reported SINR < 10 dB), MIMO is more likely to have no impact or even degrade the end user throughput than it is to have a measurable benefit on the end user throughput.

MIMO is still beneficial to the operator, even if there isn't any positive impact on end user data rates.

In our view, it is probably in the interest of the industry to pursue how the various transmission modes are allocated and under what conditions. We've only tackled two transmission modes, but there are other transmission modes available today (e.g., TM 4 – Closed Loop MIMO) with other transmission modes coming on the horizon (e.g., TM 5 – Multi-User MIMO). As discussed in Chapter 6, MIMO is still beneficial to the operator, even if there isn't any positive impact on end user data rates.

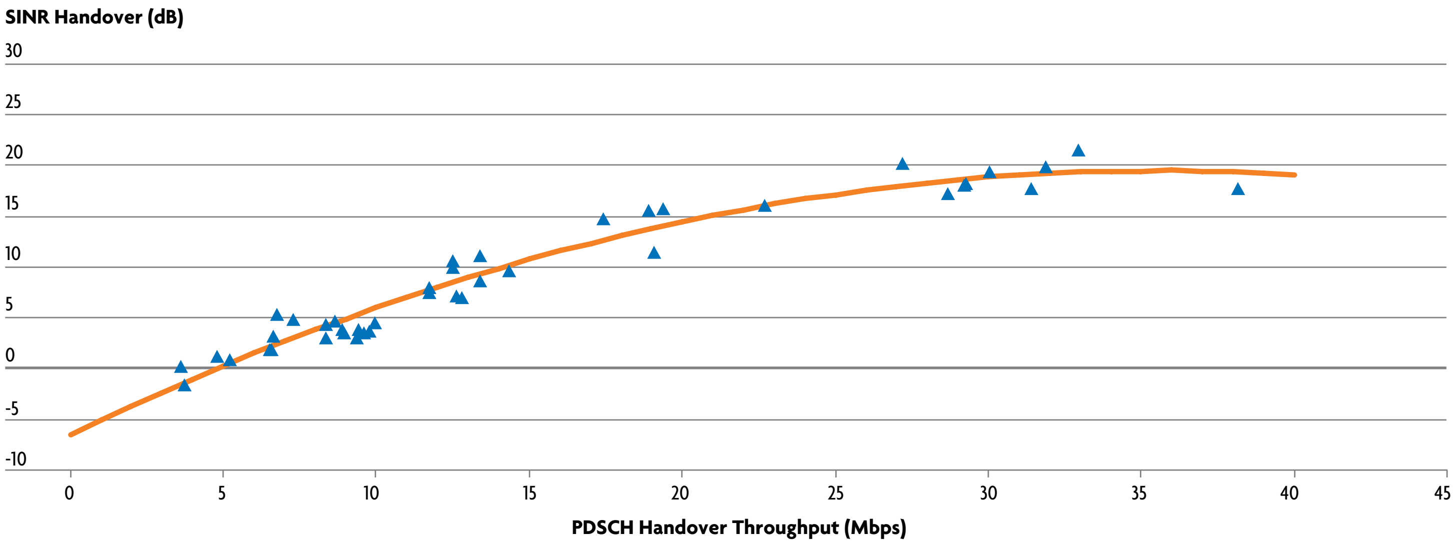
3.5 Sample Nighttime Drive Test Results – PDSCH versus SINR during Cell Handovers

We also investigated the impact of MIMO on edge-of-cell performance, or the interval of time that spans from immediately before a cell handover until immediately after a cell handover. Since the number of cell handovers during our drive tests was somewhat limited, our analysis of the data is less precise. However, it is still evident that the correlation between MIMO performance and SINR still exists. If MIMO (TM 3 availability) had a positive impact on edge-of-cell throughput then it was because the reported SINR values were favorable. If the availability of TM 3 didn't have a measurably favorable impact on edge-of-cell throughput then it was because the reported SINR values were single-digit or negative values.

Figure 29 provides a plot of the average edge-of-cell throughput values and the corresponding SINR values with TM 3 enabled. The average reported SINR was only 9.1 dB so one would not expect a meaningful benefit from MIMO.

Figure 29. Physical Layer Throughput Versus SINR Scatterplot at Edge of Cell with TM 3 Enabled, July 18th 0127 hours – Santa Clara Band 4 Network

PDSCH Throughput (Median) = 12.12 Mbps PDSCH Throughput (Average) = 15.10 Mbps
SINR (Average) = 9.10 dB



Source: Signals Research Group

To the extent that the availability of TM 3 benefits edge-of-cell throughput, it is only when the reported SINR values are favorable.

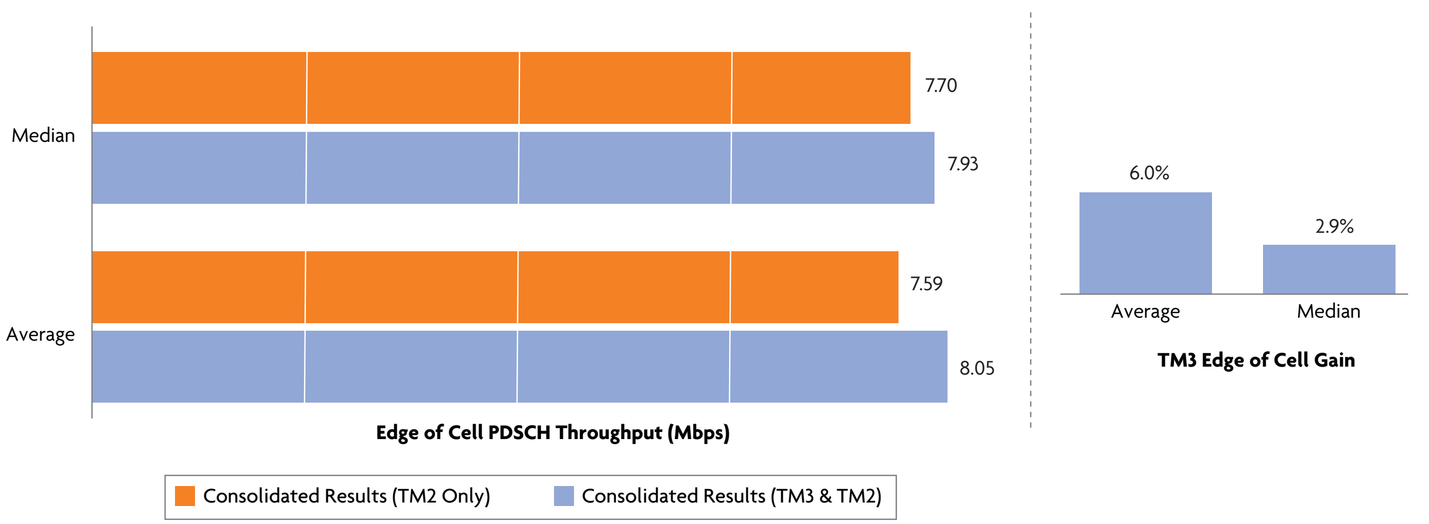
Using an identical methodology that we used to create the previous figures and tables, we arrive at the information shown in the next series of tables and figures. Table 5 and Figure 30 show the results for the Knoxville network. Table 6 and Figure 31 show the results for the Santa Clara network. Readers shouldn't get too worked up over the actual gains shown for the two markets or try to reach additional conclusions. To the extent that the availability of TM 3 benefits edge-of-cell throughput, it is only when the reported SINR values are favorable.

Table 5. Physical Layer Throughput Gains with TM 3 Enabled Versus TM 2 Only at Edge of Cell as a Function of SINR – Knoxville Band 5 Network

	PDSCH Throughput - Average (Mbps)				
	SINR > 25 dB	20 dB < SINR < 25 dB	15 dB < SINR < 20 dB	10 dB < SINR < 15 dB	SINR < 10 dB
TM 3 and TM 2	**50.68**	**42.26**	**31.37**	**18.63**	**9.47**
July 18th, 0103	51.86	43.63	32.68	17.85	8.27
July 18th, 0127	50.01	41.31	31.34	19.12	9.31
July 18th, 0151	46.68	41.13	31.27	19.68	10.56
July 18th, 0210	51.06	42.65	30.85	18.38	9.61
July 18th, 0232	53.79	42.57	30.70	18.11	9.63
TM 2 Only	**30.84**	**29.64**	**26.21**	**17.56**	**10.40**
July 18th, 0105	31.16	29.71	25.63	17.90	10.16
July 18th, 0126	30.90	29.77	26.33	17.05	9.96
July 18th, 0147	30.31	29.33	26.59	17.08	11.66
July 18th, 0218	30.96	29.77	26.28	18.20	9.79

Source: Signals Research Group

Figure 30. Physical Layer Throughput Gains with TM 3 Enabled Versus TM 2 Only at Edge of Cell as a Function of SINR – Knoxville Band 5 Network



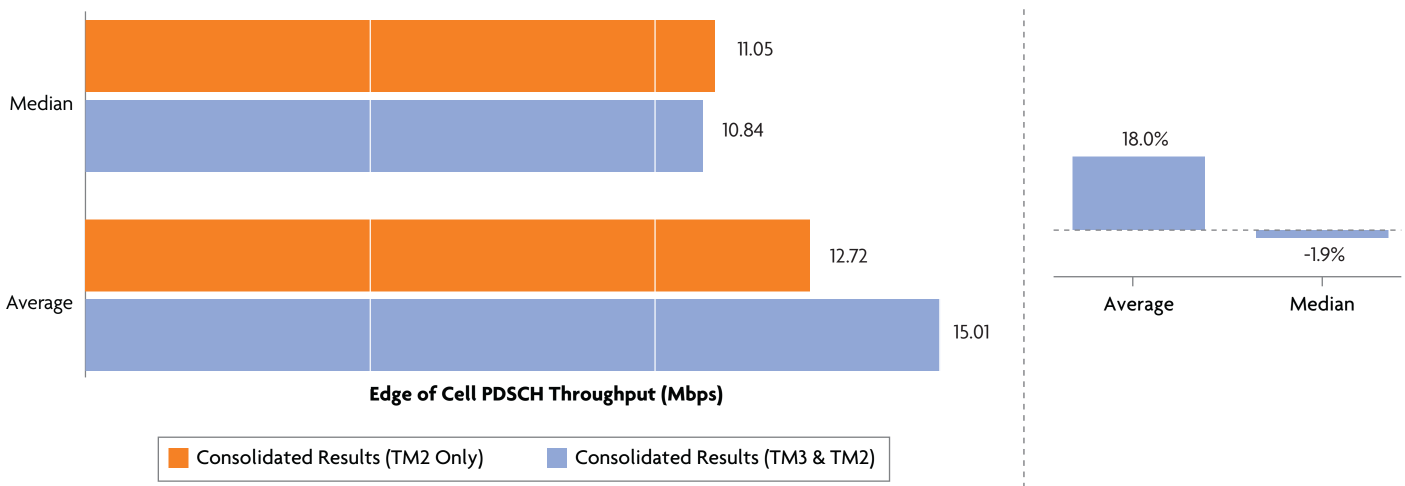
Source: Signals Research Group

Table 6. Physical Layer Throughput Gains with TM 3 Enabled Versus TM 2 Only at Edge of Cell as a Function of SINR – Santa Clara Band 4 Network

	PDSCH Throughput - Average (Mbps)				
	SINR > 25 dB	20 dB < SINR < 25 dB	15 dB < SINR < 20 dB	10 dB < SINR < 15 dB	SINR < 10 dB
TM 3 and TM 2	**50.68**	**42.26**	**31.37**	**18.63**	**9.47**
July 18th, 0103	51.86	43.63	32.68	17.85	8.27
July 18th, 0127	50.01	41.31	31.34	19.12	9.31
July 18th, 0151	46.68	41.13	31.27	19.68	10.56
July 18th, 0210	51.06	42.65	30.85	18.38	9.61
July 18th, 0232	53.79	42.57	30.70	18.11	9.63
TM 2 Only	**30.84**	**29.64**	**26.21**	**17.56**	**10.40**
July 18th, 0105	31.16	29.71	25.63	17.90	10.16
July 18th, 0126	30.90	29.77	26.33	17.05	9.96
July 18th, 0147	30.31	29.33	26.59	17.08	11.66
July 18th, 0218	30.96	29.77	26.28	18.20	9.79

Source: Signals Research Group

Figure 31. Physical Layer Throughput Gains with TM 3 Enabled Versus TM 2 Only at Edge of Cell as a Function of SINR – Santa Clara Band 4 Network



Source: Signals Research Group

4.0 Detailed Results – stationary positions

The officer determined that daddy was an outstanding citizen so the testing resumed after only a temporary delay.

In addition to conducting drive tests over random routes within the test clusters, we also conducted stationary testing. We selected the test locations, but they were not randomly selected. Instead, we selected locations so that we could include a mix of ideal network conditions and more challenging conditions. We also wanted to park in areas that we deemed relatively safe. Despite taking these precautions, a certain 5 year-old boy loves to tell his friends how “Santa Clara’s Finest” thought daddy was a burglar. Fortunately, the officer determined that daddy was an outstanding citizen so the testing resumed after only a temporary delay.

Figure 32 shows the stationary test locations in Knoxville and Figure 33 shows the stationary test locations in Santa Clara.

Figure 32. Locations of Stationary Points - Knoxville

Source: Signals Research Group

Figure 33. Locations of Stationary Points - Santa Clara

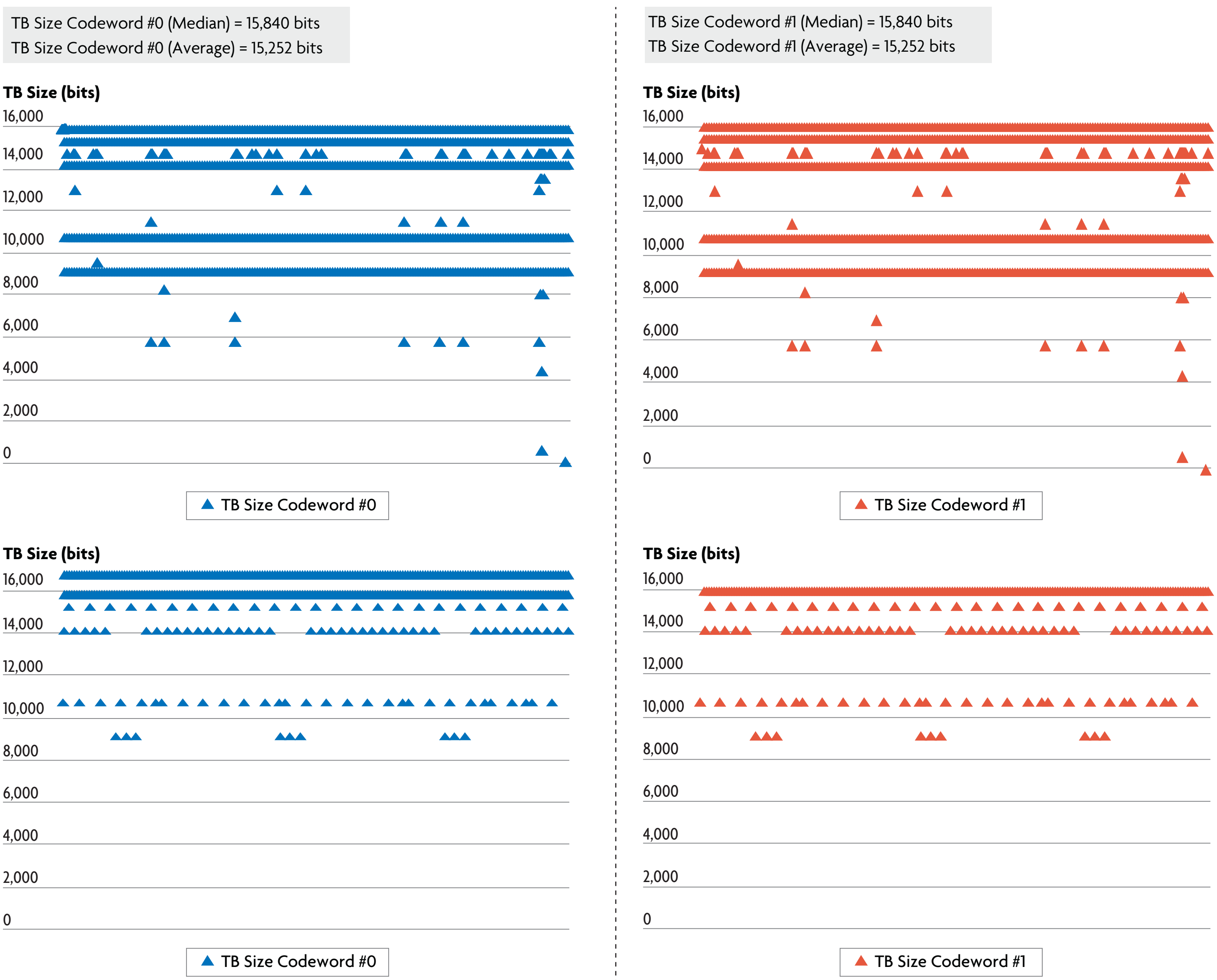
Source: Signals Research Group

Figure 34 and Figure 35 show the results from "Point 7" in Knoxville. In both figures, the top figure(s) shows the assignment of transport block sizes (TBS) during the entire test, which lasted slightly more than 60 seconds, on a per sub-frame basis, or once every millisecond. The bottom figure(s) shows a zoomed in view of the data. The length of time for the bottom figure(s) is only ~0.5 seconds. We've included these bottom figures to show an interesting pattern in how the TBS sizes were assigned. We believe that the lower TBS values, which appear in a predictable pattern, stem from the various overhead channels that are a natural part of the LTE protocol. Since we are not doing an analysis of network scheduler efficiencies, we didn't examine the matter in detail, although we did observe patterns in both networks.

Point #7 represented a location where the availability of TM 3 resulted in a near doubling of the end user throughput.

As suggested in the two figures, Point #7 represented an ideal location and one where the availability of TM 3 resulted in a near doubling of the end user throughput. With TM 3, the average Physical Layer throughput was 30.3 Mbps. Without TM 3, the average Physical Layer throughput was 15.2 Mbps.

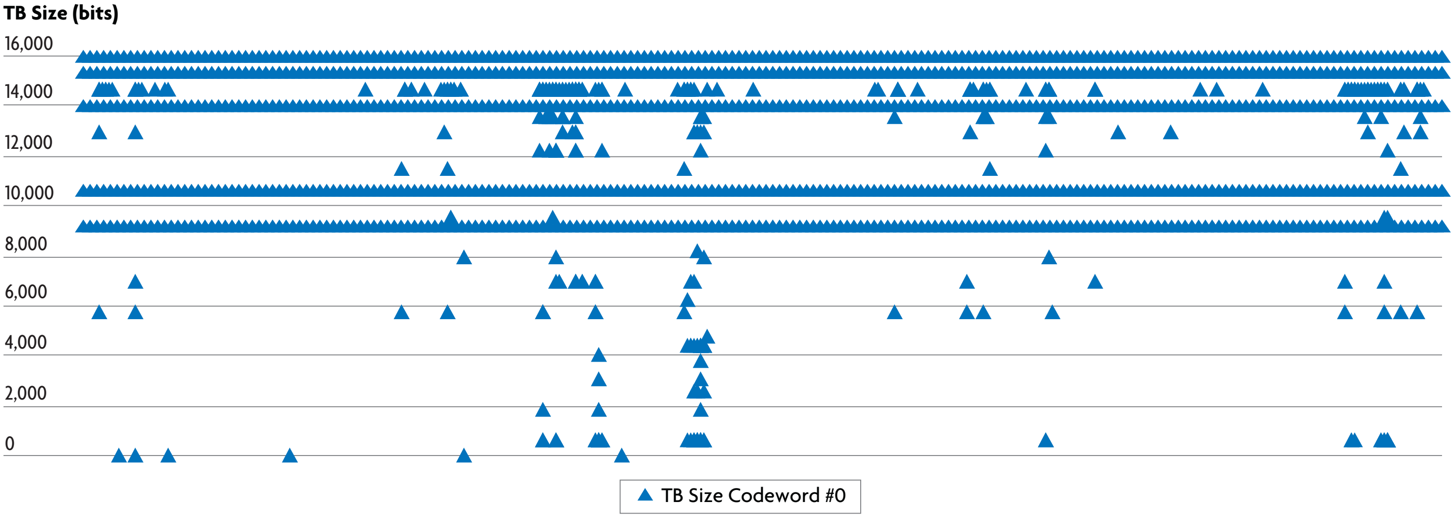
Figure 34. Transport Block Size Assignments with TM 3 Enabled, Point 7 – Knoxville, Band 5 Network

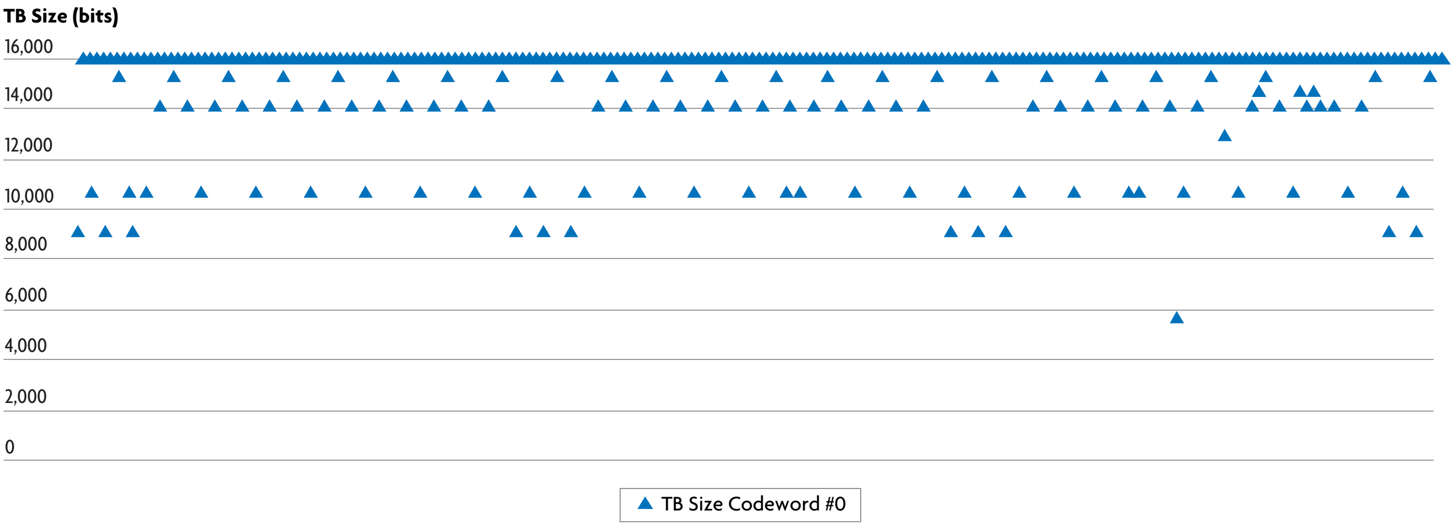


Source: Signals Research Group

Figure 35. Transport Block Size Assignments with TM 2 Only, Point 7 – Knoxville, Band 5 Network

TB Size Codeword #0 (Median) = 15,840 bits
TB Size Codeword #0 (Average) = 15,196 bits



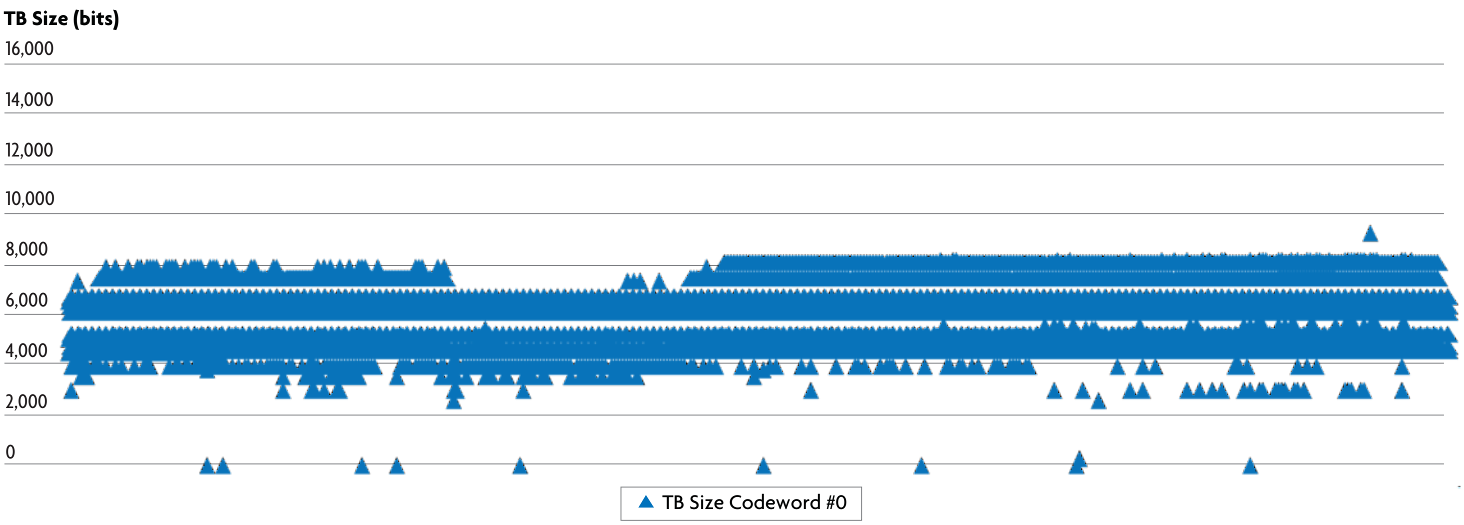


Source: Signals Research Group

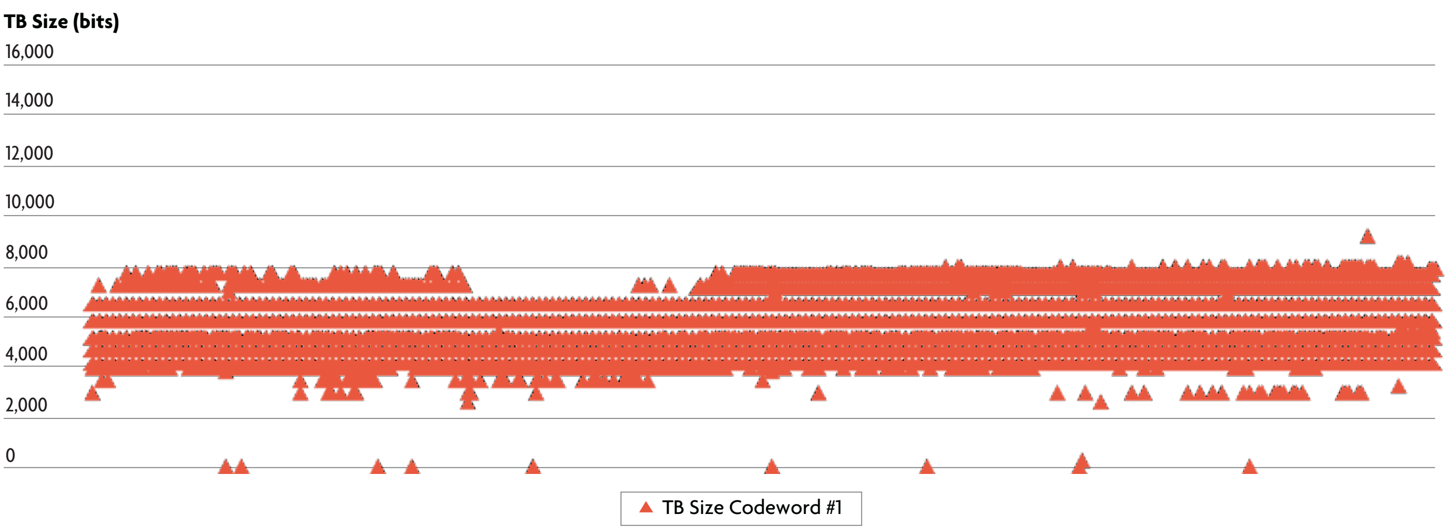
Figure 36 and Figure 37 show results from a more typical location. In this case, the availability of TM 3 increased the end user throughput by 35.4%. Note also that Rank Indicator 2 was used 100% of the time. As documented in the results table in the appendix, the average SINR was modestly higher on the first night (11.4 dB) than on the second night (10.0 dB) and this condition also impacted the throughput.

Figure 36. Transport Block Size Assignments with TM 3 Enabled, Point 3 – Knoxville, Band 5 Network

TB Size Codeword #0 (Median) = 6,456 bits
TB Size Codeword #0 (Average) = 6,247 bits
SINR (Average) = 11.4 dB



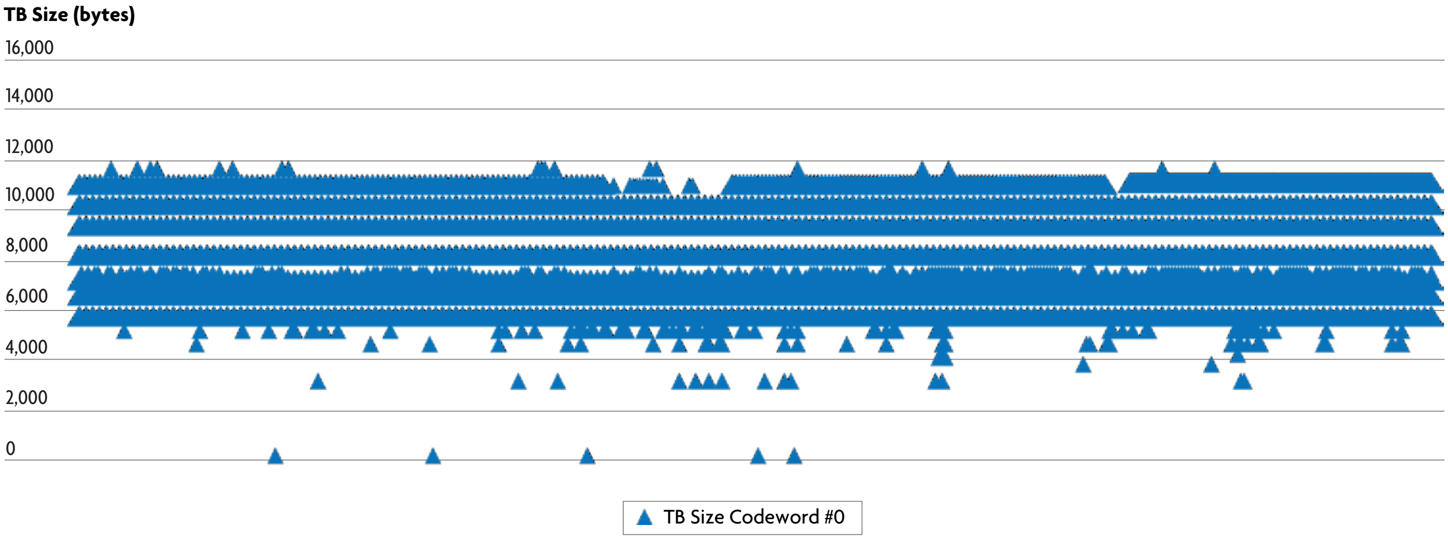
TB Size Codeword #1 (Median) = 6,456 bits
TB Size Codeword #1 (Average) = 6,239 bits



Source: Signals Research Group

Figure 37. Transport Block Size Assignments with TM 2 Only, Point 2 – Knoxville, Band 5 Network

TB Size Codeword #0 (Median) = 9,144 bytes
TB Size Codeword #0 (Average) = 9,100 bytes
SINR (Average) = 10 dB

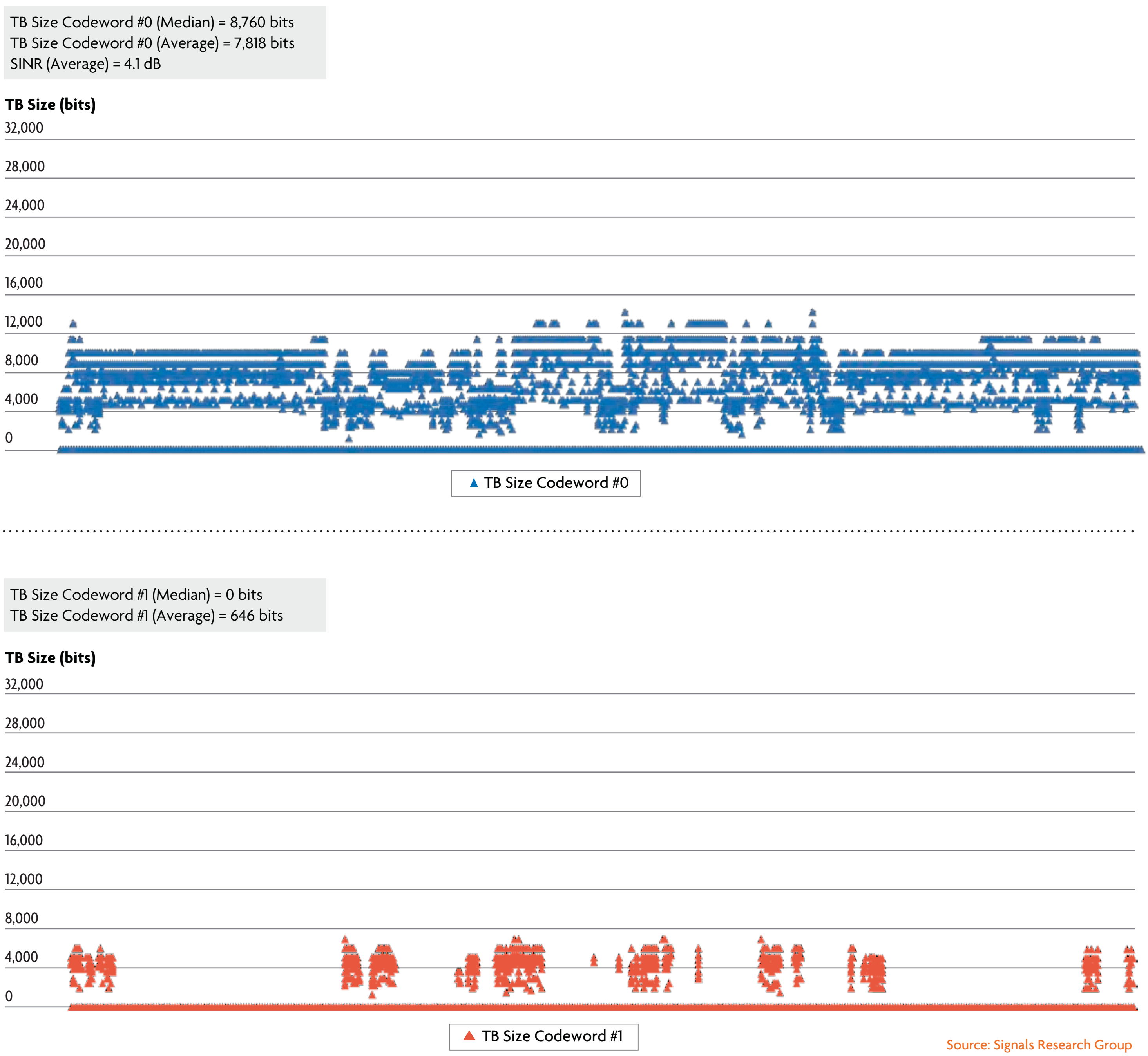


Source: Signals Research Group

Figure 38 and Figure 39 show results from a somewhat challenging condition in Santa Clara. At Point #2, the Physical Layer throughput with TM 3 enabled was 9.1 Mbps and when the network was configured to only support TM 2 the throughput was measurably higher, or 11.5 Mbps – the SINR was also a bit higher with TM2, or 6.7 dB versus 4.1 dB. We're not suggesting that the differences in the network configurations had an impact on the SINR but it is relevant that the network conditions were not identical due to a likely host of reasons. As shown in the appendix, with TM 3 available, Rank Indicator 2 was only requested/used 12.4% of the time.

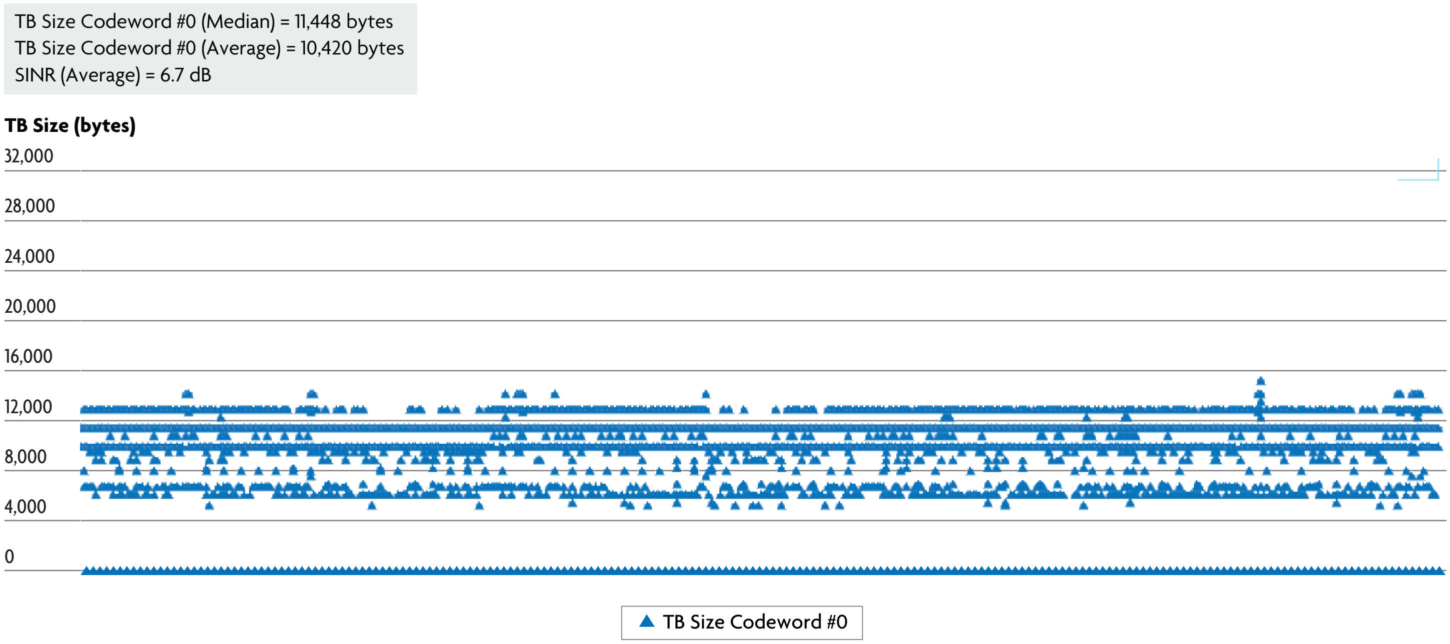
In the appendix we include results from an ideal location in which TM 3 nearly doubled the end user throughput (61.7 Mbps versus 30.9 Mbps). Ironically, it was also at this location where we had our 2 AM conversation with The Law. This set of figures also shows an enhanced view which shows what we believe are lower TBS allocations due to overhead channels.

Figure 38. Transport Block Size Assignments with TM 3 Enabled, Point 2 – Santa Clara, Band 4 Network



Source: Signals Research Group

Figure 39. Transport Block Size Assignments with TM 2 Only, Point 2 – Santa Clara, Band 4 Network



Source: Signals Research Group

5.0 Detailed Results – high-speed vehicular

We conducted freeway testing in both markets but we did a much better job of collecting useful information that we could later compare in the Santa Clara market, largely because we knew the area. As such, we are only showing results from this market.

Figure 40 shows the assignment of transmission modes when TM 3 was enabled. Figure 41 shows comparable information when only TM 2 was available. Note that the presence of TM3 in the second figure occurred in areas immediately outside of the test cluster, otherwise everything was TM 2. In the analysis that follows (e.g., the information shown in Figure 42 and Figure 43) we excluded these results when doing the calculations and when creating the figures.

Figure 40. Transmission Mode Assignments with TM 3 Enabled, July 18th, 0529 hours – Santa Clara Band 4 Network (geo plot)

Source: Signals Research Group

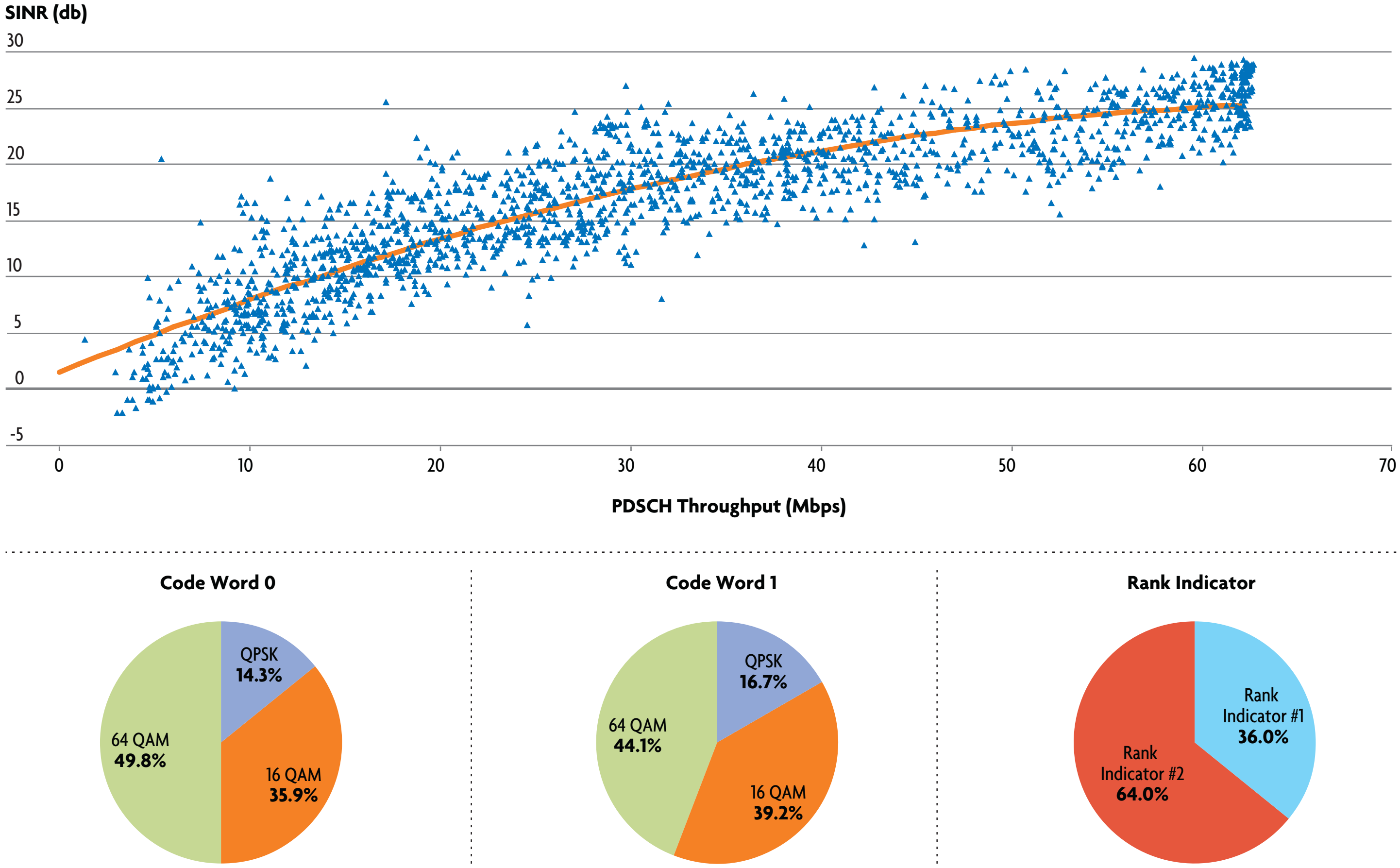
Figure 41. Transmission Mode Assignments with TM 2 Only, July 19th, 0410 hours – Santa Clara Band 4 Network (geo plot)

Source: Signals Research Group

Comparing Figure 42 and Figure 43, it is evident that even at high speeds (we tried to keep the needle right 60 mph), TM 3 increased the average throughput by nearly 14%. In both drive tests, it is also evident that the network conditions were very favorable as shown by the high availability of 64 QAM. With TM 2 Only, 64 QAM was used a very impressive 77.3% of the time. Clearly, the Highway 101 corridor is very important to mobile operators.

Figure 42. Physical Layer Throughput Versus SINR Scatterplot Plus Assorted KPIs with TM 3 Enabled, July 18th 0529 hours – Santa Clara Band 4 Network

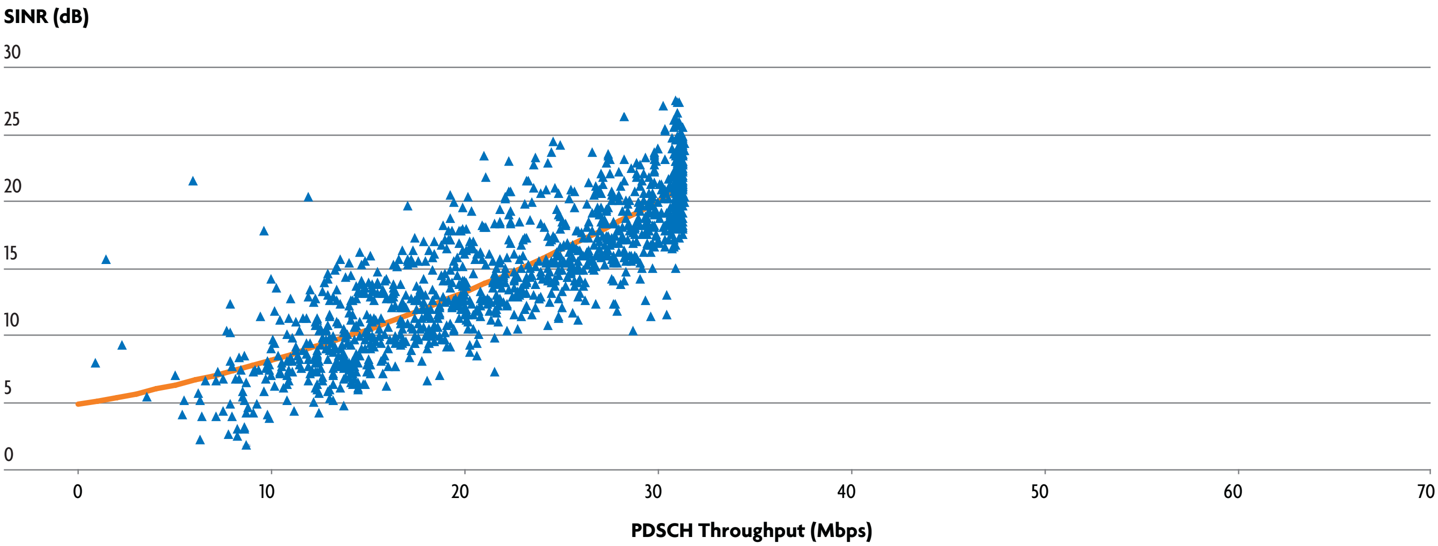
PDSCH Throughput (Median) = 25.91 Mbps PDSCH Throughput (Average) = 25.03 Mbps
SINR (Average) = 14.13 dB

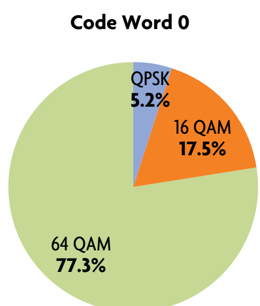


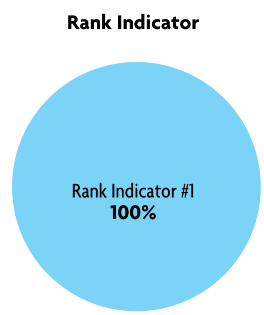
Source: Signals Research Group

Figure 43. Physical Layer Throughput Versus SINR Scatterplot Plus Assorted KPIs with TM 2 Only, July 19th 0410 hours – Santa Clara Band 4 Network

PDSCH Throughput (Median) = 22.40 Mbps PDSCH Throughput (Average) = 22.0 Mbps
SINR (Average) = 14.91 dB







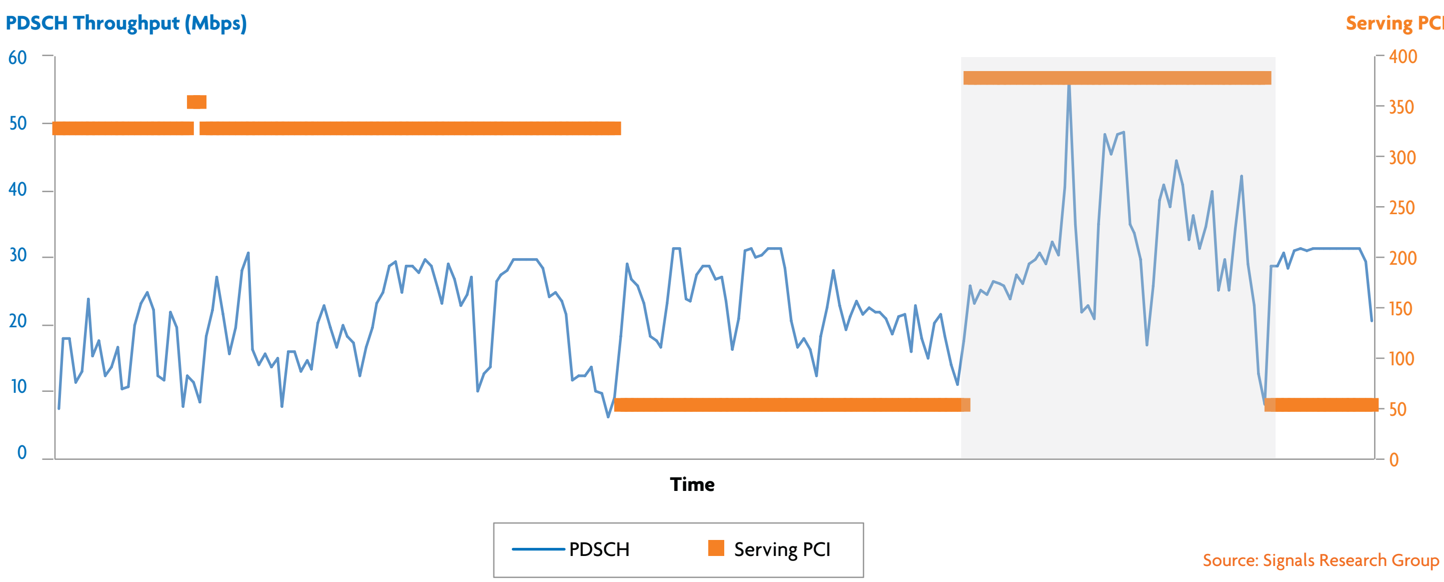
Source: Signals Research Group

The last two figures in this section plot the Physical Layer throughput as a function of time. We've tried to line up the two figures so that they show the same areas within the network. The grey box "hides" an area that fell outside of the test cluster and where TM 3 was enabled on both nights – this area was excluded when making the plots in Figure 42 and Figure 43. By comparing the two figures it is possible to see where and to what degree the use of TM 3 helped to increase the throughput.

Figure 44. Physical Layer Throughput Versus Serving PCI with TM 3 Enabled, July 18th 0529 hours – Santa Clara Band 4 Network

Source: Signals Research Group

Figure 45. Physical Layer Throughput Versus Serving PCI with TM 2 Only, July 19th 0410 hours – Santa Clara Band 4 Network



Source: Signals Research Group

6.0 User Experience Tests (Web browsing and YouTube)

The wired Internet can become the bottleneck of the wireless Internet.

Very few mobile data users continuously "pound the network" for a sustained period of time. Instead, they do more modest data snacking – load a web page, synch an email account, watch a video. From past experiences (reference SA 10/19/2011, "Quantifying the User Experience") we knew that throughput doesn't have a major influence on the typical user experience once the minimum throughput exceeds somewhere in the range of 5 Mbps for web page loading. With applications that inherently require more aggressive data transactions, such as downloading from iTunes or Google Play, the throughput becomes more important, but there are still upper thresholds beyond which the ability to deliver higher data rates serves no useful purpose. This situation generally occurs when the server hosting the data source cannot supply enough data to fill the data pipe. Yes, the wired Internet can become the bottleneck of the wireless Internet.

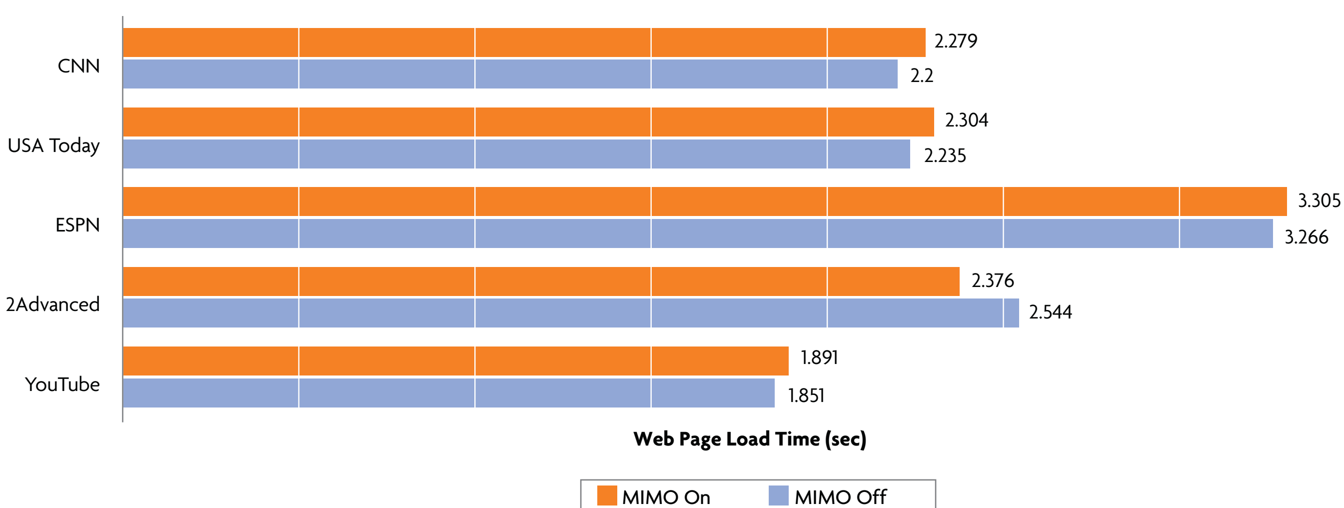
In this chapter, we provide a variation of the user experience study that we conducted in 2011. Specifically, during our data testing and analysis we looked at the impact of MIMO when it comes to loading a web page and watching a YouTube video.

The results shown in this chapter were obtained under ideal conditions from stationary locations.

For the web browsing tests we used Spirent's (formally Metrico Wireless) Datum product to load web pages on the smartphone in a predictable manner and to measure and record how long it took to fully load each page. The results shown in this chapter were obtained under ideal conditions from stationary locations. We collected the results in Knoxville in the creature comforts of our hotel. We ran the first suite of tests when TM 3 was enabled and then repeated the suite of tests immediately after the network was configured to support TM 2. There was only a very short time gap between the two tests and the phone remained in the exact location. In Santa Clara, the web page tests were conducted on different nights and since the content of the web sites (size of web page, number of external links, etc.) probably changed between the two tests we must acknowledge that our test plan had some deficiencies.

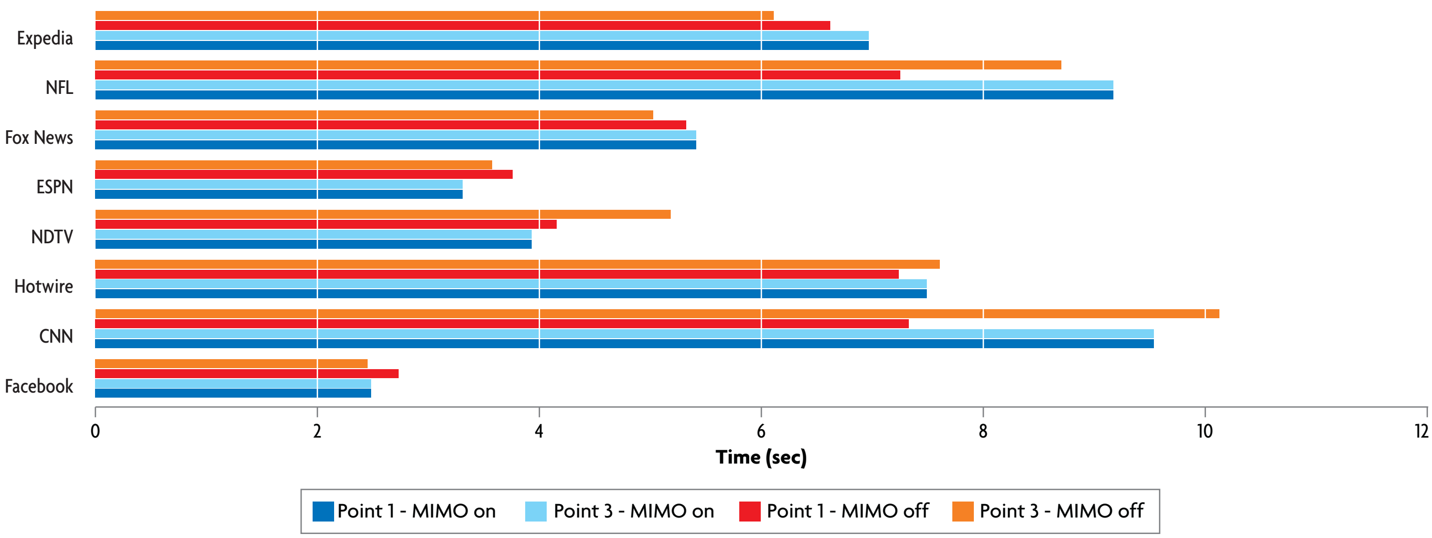
Figure 46 shows the results from the Knoxville network and Figure 47 shows the results from the Santa Clara network. Taken at face value, the results in Figure 46 suggest that MIMO caused the web pages to take a longer period of time to load – the one exception was "2Advanced" which is a website with a much larger than normal amount of data content. The Santa Clara results, which are quantified in Table 7, also seem to support the notion that MIMO degrades the user experience.

Figure 46. Web Page Load Times with and without TM 3 Enabled – Knoxville Band 5 Network



Source: Signals Research Group

Figure 47. Web Page Load Times with and without TM 3 Enabled – Santa Clara Band 4 Network



Source: Signals Research Group

Rest assured, we are not reaching that conclusion. Instead, we believe that the results largely stem from the lack of a meaningful sample size of data points. We had 4-5 hours to collect the data so we could only load each web page a limited number of times. In Knoxville, for example, we loaded each web page 10 times with TM 3 enabled and only 5 times with TM 3 turned off.

Table 7. Comparable Web Page Load Times - Santa Clara Band 4 Network

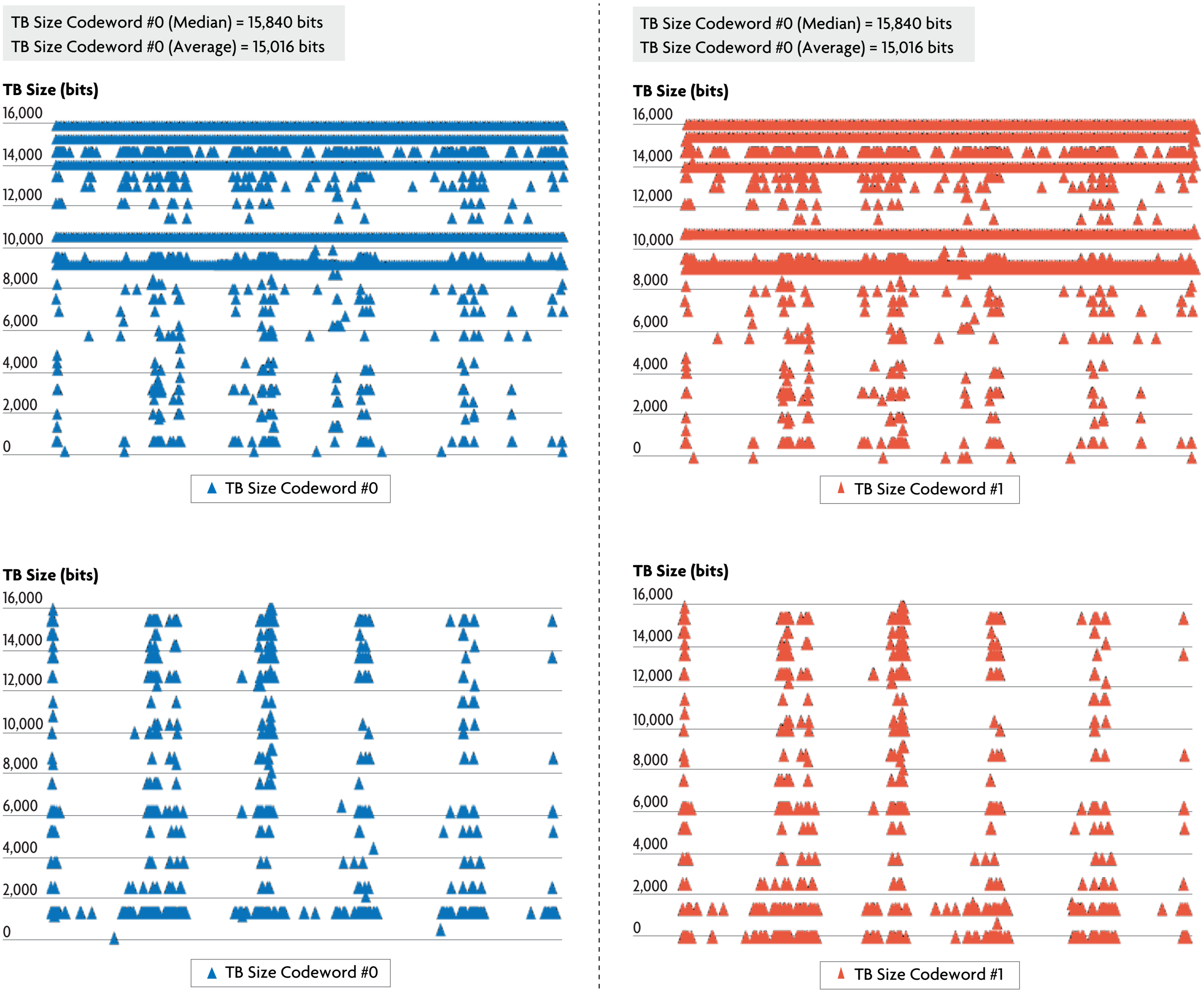
	TM 2 Only Average	TM 3 Enabled Average	MIMO % Gain
Expedia	6.36	6.97	-8.6%
NFL	7.98	9.17	-13.0%
Fox News	5.17	5.41	-4.5%
ESPN	3.67	3.31	10.8%
NDTV	4.67	3.93	18.8%
Hotwire	7.42	7.49	-0.9%
CNN	8.73	9.54	-8.5%
Facebook	2.59	2.48	4.3%

Source: Signals Research Group

Faster web page load times are generally a function of lower latency and not higher throughput.

Our conclusion from analyzing these results is that from an end user perspective, MIMO did not have any impact on the user experience. This result is no different than obtaining comparable results with a 20 Mbps connection and a 40 Mbps connection. Figure 48 helps explain why this is the case. The top two figures show the allocation of TBS while doing an FTP data session and the bottom two figures show the TBS allocation while doing a concurrent web browsing session from the same ideal location. The figure shows the maximum capabilities of the network/MIMO are seldom achieved with web browsing – note the big differences in the median and average TBS values between the two sets of figures. Putting it another way, faster web page load times are generally a function of lower latency and not higher throughput.

Figure 48. Transport Block Size Assignments with TM 3 Enabled with FTP and Web Browsing, Point 7 – Knoxville, Band 5 Network



Source: Signals Research Group

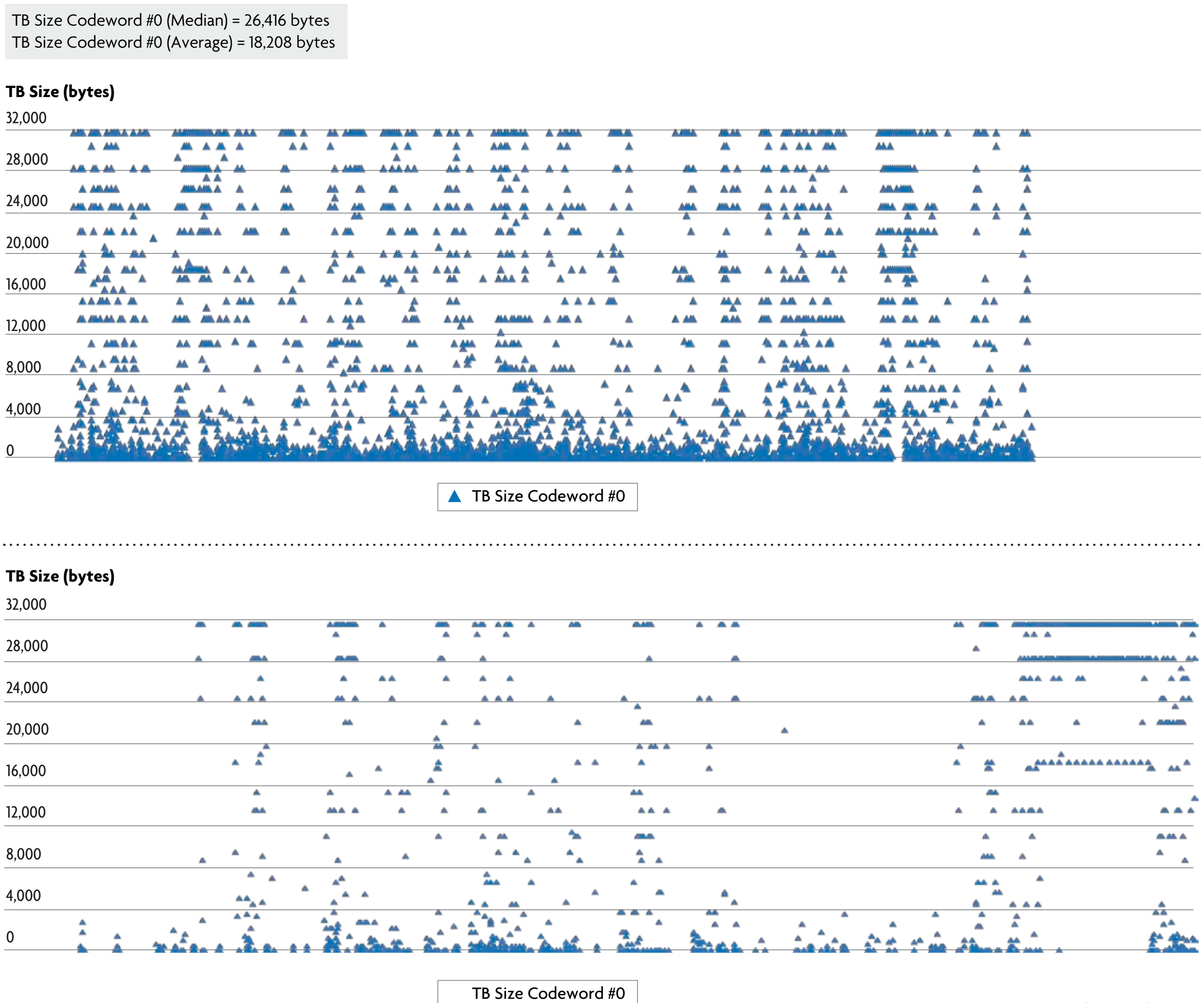
Figure 49 (TM 3 enabled) and Figure 50 (TM 2 only) show results from the Santa Clara market. The bottom figure(s) zoom in on a very limited amount of time from the overall test. There are two interesting observations. First, the average TBS with TM 2 only is roughly the same size as the sum of the two average TBS values from the TM 3 enabled test. This similarity also suggests that MIMO didn't benefit the end user. The second observation is a bit bizarre. In the TM 2 only scenario, there is a fairly material difference between the average and median TBS values. However, in the TM 3 enabled results, the differences are overwhelming. The average TBS values are ~9,270 bits but the median TBS values are only ~580 bits. We checked and rechecked the log file to confirm the values. We also reviewed the data in detail to confirm that the distribution of very low TBS values was much higher with TM 3 enabled.

Figure 49. Transport Block Size Assignments with TM 3 Enabled with Web Browsing, Point 3 – Santa Clara, Band 4 Network

Source: Signals Research Group

For now, we are not sure if this is a good thing, a bad thing, an anomaly, or something that should be expected for reasons that we and others can't explain. What we do know is that in the Knoxville network, the scheduler "only" used Rank Indicator 2 for 78% of the time during the web page load tests even though the percentage was 100% with the FTP tests from the same location and with ideal network conditions. In the Santa Clara network, Rank Indicator 2 was used for 100% of the time during the web browsing tests – the conditions were also near perfection.

Figure 50. Transport Block Size Assignments with TM 2 Only with Web Browsing, Point 3 – Santa Clara, Band 4 Network

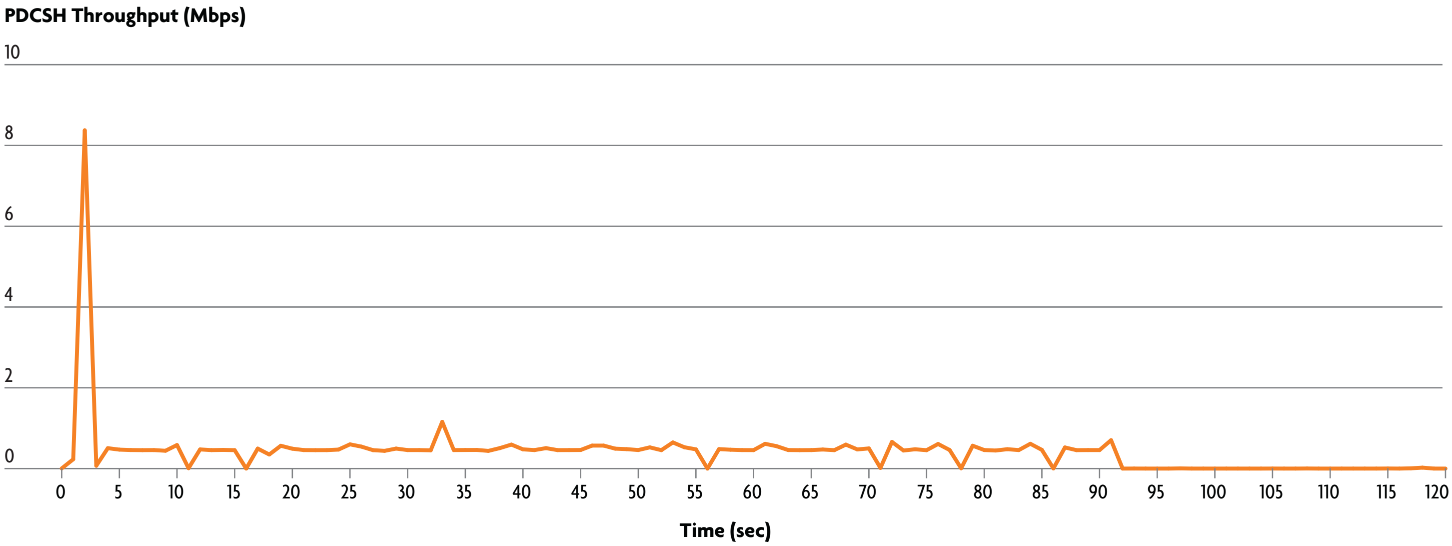


Source: Signals Research Group

YouTube seldom took full advantage of the true throughput capabilities of the network, meaning that MIMO didn't benefit the user experience.

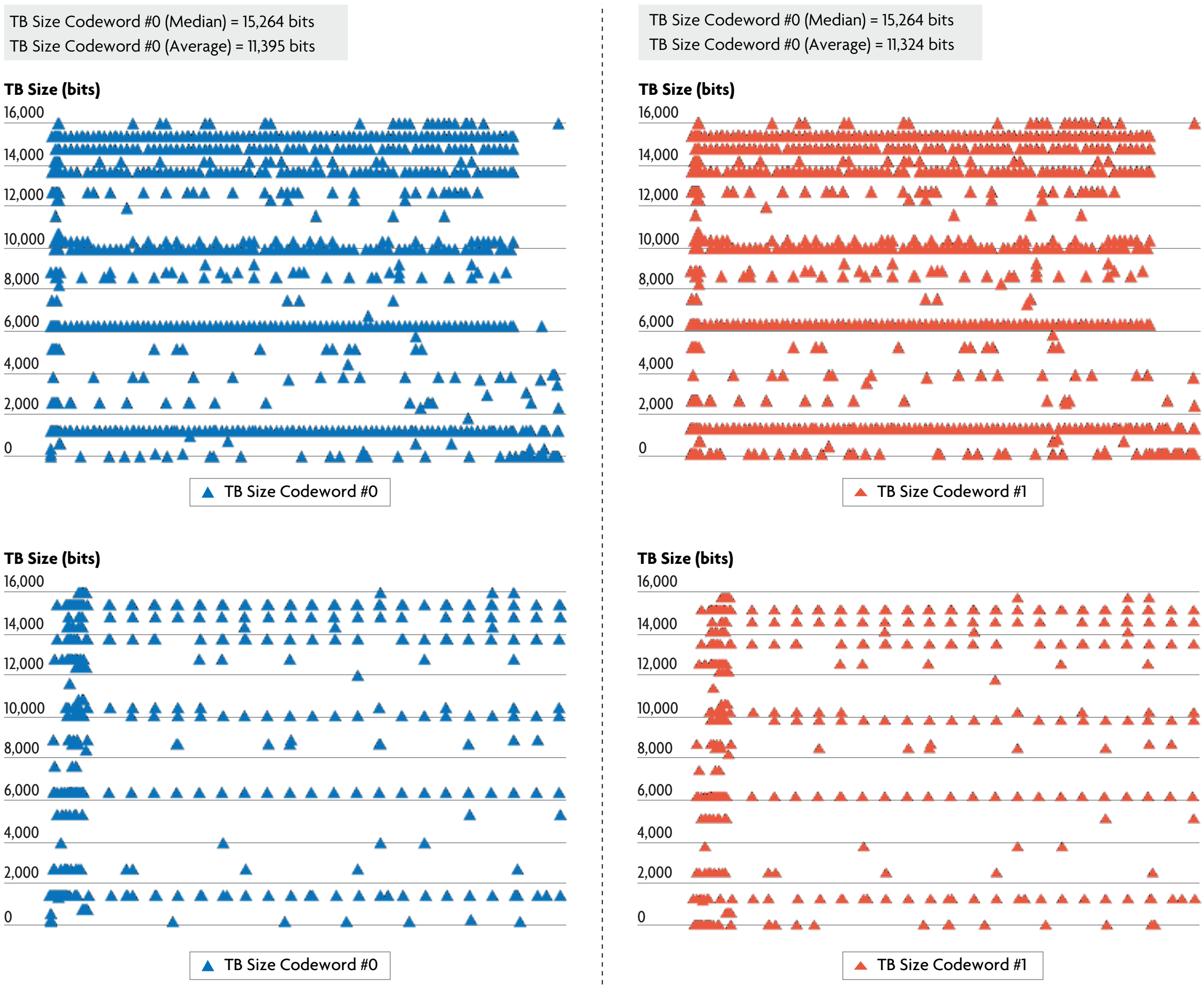
Figure 51 and Figure 52 show results while using YouTube. The test was conducted with near ideal network conditions from our hotel room with TM 3 enabled. Although the network was capable of delivering ~30 Mbps, the maximum throughput (averaged with a time increment of one second) was barely over 8 Mbps. Figure 52, in particular the bottom two figures, provide clarity into what was taking place. The largest TBS values were being used but they were being used very infrequently. In fact, once the video buffer was full (the blob at the beginning of the figures) the network scheduler only needed to schedule resources periodically to keep the video playing. We went back and zoomed in on the time period when the video buffer was being filled. Even during this time period, the maximum TBS values were only assigned periodically. Putting it all together, the quality of the user experience while viewing the YouTube video would have been no different if TM 3 had been disabled.

Figure 51. Physical Layer Throughput with YouTube, Hotel – Knoxville, Band 5 Network



Source: Signals Research Group

Figure 52. Transport Block Size Assignments with TM 3 Enabled with YouTube, Hotel – Knoxville, Band 5 Network



Source: Signals Research Group

With MIMO, these applications can be delivered more efficiently, thus benefiting the operator and indirectly benefiting the mobile data user.

There is still a huge reason why MIMO benefits operators with these applications and why MIMO indirectly benefits mobile data users. With MIMO, these applications can be delivered more efficiently. The web pages may not load any faster, but if fewer resources are required, then the resources are available for other users and their applications. We analyzed two of the log files involving web page loading – one file pertained to a time when TM 3 was enabled and one file pertained to a time when only TM 2 was available. We found that the average number of assigned resource blocks was roughly twice as high when only TM 2 was available versus when TM 3 was enabled. In most of our testing, we wouldn't observe any differences in the number of assigned resource blocks since the goal of these tests was to maximize throughput so the network was always trying to assign as many resources as possible.

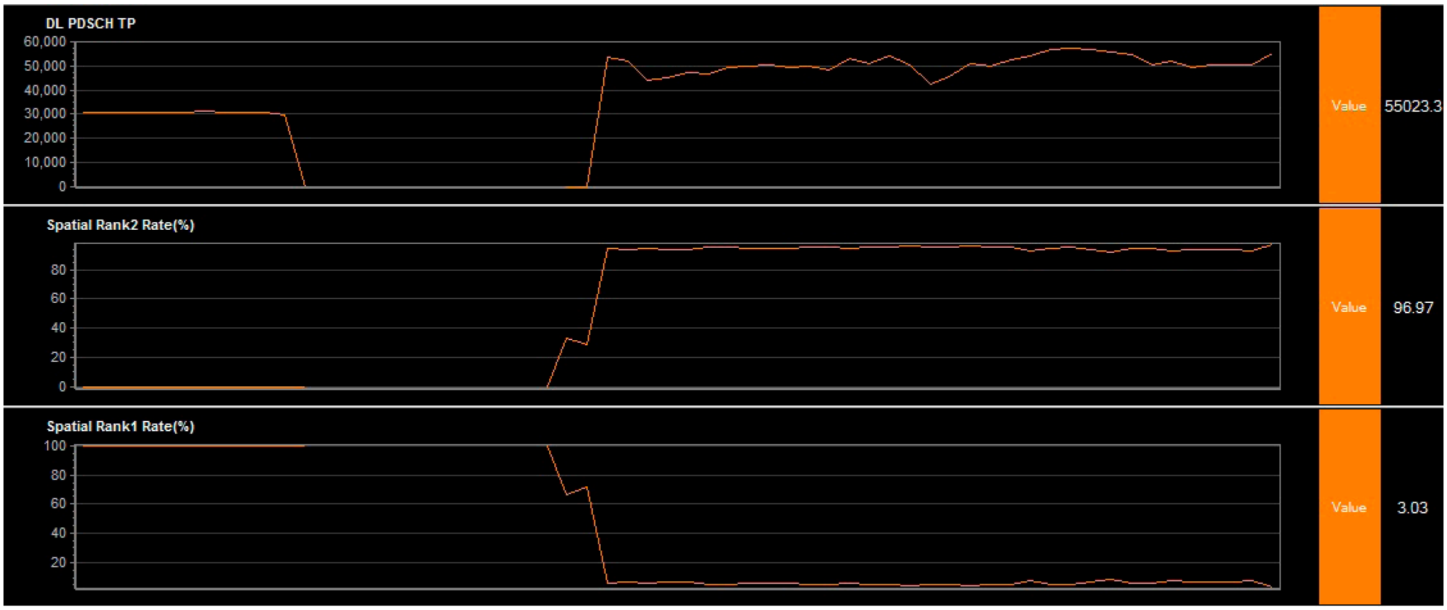
7.0 Test Methodology

We used the Accuver suite of drive test solutions for this study.

For the MIMO testing we once again used the Accuver XCAL drive test tool to collect the data and the Accuver XCAP post-processing tool to analyze the data and to help us create the figures that appear in this report.

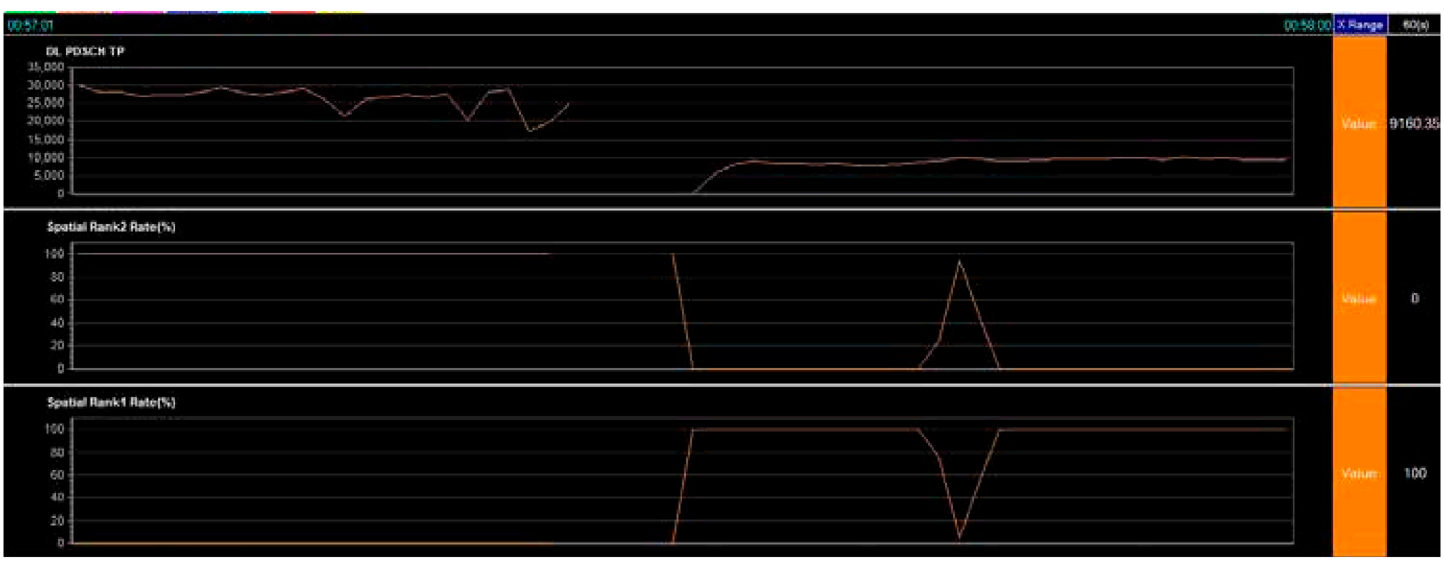
Figure 53 and Figure 54 illustrate a typical display that we used when collecting the data. Both figures are especially interesting since they capture the moment in time when the operator turned on TM 3 (Figure 53) and the moment in time when the operator turned off TM 3 (Figure 54) – note the allocation of Rank Indicator values in both figures. Both figures stem from testing that we did in our hotel – the first figure is from Santa Clara and the second figure is from Knoxville.

Figure 53. XCAL in Action



Source: Accuver and SRG

Figure 54. XCAL in Action



Source: Accuver and SRG

The entire effort was self-funded with our subscription-based model being the only way we are compensated for our effort.

The two operators who supported this effort provided us with smartphones to collect the data, SIM cards without any data restrictions, and [most importantly] they were willing to reconfigure their networks for our benefit and the benefit of our subscribers. As a courtesy, we provided both operators with a pre-brief of the results. This pre-brief also gave us the opportunity to ask some questions. As it is the case with all of our Signals Ahead reports, other than the aforementioned logistical support, the entire effort was self-funded with our subscription-based model being the only way we are compensated for our effort.

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.

Virtually all testing took place during the nighttime hours for hopefully obvious reasons. In Knoxville, we tethered the smartphone to our Windows 7 notebook computer and then used FTP (FileZilla) to generate the data traffic. We used multiple FTP sessions to ensure that the data pipe was fully loaded and that TCP ACK/NACK round trip times did not impact the throughput.

In Santa Clara, we used the Datum client and an external Spirent/Metrico server (UDP) to generate the data traffic for the T-Mobile network. This approach was done out of necessity since we were not able to get the Samsung Galaxy S 3 to support tethering mode and provide access to the diagnostic port at the same time.

The frequency of how often the chipset reported the different KPIs that we used in this report was not consistent. Some KPIs were reported on the order of tens of milliseconds in the log file while other KPIs were reported only once per second. This approach is done to ensure that the processing, reporting and collecting of information, combined with the limitations of the notebook computer do not unintentionally degrade the performance of the modem.

As we understand it, in all instances the reported value is a median or an average value calculated for all sub-frames over the pertinent time duration versus being simply a sample value. For this reason, we believe that all values are accurate but there is a natural loss of granularity. We demonstrated this relationship when we did the YouTube analysis. While the average Physical Layer throughput never exceeded much higher than 8 Mbps, there were individual sub-frames/TTIs when the maximum TBS value/throughput was achieved.

By reparsing the data it was possible to extract many of the KPIs on a per sub-frame basis.

With XCAP, it was possible to reparse the data and extract many of the more valuable KPIs on a per sub-frame basis and we did this for the stationary testing log files. For example, we analyzed the actual allocation of transmission modes (once per sub-frame) and compared this information with the requested allocation of transmission modes (once per second) that we generally used. By taking this approach, we determined that the network scheduler assigned the mobile device the transmission mode that it requested – or at least the percentages were nearly identical. One can imagine the amount of processing time required for a lengthy test and the number of rows of data (1,000 rows for each second of the test) so we elected to limit the number of files that we reviewed in this manner. The following information identifies how frequently the KPIs were reported in the log files.

- Vehicular Speed – once per second/data collected and averaged over the entire interval
- Serving PCI – ~once every 40 ms/data collected and averaged over the entire interval
- SINR – ~once every 40 ms/data collected and averaged over the entire interval
- RSRP – ~once every 40 ms/data collected and averaged over the entire interval
- Rank Indicator 1/Rank Indicator 2 – once per second/data collected and averaged over the entire interval
- CQI – ~once every 10 ms/data collected and averaged over the entire interval

- Number of Assigned Resource Blocks – once per second/data collected and averaged over the entire interval
- MCS Code Word 0/Code Word 1/data collected and averaged over the entire interval
- Modulation Rate (QPSK, 16 QAM, 64 QAM) – ~once every 50 ms/data collected and averaged over the entire interval
- BLER – once per second/data collected and averaged over the entire interval
- PDSCH Throughput – once per second/data collected and averaged over the entire interval

We note that the average resource block allocation KPI that we presented in this report calculated the average across all sub-frames, even if they weren't assigned to the mobile device. For example, if the mobile device was assigned 40 resource blocks in the first 500 sub-frames and 0 resource blocks in the second 500 sub-frames, the RB value that we would use would have been 250.

For the scatterplots, we linked the two applicable KPIs together and then did the necessary averaging. For example, for the Physical Layer throughput versus SINR plots, we averaged all reported SINR values plus or minus one second from the reported throughput value in order to obtain the corresponding SINR value – we used this methodology for each throughput value in the log file. For the cell handover analysis, we used the first reported throughput value following a change in the Serving PCI, the next reported throughput value, and the two previous throughput values before the change in the Serving PCI to calculate the edge-of-cell throughput.

8.0 Final Thoughts

And now you know how we spent our summer vacation. We imagine that we'll return to the subject of MIMO in the future since there are other transmission modes to test, albeit nowhere near the fifty shades of MIMO that we suggested with the title of the report.

The appendix follows. It includes numerous figures that didn't find their way into the main body of the report. It also includes the results tables for the drive tests that we conducted. Until next time, be on the lookout for the next *Signals Ahead*....

Michael Thelander

Michael Thelander is the CEO and Founder of Signals Research Group. In his current endeavor he leads a team of industry experts providing technical and operator economics analysis for clients on a global basis. Mr. Thelander is also responsible for the consultancy's *Signals Ahead* research product, including its widely acclaimed "Chips and Salsa" series of reports that focus on the wireless IC industry.

Previously, Mr. Thelander was an analyst with Deutsche Bank Equity Research. Prior to joining Deutsche Bank, Mr. Thelander was a consultant with KPMG (now known as BearingPoint) and a communications officer with the United States Army. Mr. Thelander has also published numerous articles for leading trade publications and engineering journals throughout his career.

He has been an invited speaker at industry conferences around the world and he is frequently quoted by major news sources and industry newsletters, including T*he Economist, The Wall Street Journal, Investors Business Daily, Reuters, Bloomberg News,* and *The China Daily.* Mr. Thelander earned a Masters of Science in Solid State Physics from North Carolina State University and a Masters of Business Administration from the University of Chicago, Graduate School of Business.

9.0 Appendix

In the appendix we include numerous figures that didn't find their way into the main body of the report. In general, we do not include a lot of commentary since hopefully by this point the portrayed information is self-explanatory.

Table 8. Detailed Results, Part I - Knoxville

Scenario	Day / Time	Speed (MPH)	TM	Time (sec)	Trans-ferred Data (MB)	PDSCH Total (Avg)	PDSCH #0 (Avg)	PDSCH #1 (Avg)	SINR (dB)	RSRP (dBm)	RI=1 (%)	RI=2 (%)	MCS #0 (Avg)	MCS #1 (Avg)	Num of RB (Avg)	QPSK #0 (%)	16 QAM #0 (%)	64 QAM #0 (%)	QPSK #1 (%)	16 QAM #1 (%)	64 QAM #1 (%)
Drive Loop #1	6/18 0128	16.3	TM 3 & 2	1,021.0	1,598.8	12.5	7.2	6.3	13.2	-96.3	34.2	65.8	16.4	17.3	21.8	12.8	40.2	47.1	13.3	33.6	53.1
Drive Loop #1	6/18 0148	15.3	TM 3 & 2	1,091.0	1,774.8	13.0	7.4	6.1	13.5	-92.5	25.8	74.2	15.9	16.0	23.6	11.1	44.8	44.1	12.8	41.6	45.7
Drive Loop #1	6/18 0213	9.4	TM 3 & 2	1,782.0	3,152.1	14.2	7.8	6.7	14.2	-92.7	17.6	82.4	16.7	16.5	23.5	7.8	44.5	47.7	7.9	45.3	46.8
Drive Loop #1	6/18 0243	18.2	TM 3 & 2	925.0	1,432.9	12.4	7.1	5.7	12.8	-93.5	26.3	73.7	15.3	15.3	23.4	15.6	44.0	40.4	17.3	43.1	39.7
Stationary Point #1	6/18 0343	0.0	TM 3 & 2	80.0	104.8	10.5	5.4	5.2	10.0	-101.5	3.1	96.9	12.8	12.7	24.0	0.9	97.3	1.8	1.0	98.8	0.1
Stationary Point #2	6/18 0349	0.0	TM 3 & 2	50.0	94.8	15.2	7.6	7.6	16.4	-74.6	0.0	100.0	17.4	17.4	24.0	0.0	19.9	80.2	0.0	20.2	79.8
Stationary Point #3	6/18 0355	0.0	TM 3 & 2	70.0	110.5	12.6	6.3	6.3	11.4	-98.4	0.0	100.0	14.3	14.3	24.1	0.0	98.7	1.2	0.0	98.9	1.1
Stationary Point #4	6/18 0401	0.0	TM 3 & 2	59.0	182.6	24.8	12.4	12.4	26.5	-65.9	0.0	100.0	23.5	23.5	24.2	0.0	0.0	100.0	0.0	0.0	100.0
Stationary Point #5	6/18 0406	0.0	TM 3 & 2	78.0	188.8	19.4	9.7	9.7	19.3	-73.1	0.0	100.0	20.2	20.2	24.2	0.0	4.1	95.9	0.0	4.1	95.9
Stationary Point #6	6/18 0412	0.0	TM 3 & 2	93.0	205.8	17.7	8.9	8.8	17.2	-88.2	0.0	100.0	19.2	19.1	24.2	0.0	2.2	97.8	0.0	2.5	97.5
Stationary Point #7	6/18 0417	0.0	TM 3 & 2	104.0	393.9	30.3	15.2	15.2	28.2	-80.3	0.0	100.0	26.7	26.7	24.4	0.0	0.0	100.0	0.0	0.0	100.0
Drive Loop #1 - 2 devices	6/18 0427	18.82	TM 3 & 2	900.0	810.1	7.2	4.2	3.4	12.4	-89.0	27.9	72.1	15.8	16.8	13.8	15.2	41.1	43.7	12.9	35.5	51.6
Drive Loop #1 - 2 devices	6/18 0427	18.82	TM 3 & 2	900.0	804.4	7.2	4.4	3.4	13.1	-87.7	32.9	67.1	16.1	17.1	13.8	14.4	37.5	48.2	12.8	32.6	54.5
Drive Loop #2	6/18 0501	24.3	TM 3 & 2	426.0	746.7	14.0	7.8	6.4	15.8	-89.9	20.0	80.0	16.8	16.6	23.3	8.1	41.6	50.4	11.2	39.8	49.0
To Airport	6/18 0509	38.8	TM 3 & 2	1,215.0	1,661.1	10.9	7.0	4.8	11.6	-99.1	45.9	54.1	15.5	15.6	22.5	13.7	47.1	39.2	18.2	40.3	41.5
Drive Loop #1	6/18 1758	16.0	TM 3 & 2	1,051.0	1,770.8	13.5	7.6	6.4	13.1	-88.4	27.3	72.7	16.6	17.5	22.3	12.3	39.9	47.8	10.7	35.1	54.1
Drive Loop #1	6/18 1816	16.4	TM 3 & 2	1,027.0	1,622.3	12.6	7.2	5.8	11.6	-90.1	28.2	71.8	15.9	16.3	22.5	16.5	38.5	45.0	18.3	32.7	49.1
Drive Loop #2	6/18 1835	17.3	TM 3 & 2	1,391.0	2,425.4	13.9	7.7	6.7	14.0	-88.7	20.3	79.7	17.0	17.3	22.5	10.1	37.5	52.4	10.7	34.8	54.5
Drive Loop #1	6/19 0117	15.3	TM 2 Only	1,098.0	1,478.6	10.8	-	-	13.7	-84.1	96.3	3.7	20.8	-	23.3	5.1	20.2	74.8	-	-	-
Drive Loop #1	6/19 0136	15.8	TM 2 Only	1,048.0	1,398.7	10.7	-	-	13.4	-85.5	94.6	5.4	20.5	-	23.2	4.3	21.8	73.9	-	-	-
Drive Loop #1	6/19 0153	16.8	TM 2 Only	998.0	1,323.3	10.6	-	-	13.9	-84.8	94.6	5.4	20.4	-	23.4	5.7	23.0	71.3	-	-	-

Source: Signals Research Group

Table 9. Detailed Results, Part II - Knoxville

Scenario	Day / Time	Speed (MPH)	TM	Time (sec)	Trans-ferred Data (MB)	PDSCH Total (Avg)	PDSCH #0 (Avg)	PDSCH #1 (Avg)	SINR (dB)	RSRP (dBm)	RI=1 (%)	RI=2 (%)	MCS #0 (Avg)	MCS #1 (Avg)	Num of RB (Avg)	QPSK #0 (%)	16 QAM #0 (%)	64 QAM #0 (%)	QPSK #1 (%)	16 QAM #1 (%)	64 QAM #1 (%)
Drive Loop #1	6/19 0210	16.9	TM 2 Only	993.0	1,337.6	10.8	-	-	13.7	-85.0	94.9	5.2	20.6	-	23.5	4.8	19.6	75.7	-	-	-
Stationary Point #7	6/19 0229	0.0	TM 2 Only	137.0	260.0	15.2	-	-	28.0	-77.0	100.0	0.0	26.7	-	24.4	0.0	0.0	100.0	-	-	-
Stationary Point #1	6/19 0236	0.0	TM 2 Only	111.0	108.8	7.8	-	-	7.1	-100.2	100.0	0.0	17.6	-	24.2	0.0	21.3	78.7	-	-	-
Stationary Point #2	6/19 0240	0.0	TM 2 Only	165.0	201.2	9.8	-	-	13.8	-76.5	100.0	0.0	20.4	-	23.9	0.0	0.1	99.9	-	-	-
Stationary Point #3	6/19 0245	0.0	TM 2 Only	135.0	156.2	9.3	-	-	10.0	-97.3	100.0	0.0	19.6	-	24.2	0.0	0.9	99.1	-	-	-
Stationary Point #4	6/19 0249	0.0	TM 2 Only	108.0	205.1	15.2	-	-	27.9	-59.5	100.0	0.0	26.7	-	24.4	0.0	0.0	100.0	-	-	-
Stationary Point #5	6/19 0254	0.0	TM 2 Only	74.0	123.0	13.3	-	-	12.9	-72.5	100.0	0.0	24.4	-	24.4	0.0	0.0	100.0	-	-	-
Stationary Point #6	6/19 0257	0.0	TM 2 Only	85.0	121.3	11.4	-	-	14.2	-83.7	100.0	0.0	22.5	-	23.7	0.0	0.0	100.0	-	-	-
Drive Loop #1 - 2 devices	6/19 0300	17.48	TM 2 Only	959.0	627.8	5.2	-	-	11.6	-87.1	96.1	4.0	19.6	-	12.4	7.9	23.5	68.6	-	-	-
Drive Loop #1 - 2 devices	6/19 0300	17.48	TM 2 Only	967.0	635.1	5.3	-	-	12.0	-92.0	96.4	3.6	19.4	-	12.7	7.4	27.8	64.8	-	-	-
Drive Loop #2	6/19 0316	21.1	TM 2 Only	815.0	1,193.7	11.7	-	-	15.5	-85.4	95.8	4.2	22.1	-	23.6	1.6	14.3	84.2	-	-	-
Random Freeway Driving	6/19 0330	41.06	TM 2 Only	1,268.0	1,980.8	12.5	-	-	14.1	-85.1	71.7	28.3	19.7	-	22.7	6.7	22.6	70.7	-	-	-
Random Freeway Driving	6/19 0352	50.6	TM 2 Only	449.0	694.4	12.4	-	-	12.5	-92.9	27.4	72.6	15.9	-	21.8	18.0	37.7	44.3	-	-	-
Random Freeway Driving	6/19 0330	41.06	TM 2 Only	1,268.0	1,980.8	12.5	-	-	14.1	-85.1	71.7	28.3	19.7	-	22.7	6.7	22.6	70.7	-	-	-
Random Freeway Driving	6/19 0352	50.6	TM 2 Only	449.0	694.4	12.4	-	-	12.5	-92.9	27.4	72.6	15.9	-	21.8	18.0	37.7	44.3	-	-	-

Source: Signals Research Group

Table 10. Detailed Results, Part I – Santa Clara

Scenario	Day / Time	Speed (MPH)	TM	Time (sec)	Trans-ferred Data (MB)	PDSCH Total (Avg)	PDSCH #0 (Avg)	PDSCH #1 (Avg)	SINR (dB)	RSRP (dBm)	RI=1 (%)	RI=2 (%)	MCS #0 (Avg)	MCS #1 (Avg)	Num of RB (Avg)	QPSK #0 (%)	16 QAM #0 (%)	64 QAM #0 (%)	QPSK #1 (%)	16 QAM #1 (%)	64 QAM #1 (%)
Drive Loop #1	7/18 0103	29.0	TM 3 & 2	964.0	3,486.1	28.9	15.9	13.8	15.2	-92.3	30.5	69.5	16.1	17.3	46.9	22.3	26.8	51.0	18.0	22.4	59.6
Drive Loop #1	7/18 0127	27.2	TM 3 & 2	1,371.0	4,789.9	28.0	15.5	13.2	15.5	-91.6	27.3	72.7	16.1	17.0	46.9	19.7	30.5	49.8	15.9	28.9	55.2
Drive Loop #1	7/18 0151	27.3	TM 3 & 2	1,140.0	4,018.5	28.2	15.8	13.3	16.0	-88.9	25.7	74.3	16.6	17.0	46.7	14.1	32.9	53.0	12.6	31.8	55.6
Drive Loop #1	7/18 0210	27.2	TM 3 & 2	1,262.0	4,243.5	26.9	14.9	12.5	14.9	-92.9	27.2	72.8	15.7	16.4	46.6	20.1	33.5	46.4	18.5	30.0	51.5
Drive Loop #1	7/18 0232	28.5	TM 3 & 2	1,124.0	3,793.5	27.0	15.1	12.9	15.2	-92.0	28.5	71.5	16.0	16.9	46.7	18.8	34.1	47.1	16.4	30.2	53.4
Drive Loop #1	7/18 0253	28.0	TM 3 & 2	1,220.0	4,193.8	27.5	15.4	13.0	14.6	-92.7	29.5	70.5	15.7	16.6	46.7	20.1	34.3	45.6	16.7	31.2	52.0
Stationary Point #1	7/18 0315	0.0	TM 3 & 2	82.0	592.2	57.8	29.0	28.8	28.8	-64.8	0.0	100.0	26.8	26.8	46.0	0.4	0.0	99.6	0.3	0.0	99.7
Stationary Point #2	7/18 0322	0.0	TM 3 & 2	94.0	106.9	9.1	8.5	1.5	4.1	-112.0	87.6	12.4	10.6	5.7	49.0	17.2	82.8	0.0	100.0	0.0	0.0
Stationary Point #3	7/18 0513	0.0	TM 3 & 2	69.0	532.0	61.7	30.7	30.9	29.2	-74.8	0.0	100.0	27.0	27.0	48.8	0.0	0.0	100.0	0.0	0.0	100.0
Stationary Point #4	7/18 0553	0.0	TM 3 & 2	96.0	76.8	6.4	-	-	1.3	-118.0	100.0	0.0	7.5	0.0	49.1	7.5	100.0	0.0	-	-	-
Stationary Point #5	7/18 0600	0.0	TM 3 & 2	80.0	359.6	36.0	17.5	18.5	17.8	-92.5	0.0	100.0	19.5	19.5	48.8	0.0	0.1	99.9	0.0	0.1	99.9
Drive Loop #2	7/18 0340	22.3	TM 3 & 2	1,838.0	7,306.1	31.8	17.5	14.9	17.0	-90.6	23.7	76.3	17.7	18.0	47.1	13.3	28.7	58.0	13.3	27.6	59.1
Drive Loop #2	7/18 0413	24.3	TM 3 & 2	1,726.0	6,666.7	30.9	17.1	14.4	16.7	-90.9	24.1	75.9	17.4	17.6	47.2	13.8	30.6	55.6	14.1	28.9	57.0
Drive Loop #2	7/18 0442	24.4	TM 3 & 2	1,713.0	6,595.1	30.8	16.8	14.5	16.3	-91.0	23.7	76.3	17.3	17.7	46.6	13.7	32.2	54.0	13.3	30.1	56.6
Highway #101	7/18 0529	54.6	TM 3 & 2	1,222.0	3,895.1	25.5	15.3	10.4	14.5	-87.8	33.9	66.1	16.3	15.7	46.2	13.6	36.2	50.2	15.6	39.8	44.6
Random Driving	7/18 1317	21.7	TM 3 & 2	402.0	1,316.6	26.2	13.9	12.5	15.0	-86.7	15.0	85.0	18.0	18.2	36.5	10.0	25.8	64.2	10.2	24.7	65.1
Random Driving	7/18 1404	20.4	TM 3 & 2	1,397.0	4,365.6	25.0	14.7	11.7	13.4	-95.1	36.7	63.3	15.7	16.2	44.4	19.0	36.3	44.7	18.6	33.0	48.4
Random Driving	7/18 1450	14.1	TM 3 & 2	1,914.0	4,921.4	20.6	12.7	9.6	10.8	-97.8	47.9	52.1	14.3	15.7	45.7	25.7	37.6	36.7	15.9	38.8	45.3
Random Driving	7/18 1537	7.3	TM 3 & 2	778.0	1,400.4	14.4	11.1	5.7	4.8	-105.9	78.7	21.3	12.4	14.4	46.5	34.2	52.1	13.8	45.6	16.3	38.1
Random Driving	7/18 1554	20.5	TM 3 & 2	1,787.0	5,807.8	26.0	14.5	12.1	16.2	-90.5	22.2	77.8	16.1	16.0	46.0	14.5	37.3	48.2	15.8	36.7	47.5
Drive Loop #1	7/18 1632	21.4	TM 3 & 2	1,583.0	5,698.8	28.8	16.4	13.6	15.3	-91.0	31.5	68.5	16.9	17.6	46.5	17.0	31.3	51.7	15.7	27.9	56.3
Stationary Point #1	7/19 0103	0.0	TM 2 Only	75.0	290.3	31.0	-	-	28.7	-70.5	100.0	0.0	27.0	-	49.2	0.0	0.0	100.0	-	-	-

Source: Signals Research Group

Table 11. Detailed Results, Part II – Santa Clara

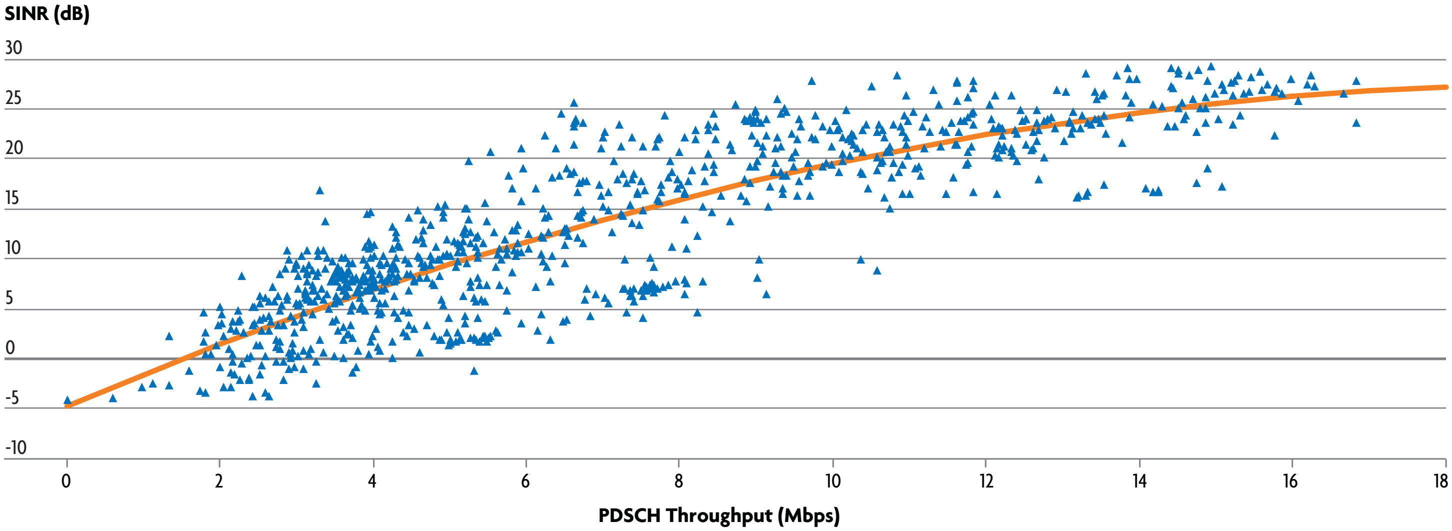
Scenario	Day / Time	Speed (MPH)	TM	Time (sec)	Trans-ferred Data (MB)	PDSCH Total (Avg)	PDSCH #0 (Avg)	PDSCH #1 (Avg)	SINR (dB)	RSRP (dBm)	RI=1 (%)	RI=2 (%)	MCS #0 (Avg)	MCS #1 (Avg)	Num of RB (Avg)	QPSK #0 (%)	16 QAM #0 (%)	64 QAM #0 (%)	QPSK #1 (%)	16 QAM #1 (%)	64 QAM #1 (%)
Stationary Point #2	7/19 0241	0.0	TM 2 Only	92.0	132.3	11.5	-	-	6.7	-107.7	100.0	0.0	13.1	-	49.2	0.0	100.0	0.0	-	-	-
Stationary Point #3	7/19 0247	0.0	TM 2 Only	77.0	297.4	30.9	-	-	28.3	-76.9	100.0	0.0	27.0	-	48.9	0.0	0.0	100.0	-	-	-
Stationary Point #4	7/19 0404	0.0	TM 2 Only	8.0	6.5	6.5	-	-	2.6	-118.2	100.0	0.0	7.6	-	46.1	99.9	0.1	0.0	-	-	-
Stationary Point #5	7/19 0358	0.0	TM 2 Only	102.0	132.6	10.4	-	-	4.3	-115.8	100.0	0.0	12.1	-	48.7	13.8	86.2	0.0	-	-	-
Drive Loop #1	7/19 0105	28.6	TM 2 Only	1,213.0	3,184.1	21.0	-	-	14.8	-92.7	100.0	0.0	20.0	-	46.7	9.6	21.3	69.1	-	-	-
Drive Loop #1	7/19 0126	28.6	TM 2 Only	1,199.0	3,162.4	21.1	-	-	14.9	-92.7	100.0	0.0	20.1	-	46.9	10.4	20.1	69.5	-	-	-
Drive Loop #1	7/19 0147	27.5	TM 2 Only	1,236.0	3,275.4	21.2	-	-	15.1	-92.5	100.0	0.0	20.2	-	46.6	10.2	19.4	70.4	-	-	-
Drive Loop #1	7/19 0218	28.4	TM 2 Only	1,202.0	3,155.3	21.0	-	-	14.7	-92.6	100.0	0.0	20.0	-	46.5	11.0	20.3	68.7	-	-	-
Drive Loop #2	7/19 0250	23.1	TM 2 Only	1,713.0	4,796.4	22.4	-	-	16.2	-91.5	100.0	0.0	21.1	-	46.9	8.2	16.7	75.1	-	-	-
Drive Loop #2	7/19 0320	24.3	TM 2 Only	1,634.0	4,575.2	22.4	-	-	16.2	-91.5	100.0	0.0	21.2	-	46.6	8.1	14.6	77.3	-	-	-
Highway #101	7/19 0410	53.5	Mixed	1,508.0	4,316.7	22.9	-	-	15.1	-86.3	N.M	N.M.	20.0	-	45.8	6.3	22.1	71.7	-	-	-
Hotel Room	7/19 0444	0.0	Mixed	2,496.0	9,859.2	31.6	N.M.	N.M.	23.2	-89.0	N.M	N.M.	26.7	N.M.	47.5	0.1	0.0	99.8	N.M.	N.M.	N.M.

Source: Signals Research Group

Figure 55. Physical Layer Throughput Versus SINR Scatterplot for Two Devices with TM 3 Enabled, June 18th 0427 hours – Knoxville Band 5 Network

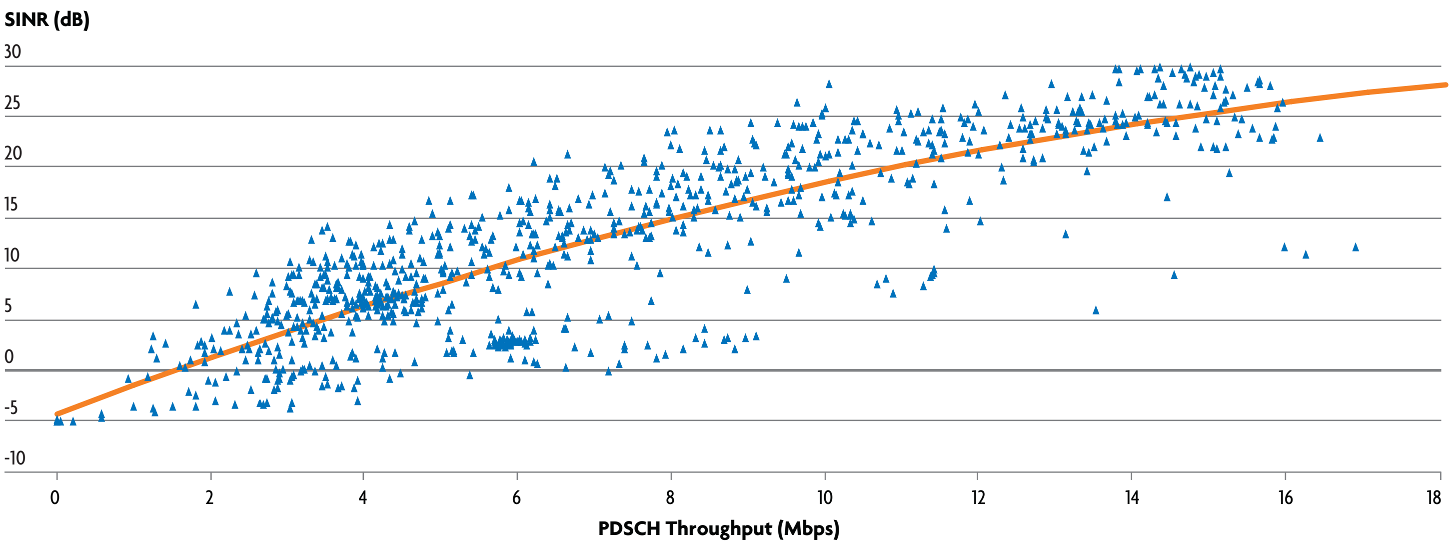
DEVICE 1

PDSCH Throughput (Median) = 6.30 Mbps SINR (Median) = 11.42 dB



DEVICE 2

PDSCH Throughput (Median) = 6.19 Mbps SINR (Median) = 11.98 dB

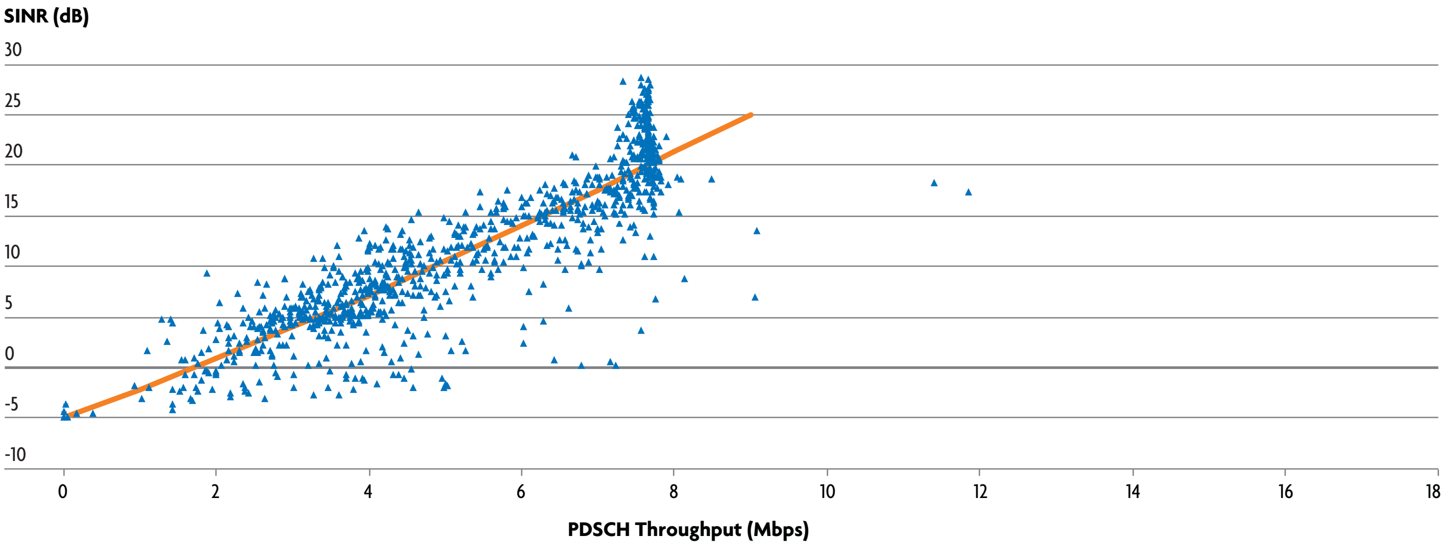


Source: Signals Research Group

Figure 56. Physical Layer Throughput Versus SINR Scatterplot for Two Devices with TM 2 Only, June 19th 0300 hours – Knoxville Band 5 Network

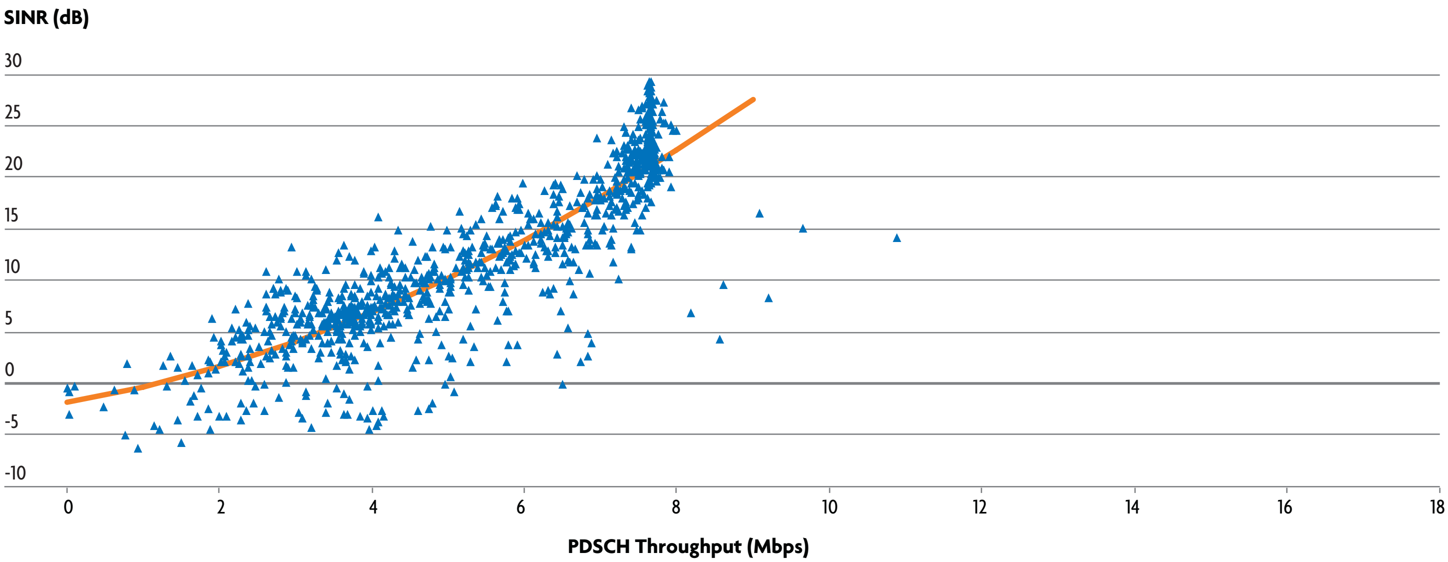
DEVICE 1

PDSCH Throughput (Median) = 5.11 Mbps   SINR (Median) = 10.96 dB



DEVICE 2

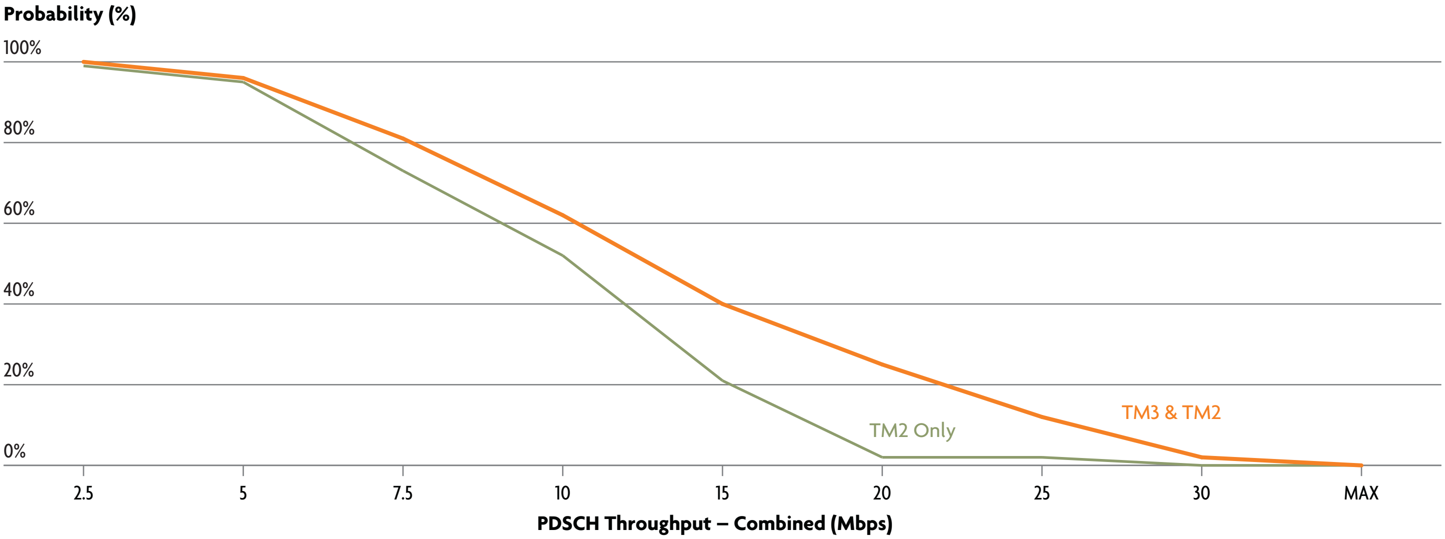
PDSCH Throughput (Median) = 5.23 Mbps   SINR (Median) = 10.95 dB



Source: Signals Research Group

Figure 57. Probability Distribution of Physical Layer Throughput for Two Devices with TM 3 Enabled and with TM 2 Only – Knoxville Band 5 Network

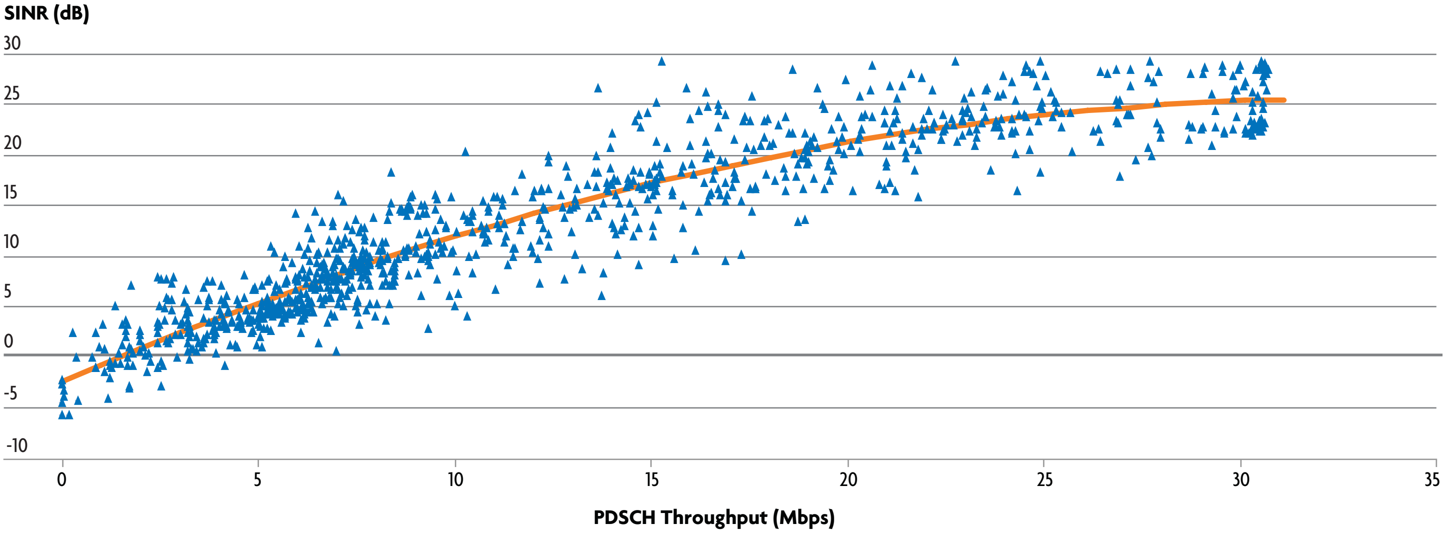
PDSCH Combined Throughput from Two Devices w/ TM3 & TM2 (Median) = 12.84 Mbps
PDSCH Combined Throughput from Two Devices w/ TM2 Only (Median) = 10.28 Mbps

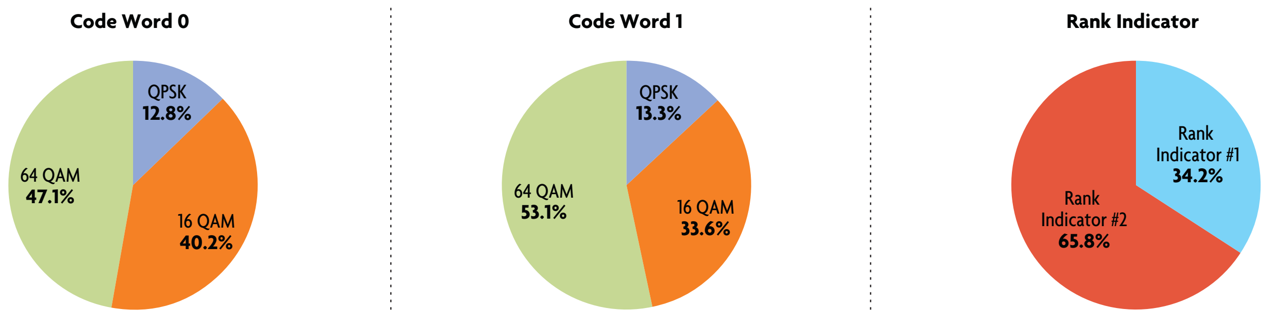


Source: Signals Research Group

Figure 58. Physical Layer Throughput Versus SINR Scatterplot Plus Assorted KPIs with TM 3 Enabled, June 18th 0128 hours – Knoxville Band 5 Network

PDSCH Throughput (Median) = 9.52 Mbps
SINR (Average) = 13.23 dB
MCS #0 (Median) = 15.92
Num of RB (Average) = 21.75
PDSCH Throughput (Average) = 12.53 Mbps
CQI (Average) = 10.93
MCS #1 (Median) = 17.36

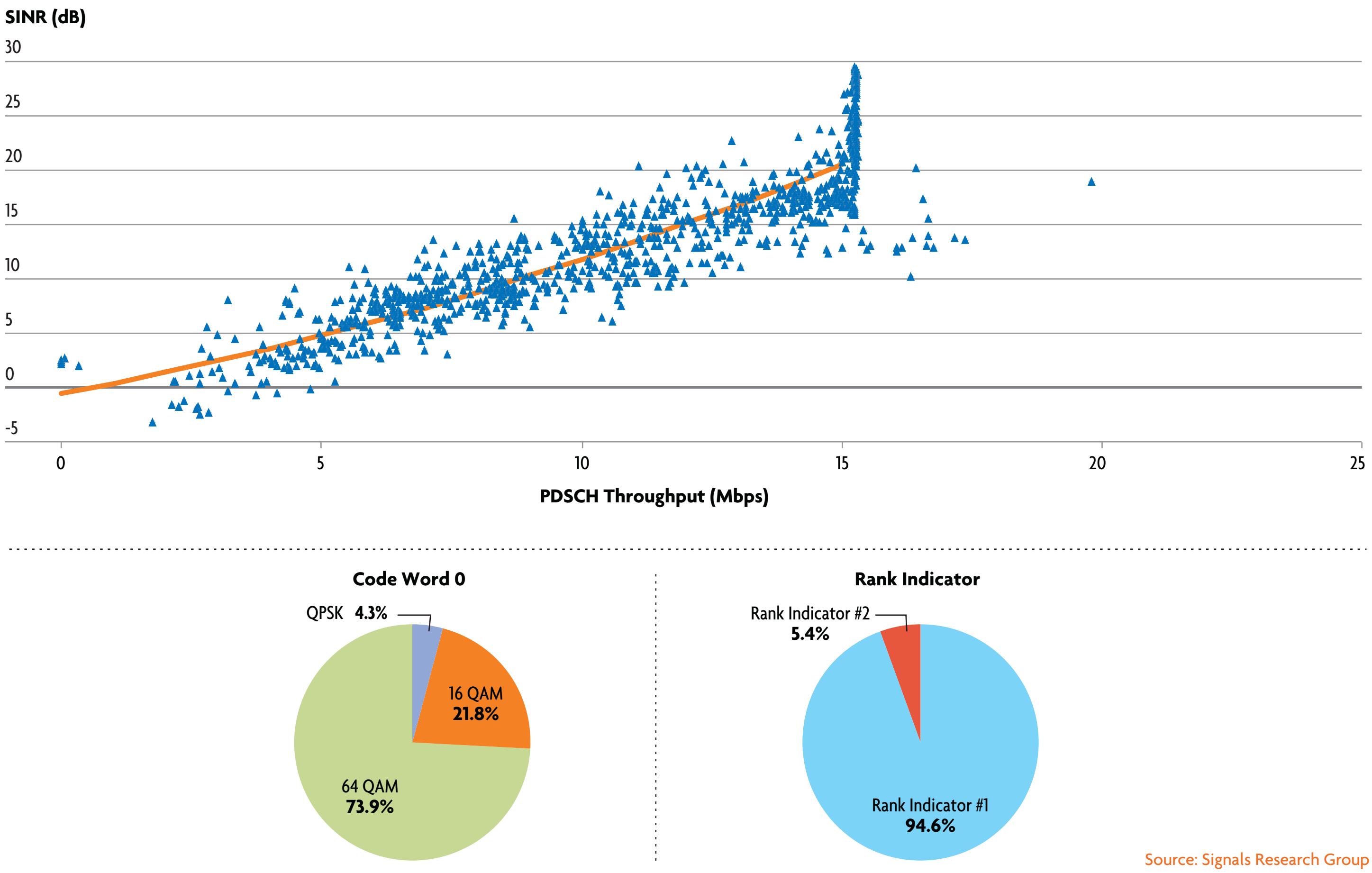




Source: Signals Research Group

Figure 59. Physical Layer Throughput Versus SINR Scatterplot Plus Assorted KPIs with TM 2 Only, June 19th 0136 hours – Knoxville Band 5 Network

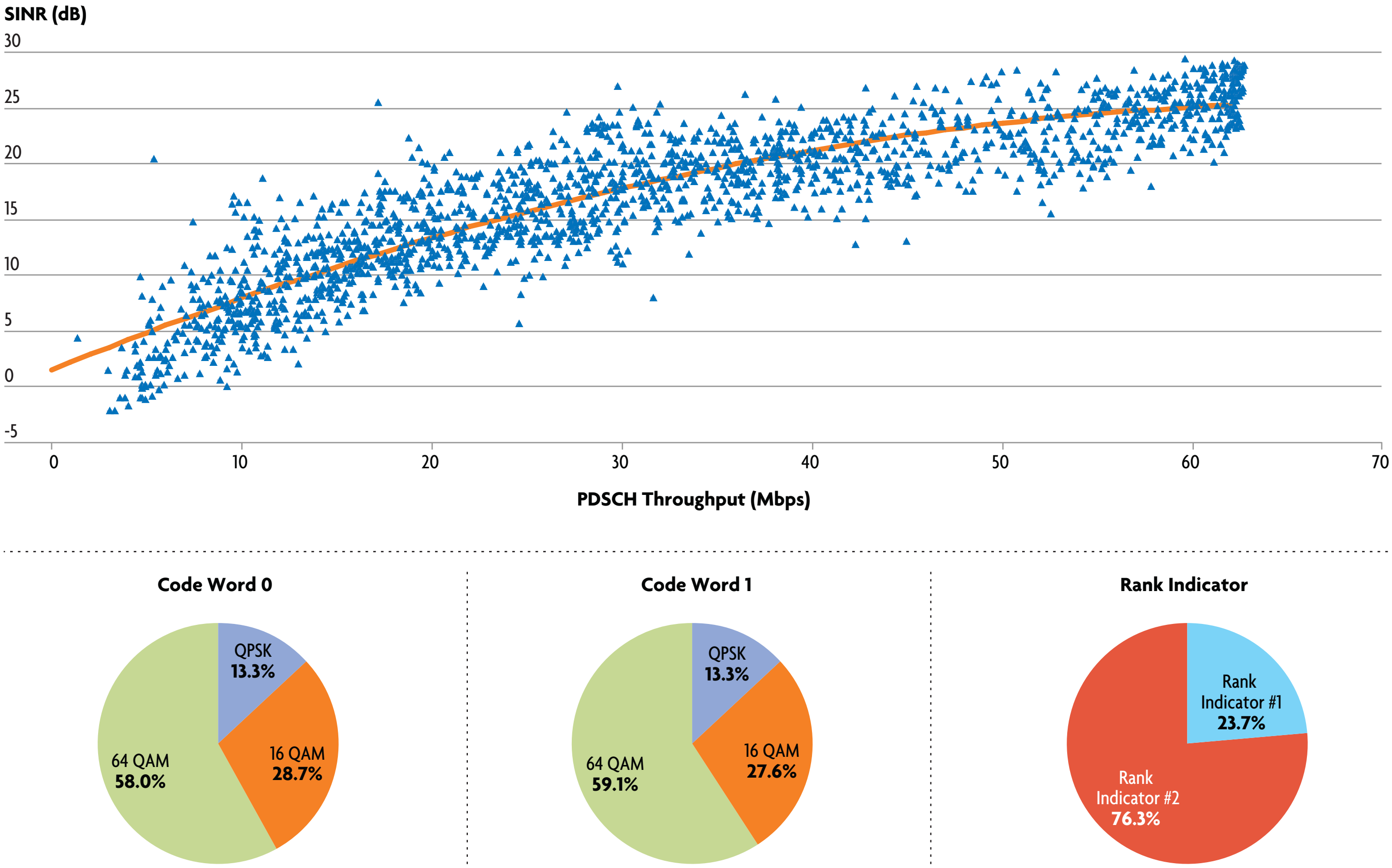
PDSCH Throughput (Median) = 10.94 Mbps	PDSCH Throughput (Average) = 10.68 Mbps
SINR (Average) = 13.4 dB	CQI (Average) = 12.75
MCS #0 (Median) = 21.72	MCS #1 (Median) = NM
Num of RBs (Average) = 23.18	



Source: Signals Research Group

Figure 60. Physical Layer Throughput Versus SINR Scatterplot Plus Assorted KPIs with TM 3 Enabled, July 18th 0340 hours – Santa Clara Band 4 Network

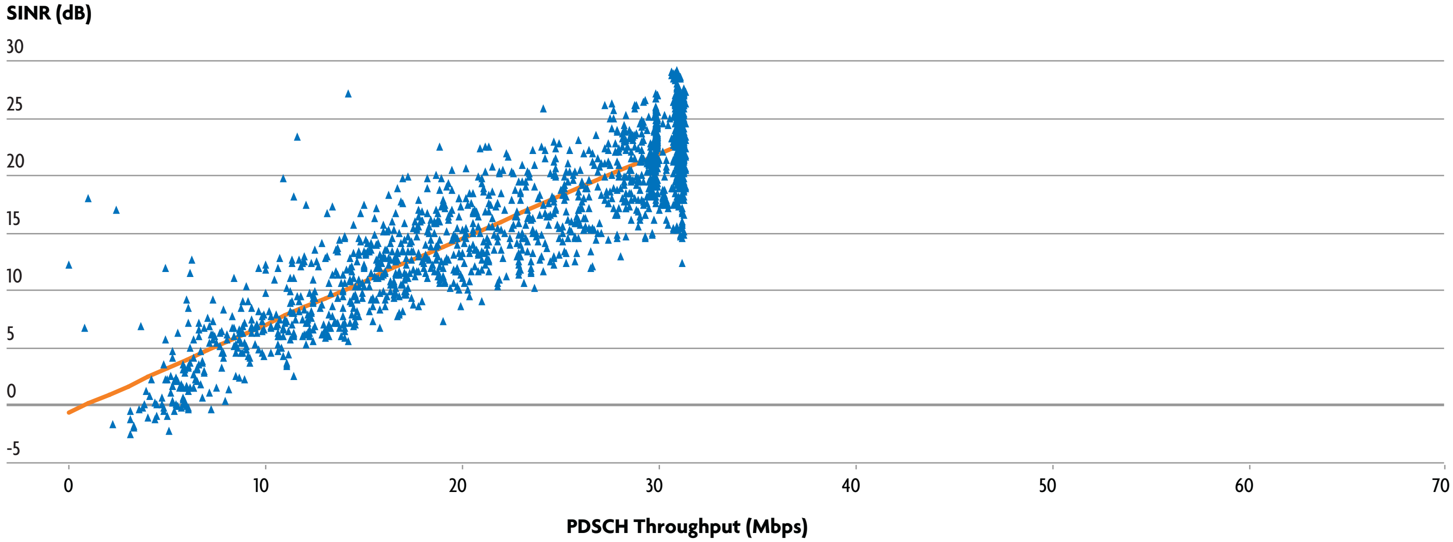
PDSCH Throughput (Median) = 28.61 Mbps
SINR (Average) = 16.95 dB
MCS #0 (Median) = 18.0
Num of RB (Average) = 47.1
PDSCH Throughput (Average) = 31.1 Mbps
CQI (Average) = 11.10
MCS #1 (Median) = 18.4

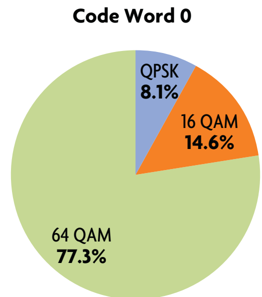


Source: Signals Research Group

Figure 61. Physical Layer Throughput Versus SINR Scatterplot Plus Assorted KPIs with TM 2 Only, July 19th 0320 hours – Santa Clara Band 4 Network

PDSCH Throughput (Median) = 24.7 Mbps	PDSCH Throughput (Average) = 22.42 Mbps
SINR (Average) = 16.25 dB	CQI (Average) = 12.81
MCS #0 (Median) = 23.12	MCS #1 (Median) = N.M.
Num of RB (Average) = 46.7	

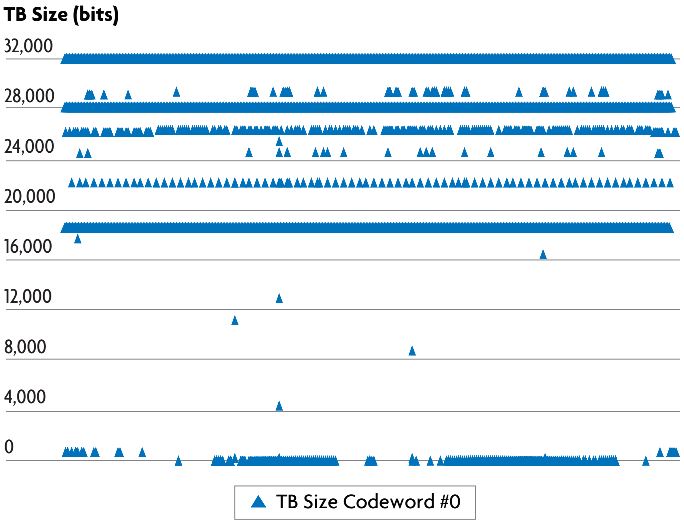


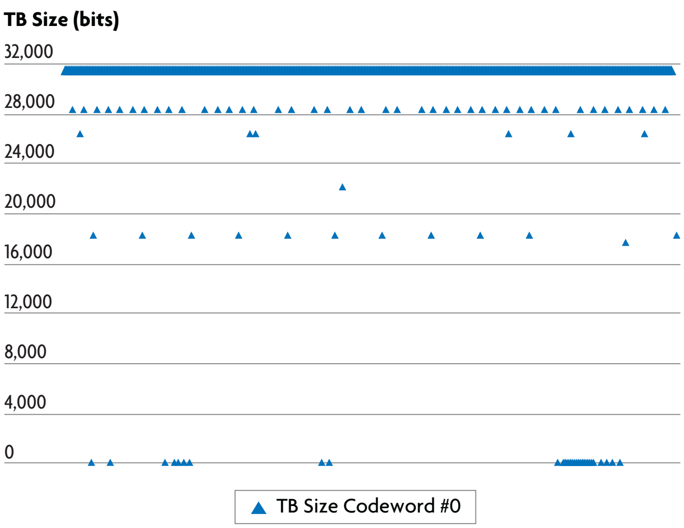


Source: Signals Research Group

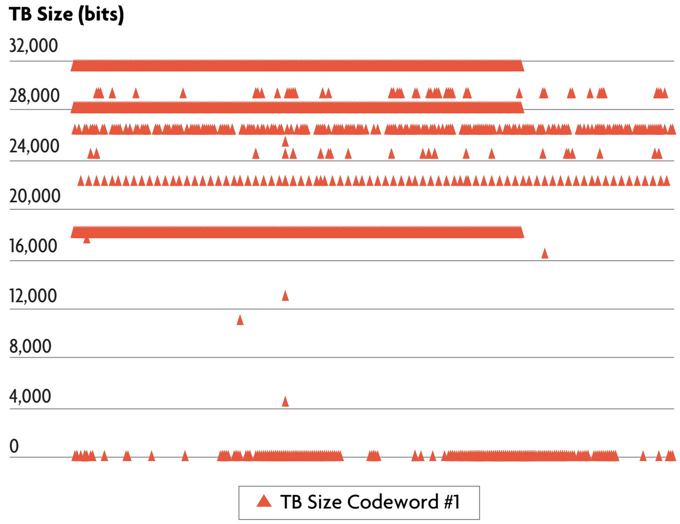
Figure 62. Transport Block Size Assignments with TM 3 Enabled, Point 3 – Santa Clara, Band 4 Network

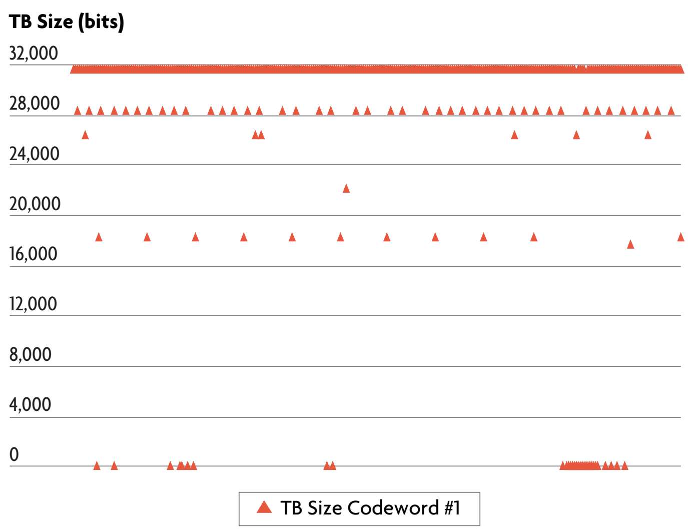
TB Size Codeword #0 (Median) = 31,704 bits
TB Size Codeword #0 (Average) = 30,998 bits





TB Size Codeword #1 (Median) = 31,704 bits
TB Size Codeword #1 (Average) = 30,989 bits

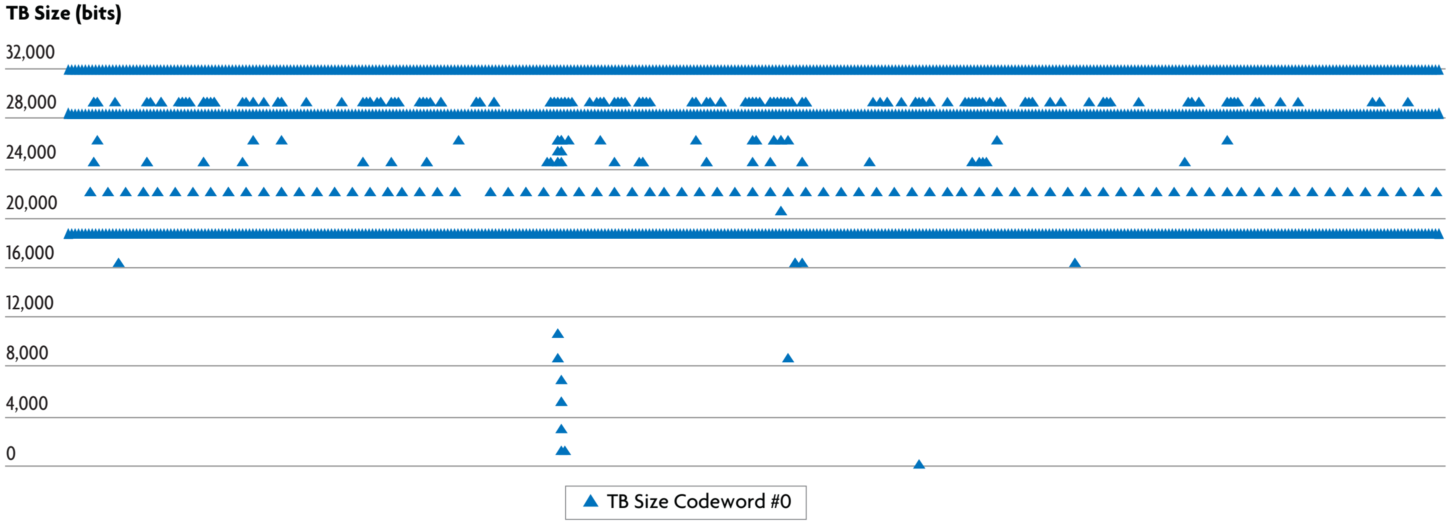


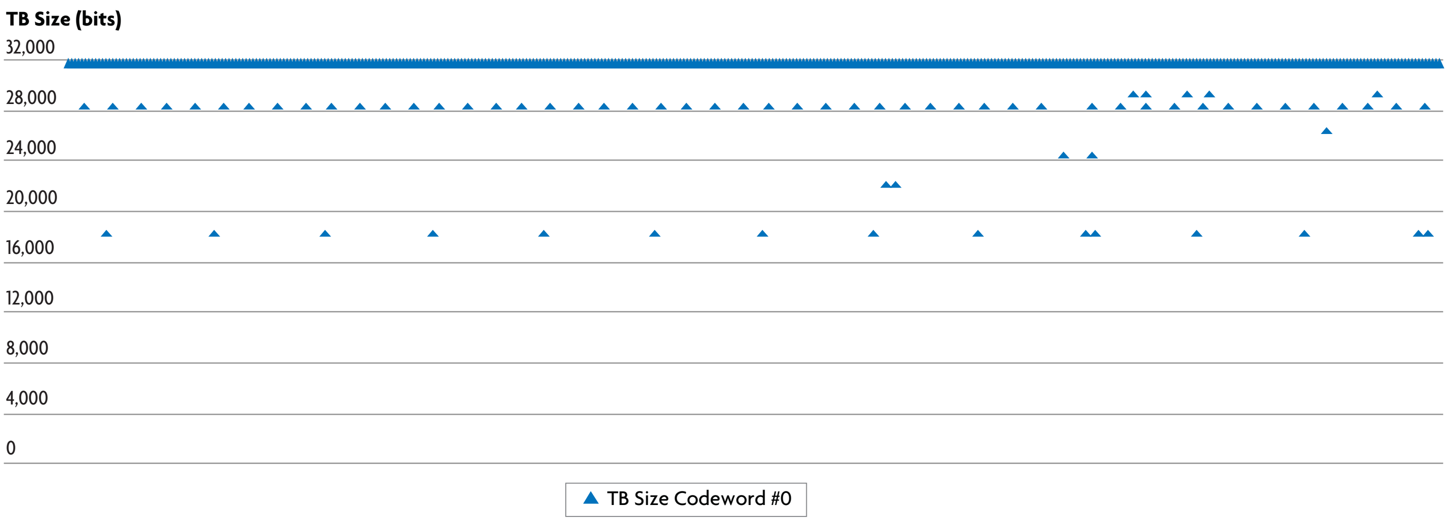


Source: Signals Research Group

Figure 63. Transport Block Size Assignments with TM 2 Only, Point 3 – Santa Clara, Band 4 Network

TB Size Codeword #0 (Median) = 31,704 bits
TB Size Codeword #0 (Average) = 31,310 bits





Source: Signals Research Group

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