SIGNALS Ahead
Redefining Research
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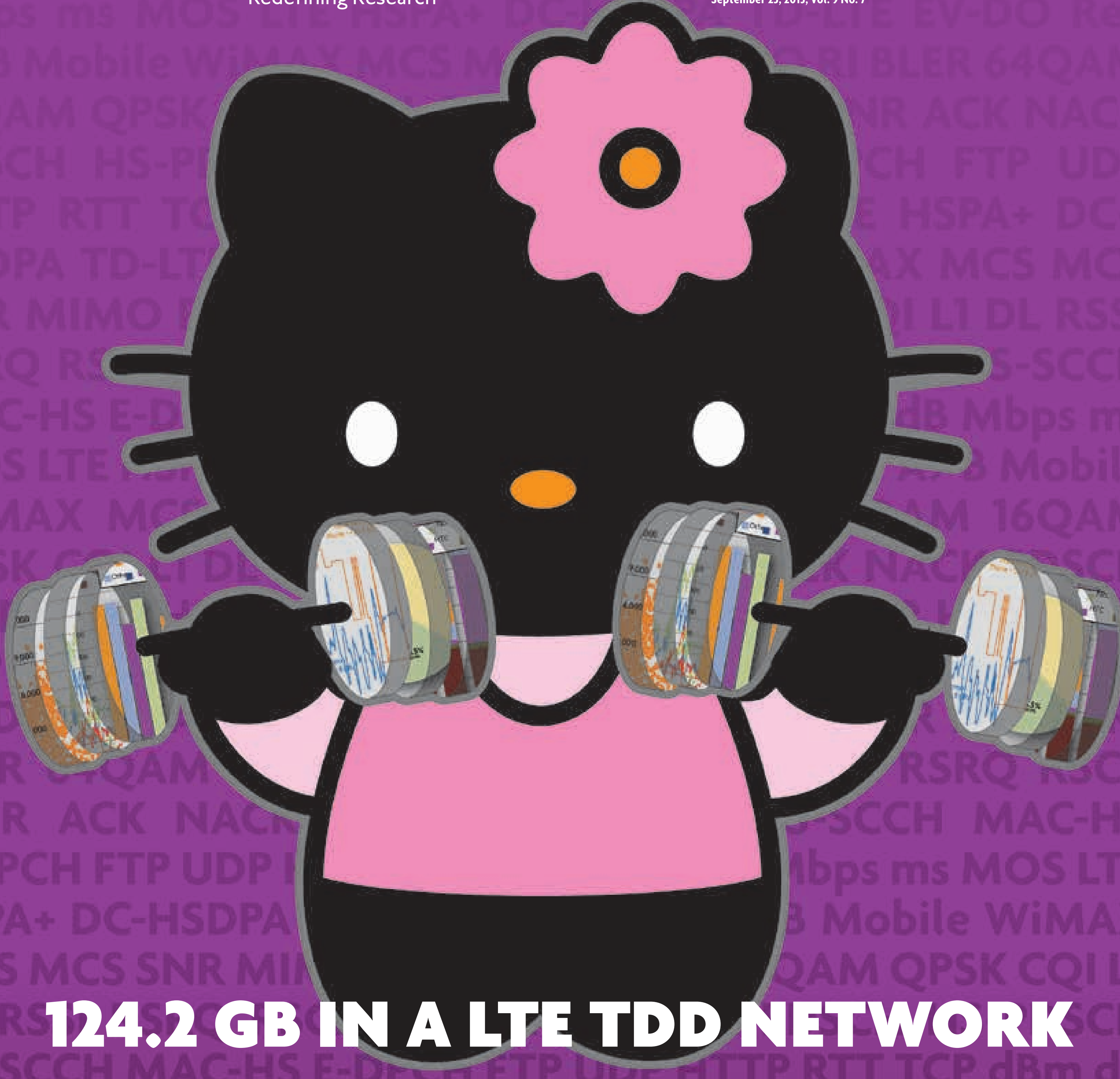

124.2 GB IN A LTE TDD NETWORK

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1.0 Executive Summary

Signals Research Group conducted what we believe is the first exhaustive [and exhausting] independent analysis of LTE TDD for public consumption. This effort would not have been possible without the support of Accuver, who provided us with access to its XCAL data collection tool and its XCAP post-processing software. We have used the solution numerous times over the last several years so we are very accustomed to using it, although we do stumble upon new capabilities and features each time we use it. In our most recent benchmark studies, specifically LTE TDD in Tokyo and LTE Advanced Carrier Aggregation in Seoul, the solution's ability to support recently introduced technology features, including Category 4 chipsets and Carrier Aggregation, proved to be invaluable.

This effort was entirely self-sponsored although we did receive logistical support in the form of test SIMs, a high bandwidth server, and mobile devices. SRG assumes full responsibility for the analysis and commentary included in this report.

In theory, the performance of LTE TDD should be largely comparable to the performance of LTE FDD.

Although LTE TDD and LTE FDD are merely different duplex options from the same standard, there is still a very robust interest in how LTE TDD performs. In theory, the performance of LTE TDD should be largely comparable to the performance of LTE FDD, and Signals Ahead readers are well-versed in that regard. However, there are practical matters, such as the frequency band where LTE TDD is deployed and the downlink/uplink configuration of the available resources, which must be considered. For this reason, we focused our drive testing and analysis on specific areas that would allow us to quantify these differences in a real world network.

The performance of the Softbank network was very impressive.

By all accounts, Softbank has deployed a very dense LTE network, in particular LTE FDD, so the performance that we observed in both networks was very impressive. The challenge for other operators is that that they are not Softbank, and they will likely struggle to replicate the results that we obtained unless they have a similar commitment, along with the financial backing, to achieve a high quality network. Softbank hopes to replicate its success in North America with Sprint and Clearwire. Their goal will not be an easy one to achieve and we wish them the best of luck.

Cutting to the chase, LTE TDD delivered meaningfully higher downlink data rates than LTE FDD and LTE FDD achieved much higher uplink data rates. This finding isn't surprising given that Softbank was using Configuration 2, meaning that its 20 MHz LTE TDD radio channel was providing the equivalent of roughly 15 MHz of spectrum in the downlink and approximately 5 MHz of spectrum in the uplink. After normalizing the results based on the amount of utilized spectrum, the picture changes and the 10 MHz LTE FDD network slightly outperforms LTE

TDD in the downlink while the 5 MHz LTE FDD network slightly outperforms LTE TDD in the uplink. Depending on the area within Tokyo, Softbank has either a 5 MHz or a 10 MHz LTE FDD network.

The comparisons between the two LTE duplex schemes become even more complicated when we take into consideration the impact of using different frequencies.

The comparisons between the two LTE duplex schemes become even more complicated when we take into consideration the impact of using different frequency bands – LTE TDD was deployed at 2565 MHz and LTE FDD was deployed at 2155/2152.5 MHz in the downlink and 1962.5 MHz in the uplink. Due to the 410 MHz that separates the two downlink transmission paths and the 602.5 MHz that separates the uplink transmission paths, there was an average difference of 12.17 dB in the downlink signal strength (RSRP) between the two networks and an 18.47 dB difference in the uplink transmit power during the uplink throughput tests that we conducted. The differences in the transmit power were much lower in the downlink throughput tests and in the Skype Video/Voice tests that we conducted. For a comparable RSRP value and channel bandwidth the two duplex schemes delivered roughly the same throughput. In the uplink, the much higher transmit power of the LTE TDD device helped to partially overcome the inherent differences in the link budget, but it isn't clear to us if the use of a higher transmit power is sustainable in the long term once network loading is more prevalent.

LTE TDD will serve as the capacity layer while LTE FDD will be used to provide ubiquitous coverage.

Ideally, an operator could have the best of both worlds and use LTE TDD for the downlink transmission path and LTE FDD for the uplink transmission path. It is more likely in the near term that LTE TDD will serve as the capacity layer while LTE FDD will be used to provide ubiquitous coverage. Operators starting off with just LTE TDD will need to pay particular attention to their coverage criteria while all operators will need to give LTE TDD strong consideration for their capacity layer, including its use in small cells that will inherently have a small coverage footprint.

MIMO was used far less frequently than we would have expected given the underlying network conditions.

We also analyzed the incremental benefits of a Category 4 device versus a Category 3 device. Our conclusion is that in this particular case the benefits were largely immaterial. However, based on some preliminary analysis of the Carrier Aggregation data from South Korea we know that a Category 4 device can deliver a very meaningful boost in user throughput and subsequently network efficiency. Part of the explanation is due to the use of a full 20 MHz channel bandwidth in the South Korean network. Another factor is likely the peculiar behavior of MIMO in the LTE TDD network that we tested. For reasons that we can't fully explain, MIMO was used far less frequently than we would have expected given the underlying network conditions. Part of the phenomenon had to do with the mobile device not requesting MIMO when we thought it should have requested it and part of it had to do with the network not assigning MIMO when the device requested it and with very favorable channel conditions as well. All this and more in this issue of *Signals Ahead*….

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IN CASE YOU MISSED IT: *SIGNALS AHEAD* BACK ISSUES

- **8/12/13 "Fifty Shades of MIMO (Quantifying the Impact of MIMO in Commercial LTE Networks)"** We provide test results and analysis that looks at the incremental impact of Transmission Mode 3 (Open Loop MIMO) versus Transmission Mode 2 (Receive Diversity) based on testing that we did in specially-configured commercial LTE networks. The results that we provide quantify how MIMO influences the downlink data rates as a function of various KPIs, including RSRP and SINR. In summary, we demonstrate that while MIMO can double the data rate, the actual benefits are far more modest, and a negative benefit is even possible. Further, we show that MIMO doesn't necessarily improve the user experience in all cases, but there is still a benefit to the operator in terms of increased network efficiency.
- **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.

2.0 Key Conclusions and Observations

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Signals Research Group conducted what we believe is the first exhaustive [and exhausting] independent analysis of LTE TDD for public consumption. This effort would not have been possible without the support of Accuver, who provided us with access to its XCAL data collection tool and its XCAP post-processing software. We have used the solution numerous times over the last several years so we are very accustomed to using it, although we do stumble upon new capabilities and features each time we use it. In our most recent benchmark studies, including LTE TDD in Tokyo and LTE Advanced Carrier Aggregation in Seoul, its ability to support recently introduced technology features, including Category 4 chipsets and Carrier Aggregation, proved to be invaluable.

Based on our analysis of the data, which was all collected while concurrently testing LTE TDD and LTE FDD, we offer the following conclusions and observations.

LTE TDD and LTE FDD are different horses for different courses. The following bullets and the analysis and commentary contained throughout this report help demonstrate the pros and cons of an operator relying solely on LTE TDD or LTE FDD as its only means of providing LTE coverage and capacity. Instead, each duplex scheme has its pros and cons and neither LTE TDD nor LTE FDD is perfect for all situations.

Data traffic is inherently concentrated in the downlink direction – by some accounts the ratio is 8 to 1 in favor of the downlink and increasing over time with the growth of video traffic. LTE TDD allows the operator to dedicate a disproportionate amount of its network resources to serve this need. LTE FDD, in its current form, requires identical and entirely separate radio channels to support downlink and uplink traffic. Therefore, the downlink channel can become capacity constrained well before the uplink channel. Further, a majority of the unused spectrum and spectrum that has yet to be auctioned is best suited for LTE TDD since there are not natural pairings of downlink and uplink spectrum in these bands. By default, operators are almost forced to use LTE TDD in these frequency bands unless they want to consider the supplemental channel feature of LTE.

Conversely, due to the frequencies where LTE TDD will most likely be deployed, LTE TDD isn't a good choice for providing wide area coverage and to the extent a user wants to transmit a lot of data, there can be shortcomings if the configuration is set to favor the downlink. Increasing the mobile device's transmit power can help overcome the use of higher frequencies, but there is a subsequent impact on the battery life. Further, as data traffic increases and higher network loading occurs, the mobile device may have to reduce the transmit power in order to minimize interference levels. One also can't ignore the inefficiencies introduced by the time guard band that is required between the downlink and uplink transmissions in order to minimize interference.

Longer term, we firmly believe that LTE TDD and LTE FDD will exist in virtually all mobile operators' networks.

With a few exceptions, most operators today are focused on only a single LTE duplex scheme. Most operators are focused initially on LTE FDD but at least one major, major operator [CMCC] is initially focused on LTE TDD. Longer term, we firmly believe that LTE TDD and LTE FDD will exist in virtually all mobile operators' networks. Operators will use LTE FDD for their coverage layer and to provide meaningful capacity in many areas. Operators will also use LTE TDD to provide at least some degree of coverage but more importantly very extreme levels of capacity where it is needed the most. This concept is similar to the "islands of 3G in a sea of 2G" mantra that existed last decade and for similar reasons. Given most operators' rationale for deploying small cells and the implied coverage area of an individual small cell, LTE TDD is likely to play a major role in the operator's small cell strategy at some point in the future.

The results that we obtained will be difficult to replicate by operators unless they have a strong commitment to network quality. By all accounts, including anecdotal commentary from others, our own observations, and data that we collected during out study, Softbank has deployed a very impressive network throughout all of greater Tokyo. We assume this comment can be made for its network across the rest of Japan but since we didn't test it, we can't make the claim. There are still differences in performance between the LTE TDD and LTE FDD networks that we will get to in a bit, but these differences would be exacerbated without a real commitment to network quality.

Operators throughout the world are planning to deploy LTE TDD as an overlay to their existing LTE FDD network. Like Softbank, these operators will use much higher spectrum for the LTE TDD network. They may try to get away with deploying LTE TDD on the same grid as the LTE FDD network, but this approach simply won't cut it. In the case of Softbank, its LTE TDD network doesn't necessarily leverage the same cell sites as its LTE FDD network, but our analysis indicates that it is still a very dense network, although not nearly as dense as its LTE FDD network.

The problem that we see potentially emerging is that operators will try to deploy LTE TDD on the cheap, just as some operators have cut corners when they deployed LTE FDD. We just returned from testing networks in Japan and South Korea so we have raised the bar considerably on what we believe qualifies as a good network.

In our neck of the woods, Softbank will soon take the reins of Sprint + Clearwire with the goal – according to Sprint – of building the best network in the world. Our view is that if Sprint can climb to a close number 3 in the United States it will be a major accomplishment. We don't doubt the operator's commitment, but it will need to address shortcomings that have plagued Sprint and Clearwire in the past. Sprint's cell grid at 1900 MHz isn't all that impressive, in particular relative to the Softbank network, and we know from prior experiences that the Clearwire Mobile WiMAX network had poor coverage in many areas. Even if LTE TDD is deployed at every single Sprint 1900 MHz cell site, the coverage wouldn't be sufficient for a standalone network. We believe the operator will use the 2.5 GHz spectrum and LTE TDD to provide a capacity layer where it is needed, and this strategy may be able to allow the operator to skimp a bit on coverage, but if the operator is planning to use the spectrum for other purposes it will run into difficulties.

All told, readers should not take the results that we present in this report and assume that they will be achievable in all network deployments involving comparable frequency bands. Instead, the actual results will depend on a number of criteria and the operator's willingness to deploy a robust network using the higher frequency bands. Fortunately, and as discussed in the previous bullet, we believe that LTE TDD will play a very important role when it comes to providing the capacity layer and as part of an operator's small cell strategy, so the lack of sufficient coverage may be a moot point. Only time will tell.

The high degree of similarity between LTE TDD and LTE FDD do not necessarily translate into similar performance characteristics. LTE TDD and LTE FDD are very similar from a standard's perspective and this feature made it very easy to analyze and compare the results. To the extent there are minor differences between the two duplex schemes, the differences generally pertain to when something is done versus how or why something is done. This situation stems from LTE TDD using the same radio channel/frequency to transmit and receive data while LTE FDD uses individual channels for the downlink and uplink transmission paths.

Setting aside these similarities, there are still meaningful performance differences between LTE TDD and LTE FDD. These differences largely pertain to how operators deploy and use LTE TDD and LTE FDD, practical matters, such as the frequencies that are available for the two duplex schemes, and the laws of physics. In the case of Softbank, we tested the operator's LTE FDD network in Band 1 (DL = ~2155 MHz; UL = ~1965 MHz) and its LTE TDD network in Band 38 (DL/UL = 2565 MHz). Depending on the region within Tokyo, the operator is using 5 MHz or 10 MHz FDD LTE channels while LTE TDD is consistently 20 MHz. Softbank has dedicated approximately 75% of its LTE TDD resources to the downlink and approximately 25% of its TDD resources to the uplink.

Without normalizing for channel bandwidth, LTE TDD meaningfully outperformed the 10 MHz and 5 MHz implementations of LTE FDD in the downlink.

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network meaningfully outperformed LTE TDD in the uplink. Specifically, the LTE TDD average downlink throughput was 31.3 Mbps, the 10 MHz LTE FDD average downlink throughput was 24.43 Mbps, and the 5 MHz LTE FDD average downlink throughput was 11.72 Mbps. Given the differences in the channel bandwidth, we would expect LTE TDD to obtain 1.5 times the 10 MHz LTE FDD throughput and 3 times the 5 MHz LTE FDD throughput. The exact differences that we measured were 1.3x and 2.7x, respectively, suggesting LTE TDD fell a bit short relative to theory and our expectations. Then again, there was also a measurable difference in the average RSRP values between LTE TDD (-86.55 dBm) and the two LTE FDD (-74.38 dBm) network configurations.

In the uplink, the 5 MHz LTE FDD average throughput (8.27 Mbps) was higher than the LTE TDD average throughput (7.61 Mbps) and the 10 MHz LTE FDD average throughput (15.85 Mbps) was more than twice as high as the LTE TDD average throughput. After normalizing for the amount of spectrum, the 5 MHz LTE FDD and LTE TDD uplink data rates should be very similar and the 10 MHz LTE FDD uplink data rates should be roughly twice those of LTE TDD since twice as much spectrum was being used. For this analysis, we assumed that Softbank's use of Configuration 2 equates to an effective use of 15 MHz of spectrum in the downlink and 5 MHz of spectrum in the uplink.

Other differences largely stem from the 410 MHz that separates the downlink frequency bands and the 602.5 MHz that separates the uplink frequency used by the LTE TDD and LTE FDD networks.

Beyond basic throughput, we also observed other differences that largely stem from the 410 MHz that separates the downlink frequency bands and the 602.5 MHz that separates the uplink frequency bands used by the LTE TDD and LTE FDD networks. For example, the average transmit power of the LTE TDD mobile device was 18.47 dB higher than the LTE FDD mobile device during drive tests involving uplink throughput testing and 8.75 dB higher during drive tests involving downlink drive tests. With more normal user applications, such as Skype Video and Skype Voice, there were also material differences that we discuss later in this report. We also observed differences in the Power Headroom KPI, which provides a good indication of when the network is uplink limited. Presently, the Power Headroom for LTE TDD and LTE FDD were generally higher than 0 dB, signifying that an uplink constraint does not exist – it was more evident in the LTE TDD results. However, it is unclear whether or not the higher transmit power levels associated with the LTE TDD network are sustainable when network traffic levels increase.

The benefits of a Category 4 device in a 20 MHz LTE TDD network were negligible. We used a Category 4 device when we tested the LTE TDD network. In theory, a Category 4 device can achieve peak throughput of 150 Mbps in a 20 MHz LTE FDD network. In a 20 MHz LTE TDD network we believe the peak data rate is approximately 120 Mbps. The higher throughput is only realized when network conditions allow the transmission of very large data packets.

We analyzed two lengthy log files at a sub-frame level and found that the maximum transport block size (TBS) seldom was higher than the theoretical capabilities of a Category 3 device. Virtually all commercial LTE devices are Category 3, which means they are limited to ~100 Mbps in a 20 MHz LTE FDD network. Specifically, we found that the Category 4 capability was only used for approximately 2% of the time. During the very brief periods that it was used, the incremental throughput was up to 13.9% higher than possible with a Category 3 device. However, when calculated over the duration of the log file the incremental benefits of the Category 4 device were negligible. We've already started doing the analysis from our Carrier Aggregation testing and the good news is that in those results we are finding a far more meaningful benefit, both in terms of the utilization rate and the incremental gains.

A potential disconnect between the requesting and assigning of MIMO could be artificially lowering the overall throughput capabilities of the network. During our testing we observed that MIMO was used far less frequently than we have observed in other networks and with seemingly similar conditions. This observation was verified when we analyzed the log files. In many instances we found that the mobile device was not requesting MIMO (Rank Indicator 2) even though the network conditions were very favorable with a SINR higher than 20 dB for a sustained period of time. In other cases, the mobile device was requesting MIMO, the network conditions were very favorable with a SINR higher well within the range of where we would expect MIMO to be used, yet the network sometimes remained with transmit diversity. When conditions were seemingly ideal and stable for a lengthy period of time, we observed dramatic increases/decreases in the throughput each time the network enabled/disabled the MIMO functionality.

Based on findings from our last report (*SA* 08/10/13, "Fifty Shades of MIMO") we know that MIMO doesn't always increase the end user throughput. In some cases MIMO may even be used when it shouldn't be used and the throughput ends up being slightly lower than it would be with transmit diversity. However, based on our analysis of the results from this study, there appears to be something that is amiss. Assuming our analysis is correct, the impact is that the LTE TDD results that we present in this report are artificially lower than they should be. It isn't possible to quantify the potential impact.

3.0 LTE TDD and LTE FDD Downlink and Uplink Overall Results

For all practical purposes LTE TDD and LTE FDD are largely identical. To the extent there are minor differences, the differences generally pertain to when something is done versus how something is done. The minor differences that do exist stem from LTE TDD sharing the same radio channel (e.g., frequency) for downlink and uplink transmissions while LTE FDD leverages separate radio channels for the downlink and uplink paths. The similarities in the two technologies, at least from a 3GPP standards perspective, hasn't prevented strong interest in how LTE TDD performs versus LTE FDD, but by the same token there is also strong interest in how a 20 MHz implementation of LTE FDD at 2600 MHz compares with a 10 MHz implementation of LTE FDD at 1700 MHz. We tackled this subject in a *Signals Ahead* report from last December (*SA* 12/05/12, "LTE Band 7 versus LTE Band 4, GAME ON!").

We limited our analysis of the operator's LTE FDD network to Band 1.

For this particular study we took a similar approach since we ultimately determined that the real interest in LTE TDD isn't [or at least shouldn't be] focused on how LTE TDD performs in absolute terms but how it performs in relative terms versus LTE FDD when practical deployment issues, such as differences in frequency bands and channel bandwidths are taken into consideration, not to mention the allocation of LTE TDD resources between the downlink and the uplink. The Softbank network is unique in that regard. Not only has the operator deployed a vast network throughout Tokyo, as well as other markets in Japan, but it has deployed LTE TDD in Band 41 (2565 MHz) and LTE FDD in at least two other bands. Given that Band 1 (DL ~2100 MHz; UL ~ 1900 MHz) is more commonly deployed across the world, we limited our analysis of the operator's LTE FDD network to this band.

It isn't appropriate to directly compare the 5 MHz and 10 MHz LTE FDD channel bandwidth results that we present in this report.

Worth noting, the LTE FDD channel bandwidth varies throughout Tokyo. In some areas the operator has 2 x 5 MHz channels and in other areas the operator has 2 x 10 MHz channels. Since we didn't have any insight into where each LTE FDD configuration existed, many of the log files contain a mix of results. For purposes of analyzing the data and presenting results in this report, we frequently, but not always, separated the results for the two channel bandwidth configurations. Since the results for the two FDD channel bandwidths were obtained in different parts of the network and at different times it isn't entirely appropriate to directly compare the two results. We also didn't separate the LTE TDD results according to the corresponding LTE FDD configuration so direct comparisons of some of the LTE TDD results with the LTE FDD results are not necessarily always straightforward, even though they are still valid. For this reason, we generally present multi-dimensional results (e.g., throughput as a function of RSRP or transmit power) in order to normalize the data. We also collected a ton of data in a very random fashion throughout central Tokyo so we believe that our results are representative of the overall network performance.

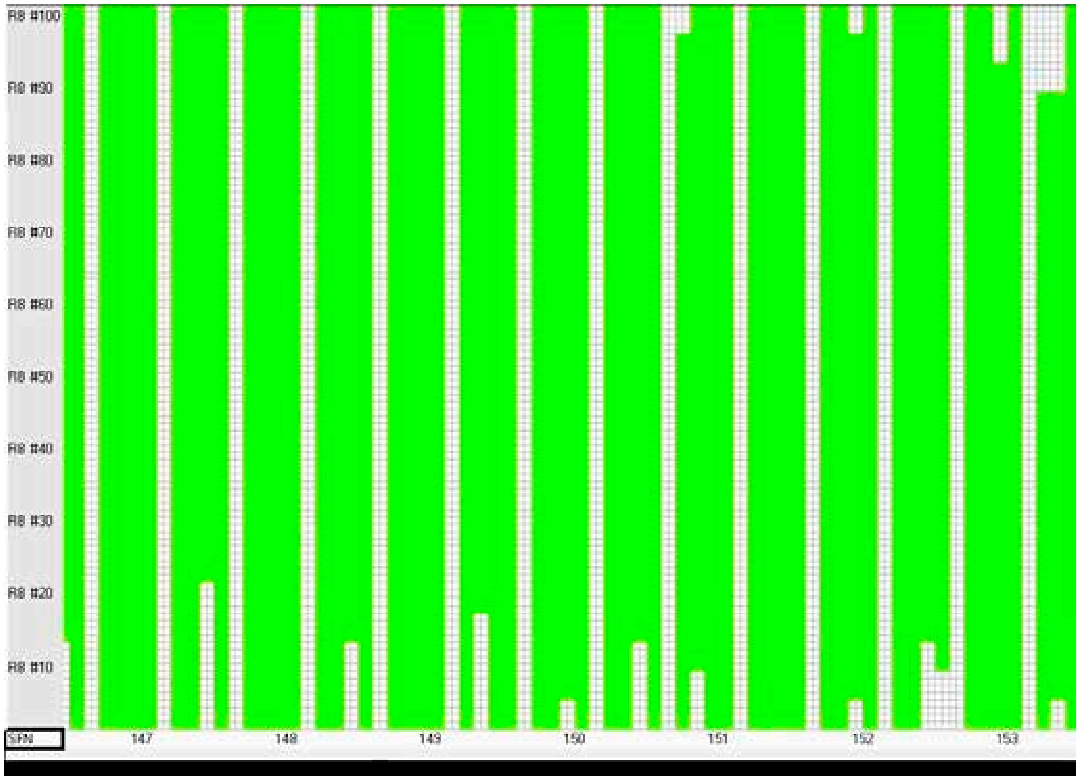
The similarities and differences between LTE FDD and LTE TDD are evident in Figure 1. The figure shows three screen shots of the XCAP post-processing tool's capabilities. The Y axis shows the number and location of the Resource Blocks that the mobile device received and the X axis shows the individual subframes that comprise a full frame.

With Configuration 2, roughly 75% of the LTE TDD resources are assigned to the downlink and 25% of the resources are assigned to the uplink.

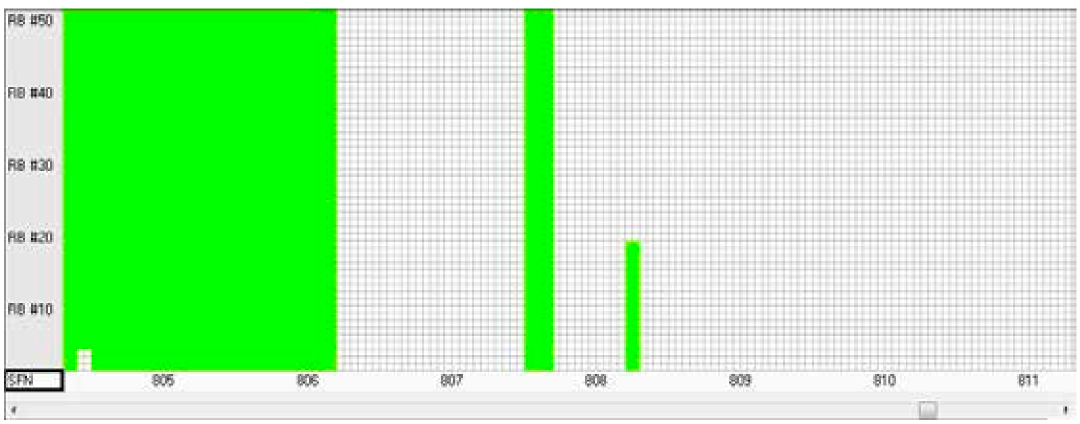
The top figure shows the LTE TDD mobile device's allocation of resource blocks during a downlink file transfer. Note that there are up to 100 Resource Blocks available with 20 MHz channels. The two empty columns that occur within each ten millisecond frame represent the one millisecond sub-frames when the mobile devices are allowed to transmit data. There are also guard bands, or short time gaps, between the downlink and uplink transmissions which are required to ensure that the downlink and uplink transmissions do not interfere with each other. We can also conclude from this figure that the operator was using Configuration 2 with roughly 75% of the LTE TDD resources assigned to the downlink and 25% of the resources assigned to the uplink. For comparison

Figure 1. LTE TDD and LTE FDD Resource Block Allocation by Sub-frame

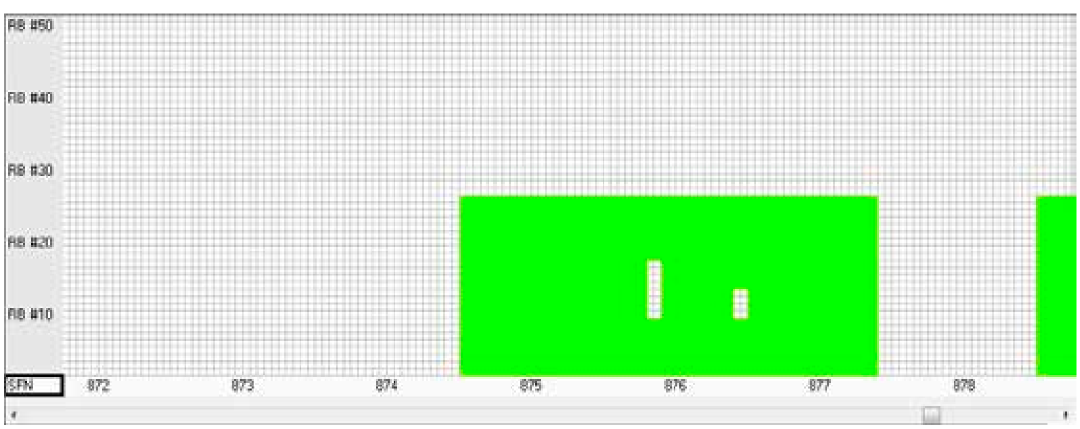
LTE TDD – 20 MHz Channel



LTE FDD – 10 MHz



LTE FDD – 5 MHz Channel



Source: Accuver XCAP and Signals Research Group purposes with the FDD results we assume that these percentages equate to 15 MHz of equivalent FDD spectrum in the downlink and 5 MHz of equivalent FDD spectrum in the uplink.

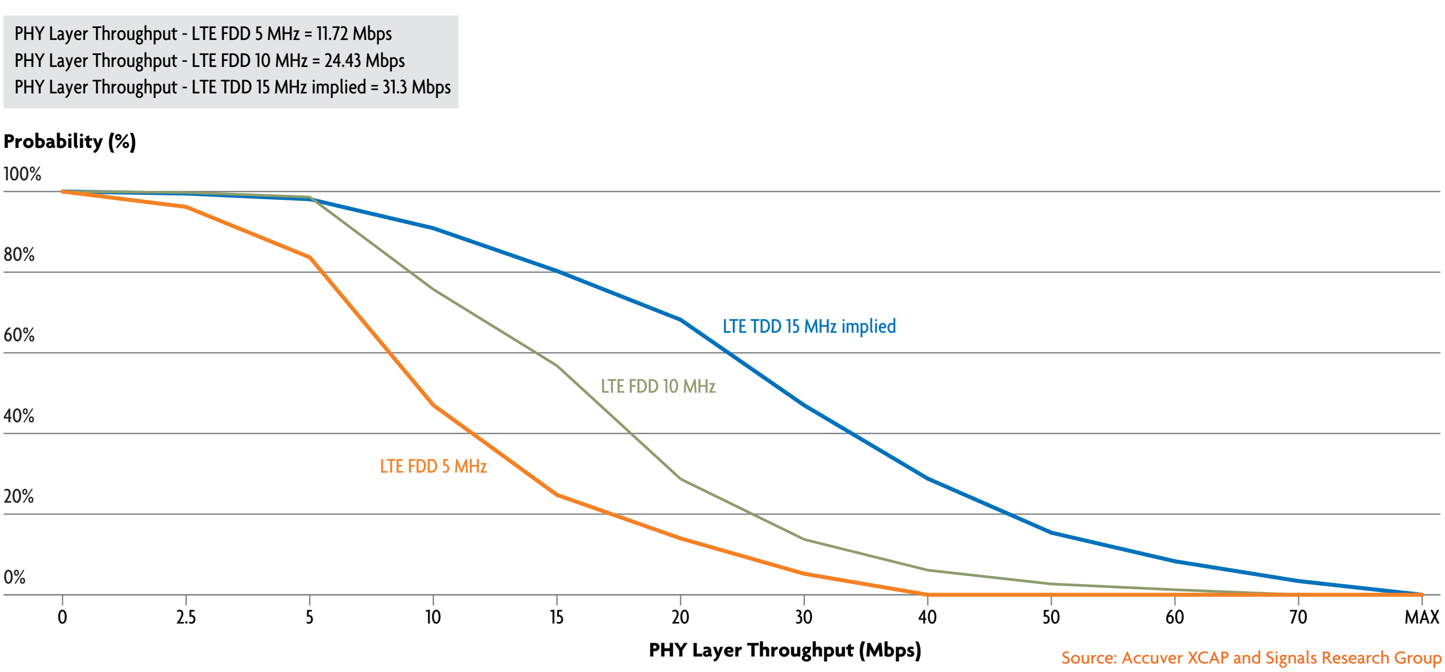
The next two figures show the same information for LTE FDD. Since the mobile device can always receive data in the channel there are not any fully unused time slots reserved for the uplink transmissions – these occur in a different radio channel. To keep things interesting we selected a time when the mobile device was switching from a 10 MHz channel with 50 possible Resource Blocks to a 5 MHz channel with 25 possible Resource Blocks. The partially filled columns in all three figures identify instances when the network resources were not assigned to the mobile device – most likely because the network assigned them to another mobile device. There was a modest time gap when the mobile device wasn't receiving any data as it moved between the two LTE FDD configurations and this situation is evident in the bottom two figures.

LTE TDD and LTE FDD have important attributes which must be considered when deploying the two networks so that they work in harmony with each other.

One reoccurring theme throughout this report is that there are pros and cons associated with LTE TDD and LTE FDD, or at least there are important attributes which must be considered when deploying the two networks so that they work in harmony with each other. In the case of LTE TDD, the operator can dedicate a disproportionate amount of network resources to the downlink, which is beneficial because upwards of 70-80% of all data traffic occurs in the downlink. Conversely, if a majority of the network resources are assigned to the downlink then there are fewer resources available for the uplink transmissions that do occur – the impact is lower uplink throughput and/or a higher transmit power, which consequently impacts battery life. For LTE FDD the spectrum is equally divided between the downlink and the uplink, suggesting that the uplink resources could be under-utilized, even when the network is capacity constrained in the downlink.

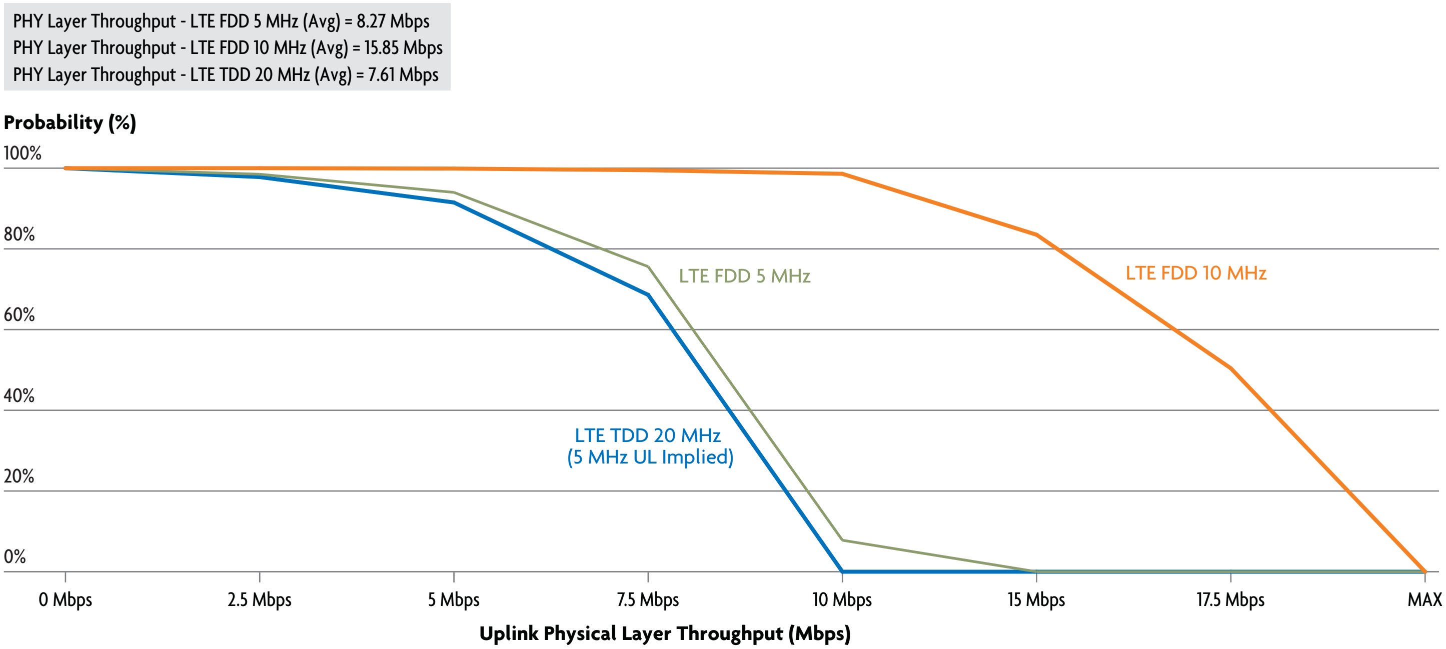
With all that being said, the next two figures provide the downlink and uplink throughput probability plots for LTE TDD and the two LTE FDD configurations. As previously indicated the two sets of FDD results were collected in different locations and at different times while the LTE TDD results span across both LTE FDD configurations. Although it isn't evident in the figures, in the downlink tests the LTE FDD mobile device was using a 5 MHz channel for 72% of the time and 28% of the time the mobile device was using a 10 MHz channel. For the uplink tests the ratio was 45% for 10 MHz and 55% for 5 MHz.

Figure 2. LTE TDD and LTE FDD Downlink Throughput Probability Plots



Source: Accuver XCAP and Signals Research Group

Figure 3. LTE TDD and LTE FDD Uplink Throughput Probability Plots



Source: Accuver XCAP and Signals Research Group

The average downlink throughput in the LTE TDD network was 31.3 Mbps (peak = 92.3 Mbps), the average throughput in the LTE FDD 10 MHz configuration was 24.43 Mbps (peak = 71.8 Mbps), and the average throughput in the LTE FDD 5 MHz configuration was 11.72 Mbps (peak = 35.4 Mbps).

Since the LTE TDD network used Configuration 2, we would expect its downlink throughput to be 1.5 times more than the LTE FDD 10 MHz network configuration

One would expect the 10 MHz LTE FDD configuration to achieve roughly twice the throughput of a 5 MHz FDD configuration, all things being equal. The LTE FDD 10 MHz configuration average throughput was 2.1 times higher but we also note that the average RSRP and average SINR for the LTE FDD 10 MHz configuration were also higher than they were while testing the LTE FDD 5 MHz configuration. We present this information and discuss the observation in an upcoming figure. Since the LTE TDD network used Configuration 2, we would expect its throughput to be 1.5 times more than the LTE FDD 10 MHz network configuration and three times more than the LTE FDD 5 MHz network configuration.

The exact percentages that we measured were 1.3x and 2.7x, respectively, suggesting LTE TDD fell a bit short relative to theory and our expectations. Then again, there was also a measurable difference in the average RSRP between LTE TDD and the two LTE FDD networks. The measured SINR was comparable. We'll revisit the comparisons when we present normalized results later in this report. However, we do note that the end user doesn't care about normalized results or the amount of channel bandwidth required to achieve the measured throughput. Instead, all he or she cares about is the throughput, or to be more specific the user experience.

The peak uplink data rate in the LTE TDD network was 9.9 Mbps

Turning to the uplink, the LTE TDD and LTE FDD 5 MHz results are directly comparable while the LTE FDD 10 MHz results should be twice as high as the other two network configurations. Doing the math, the LTE FDD 5 MHz results are slightly better than the LTE FDD 10 MHz results and the LTE TDD results are slightly worse than the LTE FDD 10 MHz results. Regarding peak uplink data rates, we documented 9.9 Mbps in the LTE TDD network, 20.5 Mbps in the LTE FDD 10 MHz network, and 10.3 Mbps in the LTE FDD 5 MHz network.

4.0 Detailed LTE TDD and LTE FDD Downlink Analysis

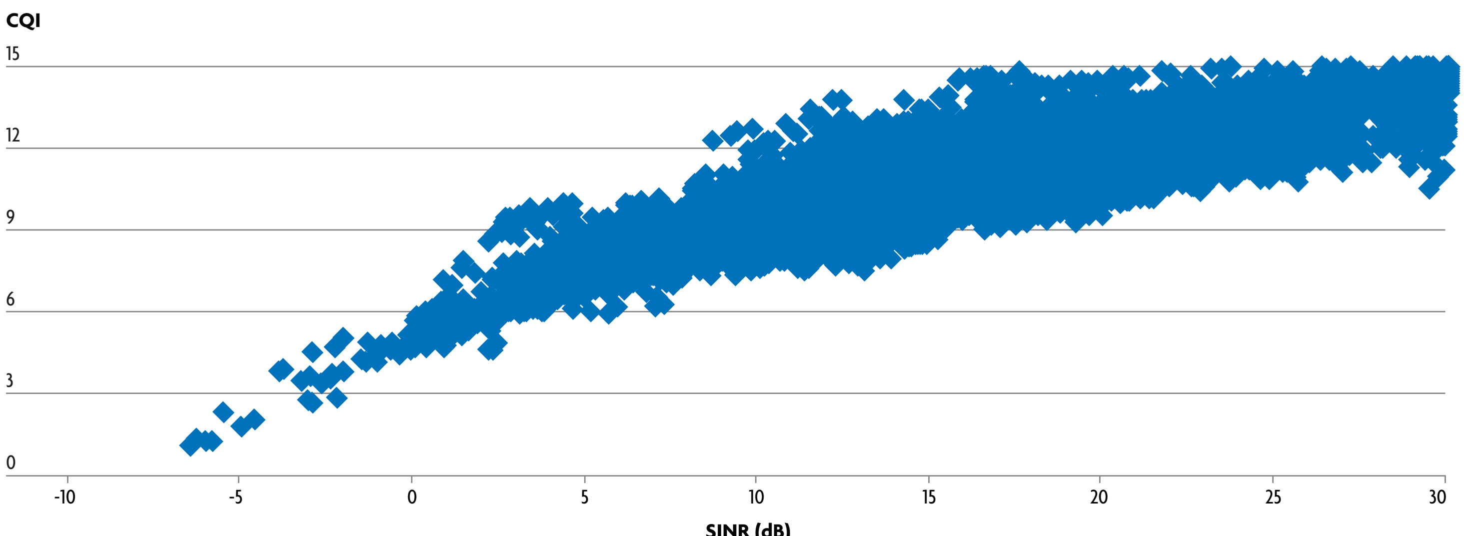
The downlink throughput results stem from testing over a 45.7 mile drive route during which time we downloaded nearly 60 GB between the two networks.

In this chapter we provide an analysis of the tests involving FTP downlink transfers. The results in this chapter stem from drive testing over a 45.7 mile drive route during which time we transferred nearly 60 GB of data on the two networks. The actual results for each network are contained in 5 separate log files but we elected to merge all of the log files in a single file in order to obtain more statistically meaningful results.

In this report and in previous reports we frequently use SINR (Signal to Interference + Noise Ratio) as a reporting metric when evaluating the performance of the network. We use SINR based on the recommendations of a few operators but we also recognize that SINR is not well-defined in the 3GPP standard. Conversely, CQI (Channel Quality Indicator) is a well-defined metric although based on some of our previous Chips and Salsa test results, chipsets do not necessarily measure and report the metric identically.

Figure 4 demonstrates how the CQI varies as a function of the SINR. We used the Accuver XCAL tool to log the two KPIs which are reported by the baseband chipset through the diagnostic port. This particular figure doesn't reveal anything about the performance of LTE TDD or LTE FDD but it is useful for some readers as a reference when we revert to the reported SINR in subsequent figures.

Figure 4. CQI as a Function of SINR – Scatter Plot



Source: Signals Research Group

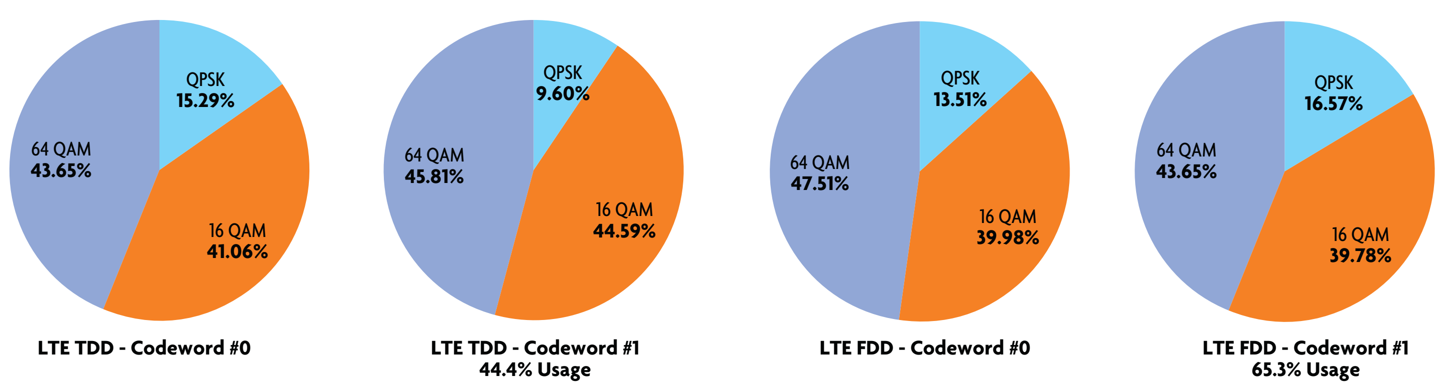
Figure 5 provides the drive routes that we used when logging the results presented in this figure. As previously indicated we drove 45.7 miles while conducting these downlink throughput tests. The total downlink throughput test time while logging the data was 192.7 minutes.

Figure 5. Downlink Testing Drive Routes

Source: Signals Research Group

Figure 6 provides a distribution of the modulation schemes. For purposes of this analysis we separated out the distributions for each code word. Further, we aggregated the 5 MHz and 10 MHz LTE FDD results since we felt that there wasn't any benefit in separating the results into the two channel bandwidth configurations. The figures indicate that the distributions, including the availability of 64 QAM, are comparable. The biggest difference is how frequently the second code word was used, in other words the availability and use of MIMO differed in the two networks.

Figure 6. Distribution of Modulation Schemes for LTE TDD and LTE FDD – pie charts



Source: Signals Research Group

The LTE TDD network used MIMO 44.4% of the time and the LTE FDD network used MIMO 65.3% of the time during the downlink transfer tests.

In the LTE TDD network, the network used MIMO 44.4% of the time while sending data to the mobile device. For the LTE FDD network, the MIMO utilization rate was 65.3%. As we demonstrated in our last report, the use of MIMO doesn't necessarily translate into higher throughput. In fact, we observed numerous instances when we felt that the use of MIMO actually degraded the achievable throughput. In Chapter 7 we revisit this topic and discuss why we think there was somewhat of a disconnect between the mobile device and the network when it came to the requesting and assigning of MIMO.

Figure 7 provides the RSRP (Reference Signal Received Power) probability distribution plots for LTE TDD and LTE FDD. RSRP is measured by the mobile device and reported back to the network. It is used to select the best cell while the measured value can provide a great indication of the throughput that can be achieved – subject to network loading. A higher (less negative) RSRP value indicates a stronger signal and, in theory, the opportunity to obtain a higher downlink data rate. As evident in Figure 7, the average RSRP of the LTE TDD network was 12.2 dB lower than the LTE FDD network. The difference is largely a reflection of the 410 MHz separation in the two frequency bands that are used for the downlink transmissions.

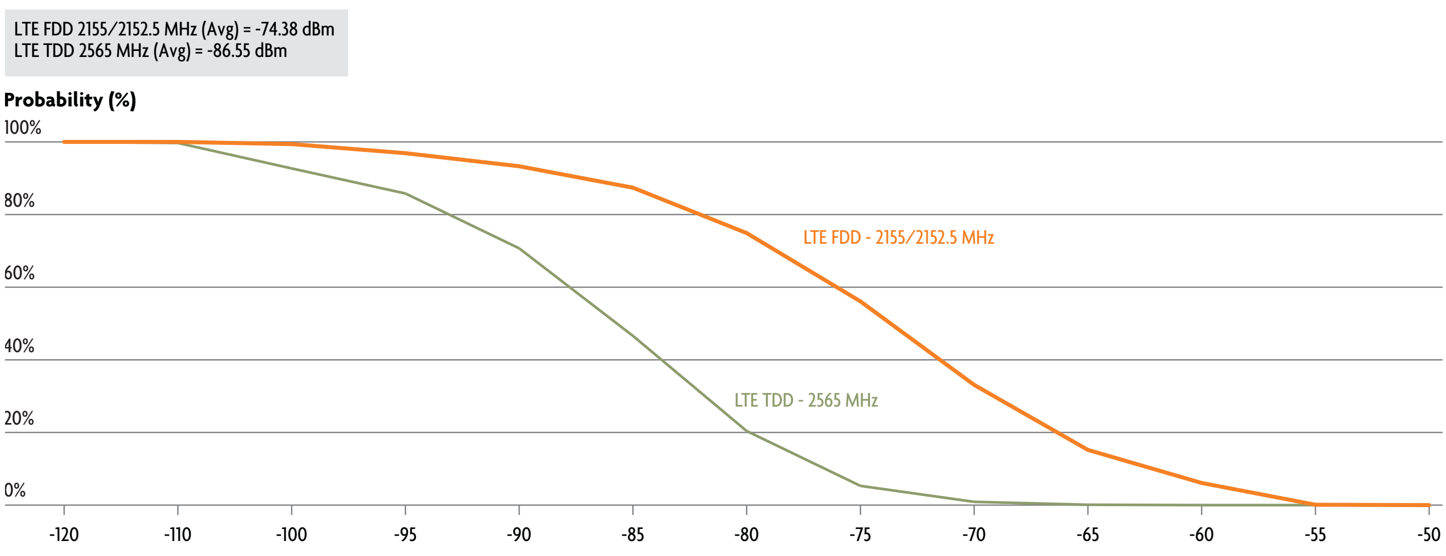
Based on comparing these results with results from other networks we tested, it is evident that the operator has deployed an extremely dense network of cells.

Another approach that can be used to analyze the data is to compare these results to other networks that we have tested. Taking this approach, it is clearly evident that the operator has deployed an extremely dense network of cells and that it delivers a very strong signal throughout much of its network, at least on a relative basis to other operators' networks. For example, in our Rogers Wireless testing in Vancouver (reference Figure 8) we recorded an average RSRP of -84.8 dBm in Band 4 (DL = 2115 MHz) and an average RSRP of -89.8 dB in Band 7 (2650 MHz) during our drive testing. The difference in the average RSRP between the two bands in Vancouver was only 5 dB, or much closer in relative terms to each other than the Tokyo results. More recently, in our testing of T-Mobile's LTE network in Santa Clara the average RSRP during many of the drive tests was at or below -90 dBm.

In our outdoor drive testing, the RSRP for the LTE FDD network never fell below -100 dBm and it was below -100 dBm for only 7.3% of the time with the LTE TDD network.

Using RSRP as the sole criteria for network design and coverage, one could infer that Softbank provides better coverage with its LTE TDD network at 2565 MHz than T-Mobile in Band 4 and Rogers in Band 7 – Softbank's LTE TDD network came somewhat close in topping Rogers' Band 4 network. Put another way, during our [outdoor] drive testing, the RSRP never fell below -100 dBm in the LTE FDD network (Band 1). For LTE TDD the RSRP was below -100 dBm for 7.3% of the

Figure 7. RSRP for LTE TDD and LTE FDD – probability plots

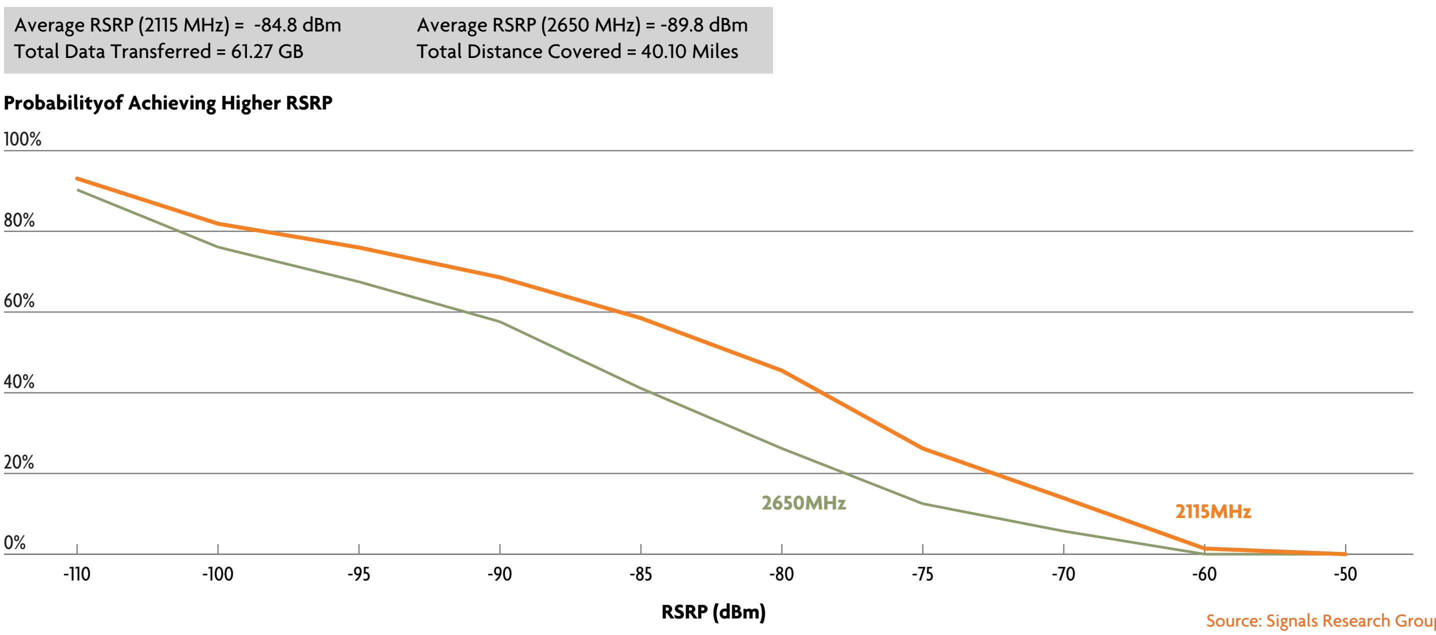


Source: Signals Research Group

time and it was only below -110 dBm for a fraction of a percentage point. Obviously, when the RSRP is at -100 dBm while outdoors, we suspect that the in-building coverage would be questionable. If we calculate the separate RSRP values for the two LTE FDD channel bandwidth configurations, we find that the two values are comparable, or -74.8 dBm for the 5 MHz LTE FDD channel allocation and -73.4 dBm for the 10 MHz LTE FDD channel allocation.

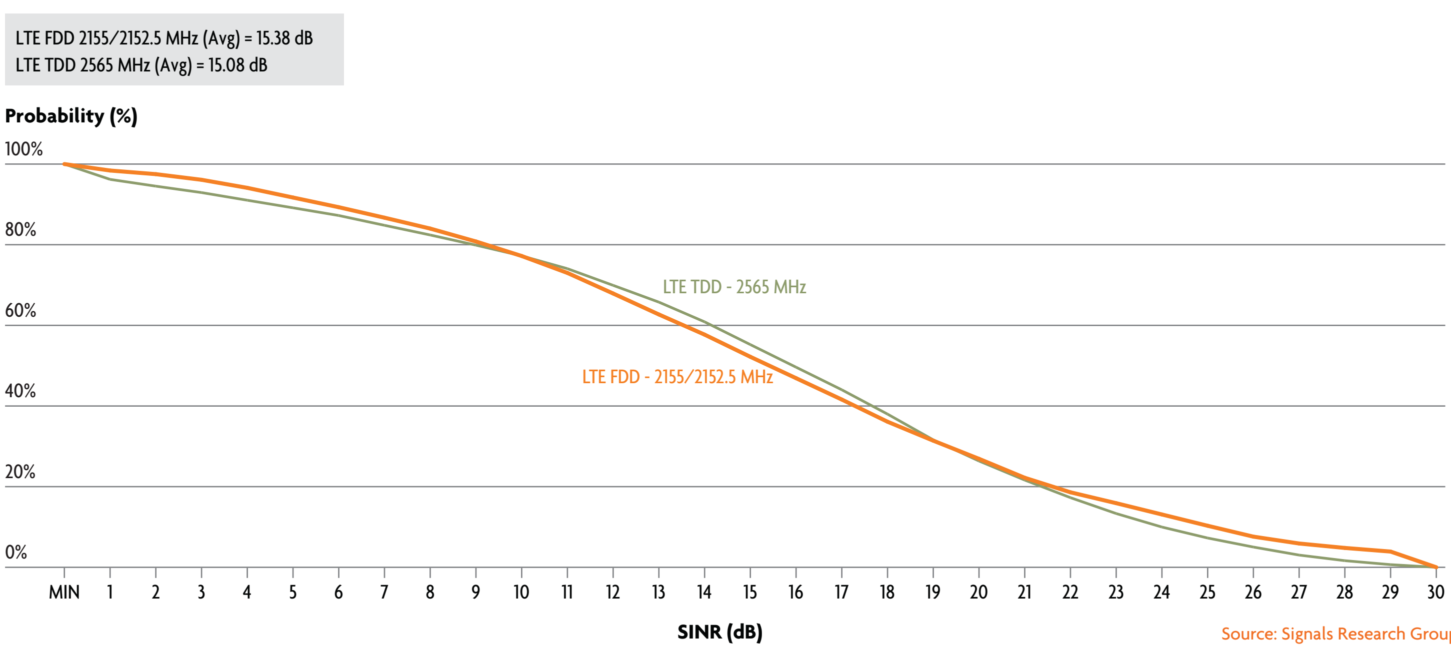
Figure 9 provides the SINR probability distribution plots for LTE TDD and LTE FDD. By and large the aggregate results are comparable. Although this information isn't presented, the average SINR for the 5 MHz (15.0 dB) and 10 MHz LTE FDD (16.2 dB) implementations are also comparable.

Figure 8. RSRP for Band 7 and Band 4 in the Rogers Wireless Network – probability plots



Source: Signals Research Group

Figure 9. SINR for LTE TDD and LTE FDD – probability plots

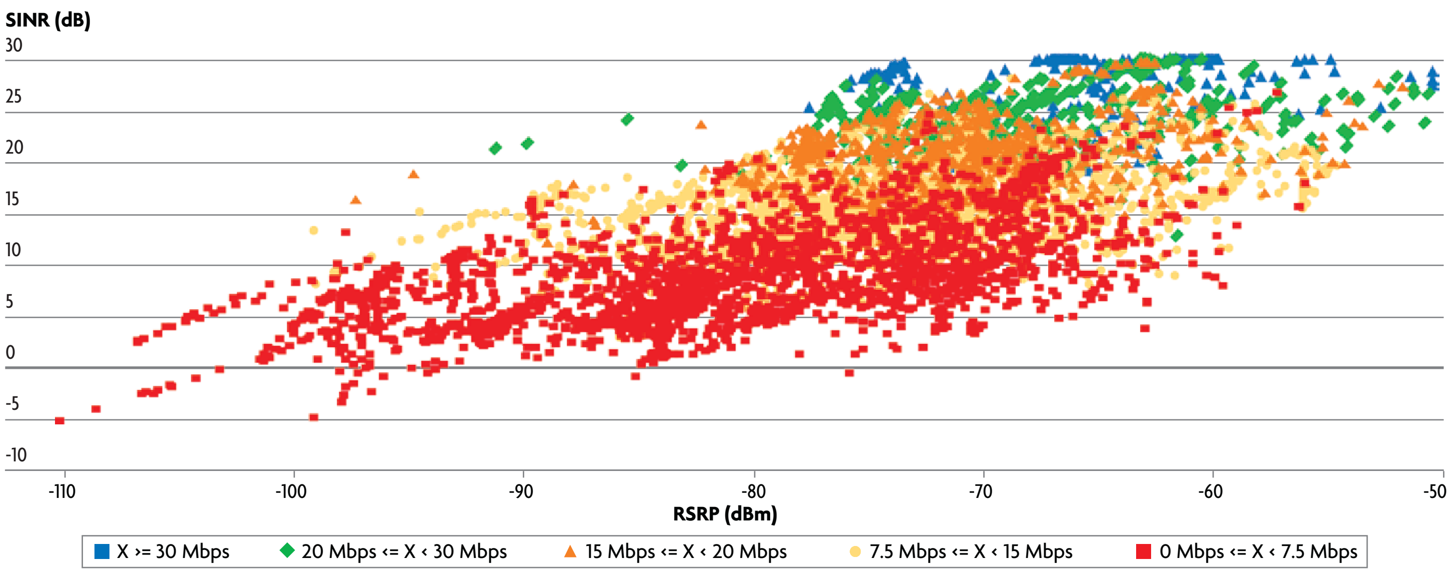


Source: Signals Research Group

The last three figures in this chapter provide a wealth of information and the results are normalized to the RSRP and SINR values that were reported when the corresponding throughput was obtained. All three figures group the throughput values into discrete buckets. We used the identical buckets for LTE TDD and LTE FDD 10 MHz but we elected to define different throughput ranges for LTE FDD 5 MHz so that the differences in the throughput would be more evident. Figure 10 provides the results for the LTE FDD 5 MHz network and Figure 11 provides the results for the LTE FDD 10 MHz network. Figure 12 provides the results for the LTE TDD network.

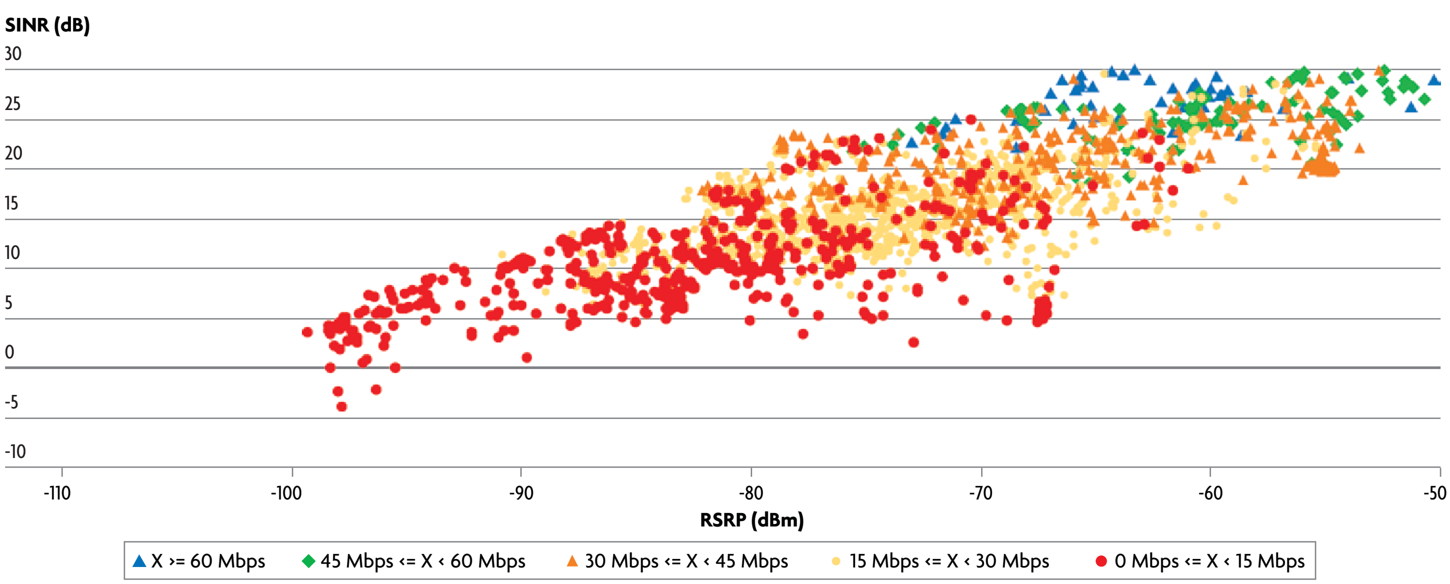
In all three figures it is evident that there is a correlation between SINR and RSRP. Further, with higher SINR and RSRP values the throughput that we observed was generally higher. The biggest difference that we observe in the figures after adjusting for the variances in the channel bandwidth is that the LTE TDD results are shifted to the left (lower RSRP) compared with the two LTE FDD results. Put another way, for comparable network characteristics and channel bandwidths we would expect largely comparable results between LTE FDD and LTE TDD.

Figure 10. Downlink Physical Layer Throughput for LTE FDD 5 MHz as a Function of RSRP and SINR – scatter plot



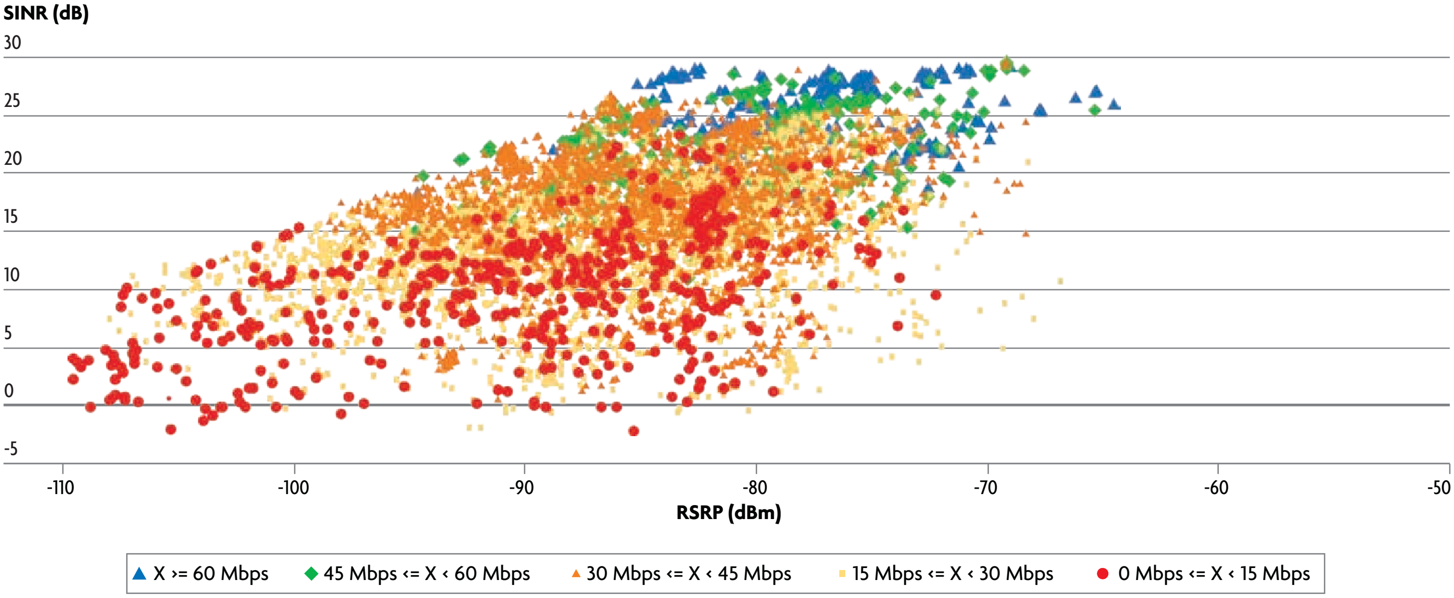
Source: Signals Research Group

Figure 11. Downlink Physical Layer Throughput for LTE FDD 10 MHz as a Function of RSRP and SINR – scatter plot



Source: Signals Research Group

Figure 12. Downlink Physical Layer Throughput for LTE TDD as a Function of RSRP and SINR – scatter plot



Source: Signals Research Group

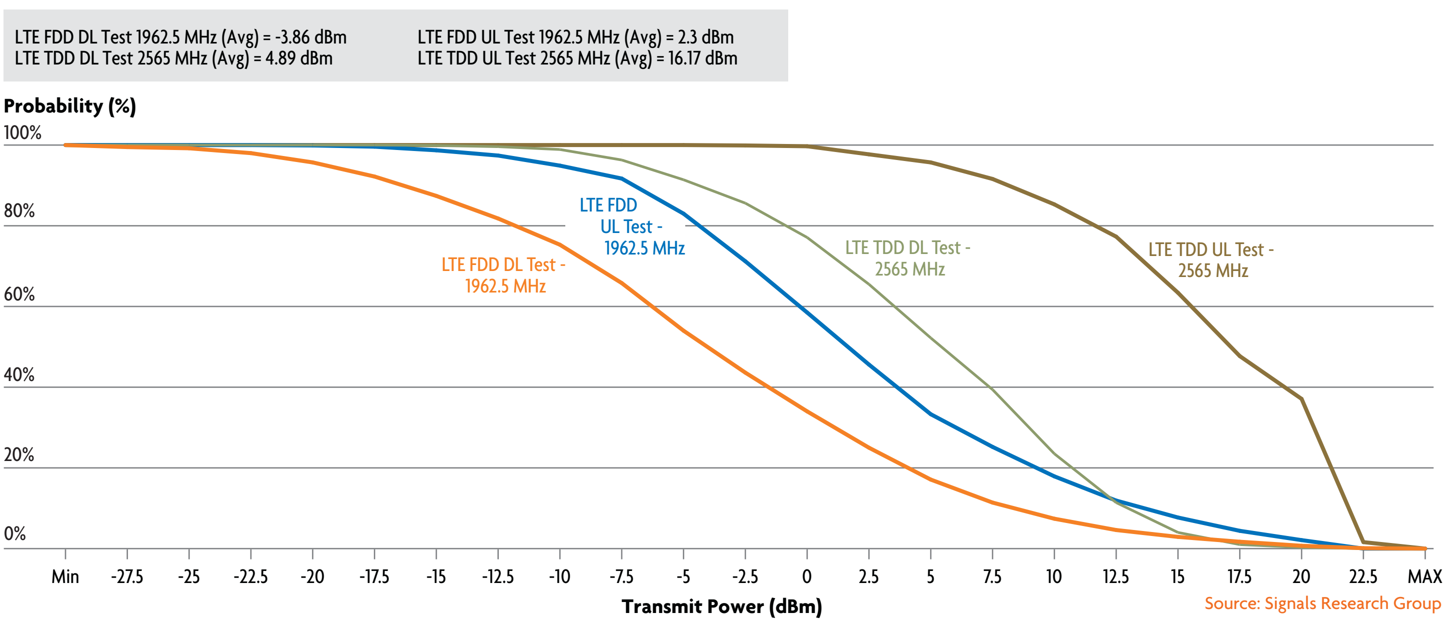
5.0 Detailed LTE TDD and LTE FDD Uplink Analysis

The uplink results are based on transferring a total of 13.24 GB between the two networks while driving 18.9 miles.

In this chapter we provide detailed results and analysis for the uplink throughput tests that we conducted. In addition to providing the basic throughput values, we analyze throughput as a function of various KPIs, including transmit power and Power Headroom, as well as performance at the edge of the cell. The uplink results are based on transferring a total of 13.24 GB between the two networks while driving 18.9 miles.

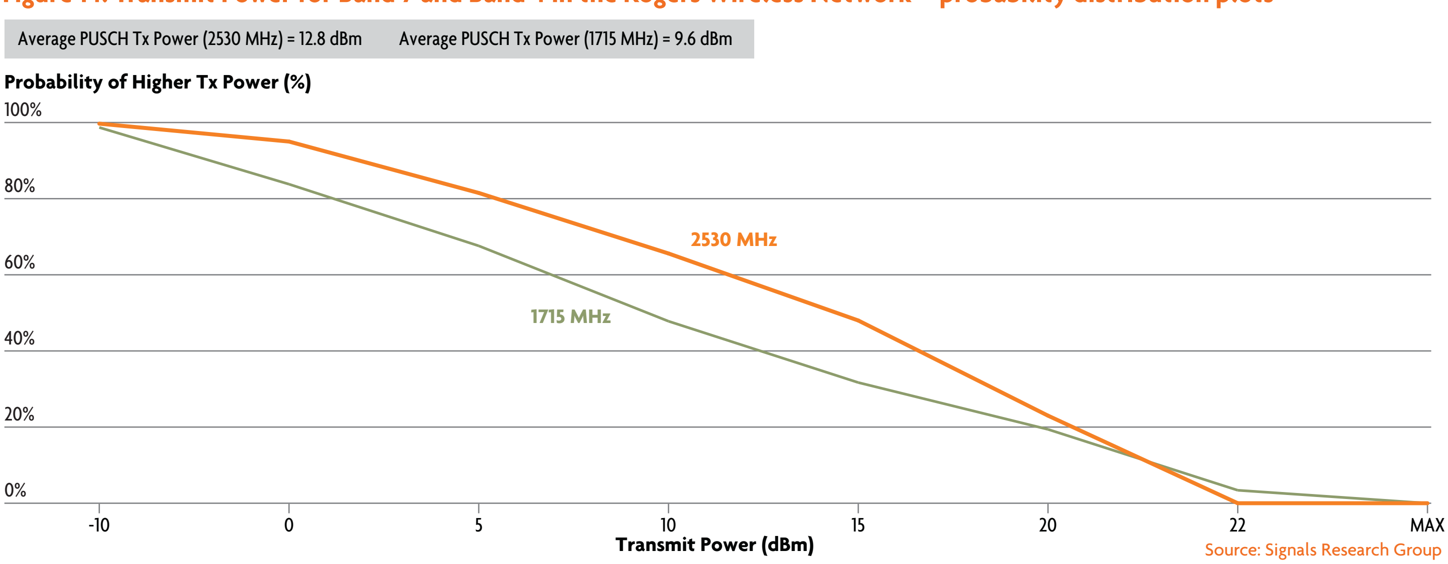
Figure 13 provides probability distribution plots of the uplink transmit power for the LTE TDD and LTE FDD mobile devices that we tested. We did not separate the 5 MHz and 10 MHz FDD results in this figure but we do look at them individually later in this report. The figure includes the transmit power levels that we logged during the uplink throughput tests that we analyze in this chapter and the uplink transmit powers that we observed during the downlink throughput tests that we discussed in the previous chapter. For comparison purposes, we are also including results from the Rogers Wireless network that we tested last year (reference Figure 14).

Figure 13. Transmit Power for LTE TDD and LTE FDD during Downlink and Uplink Throughput Tests – probability plots



Source: Signals Research Group

Figure 14. Transmit Power for Band 7 and Band 4 in the Rogers Wireless Network – probability distribution plots



Source: Signals Research Group

Comparing the results in the two figures, a couple of notable observations stand out. First, it is evident that the LTE TDD mobile device is transmitting at a considerably higher power level than the LTE FDD device. For the downlink throughput tests there is an 8.8 dB difference and for the uplink throughput tests there is an 18.5 dB difference. In fact, the LTE FDD device transmitted at a lower level during the uplink throughput tests than the LTE TDD device transmitted during the downlink throughput tests. Relative to the results from Vancouver, the LTE FDD transmit levels are 7.3 dB lower in Tokyo and the LTE TDD transmit power levels are 3.4 dB higher than the Band 7 FDD results from Vancouver.

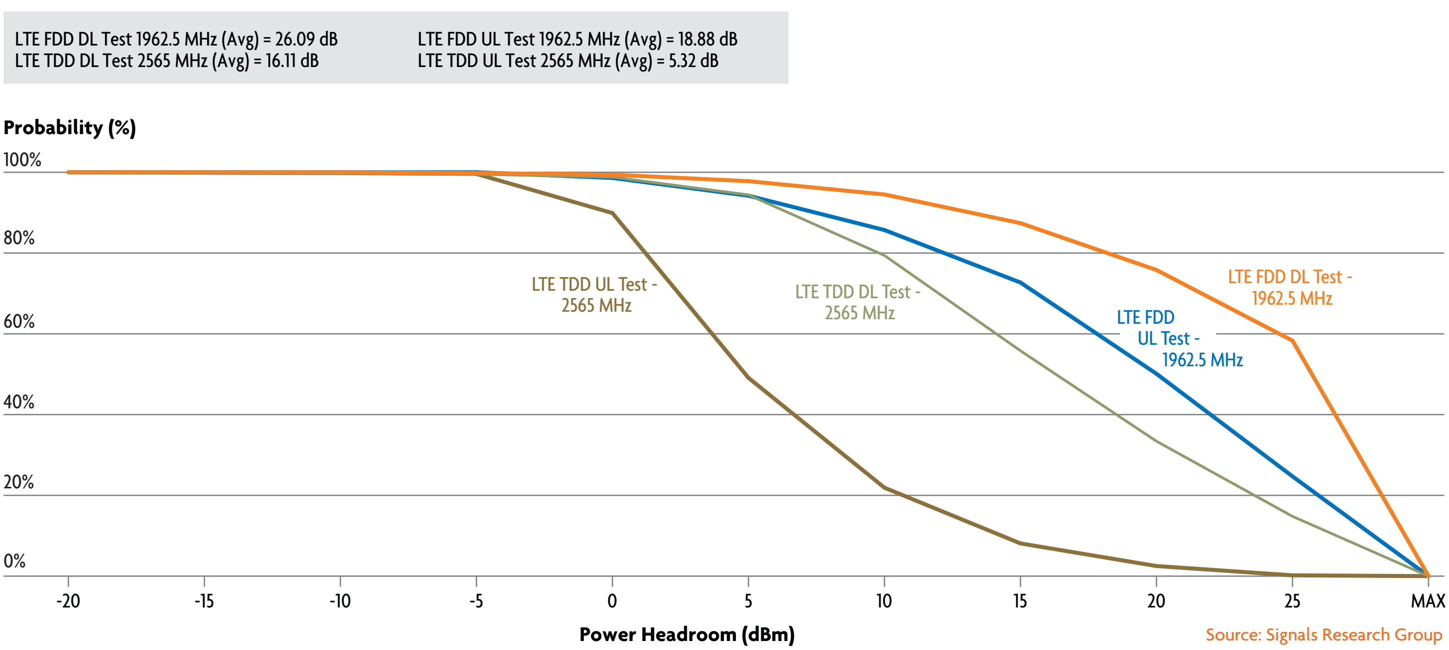
One would expect higher transmit powers with the LTE TDD device since it was operating in a higher frequency band while the LTE FDD transmit power levels are impressively low.

One would expect higher transmit powers with the LTE TDD device since it was operating in a higher frequency band while the LTE FDD transmit power levels are impressively low – perhaps another indication that the operator has built a very dense network. In the near term, the relatively high transmit powers with the LTE TDD device may be an acceptable tradeoff for higher uplink throughput. However, it isn't clear if these levels are sustainable when the network encounters higher loading. Further, one must consider the impact on battery life. These results, combined with the results from the last chapter, suggest the need for a hybrid LTE TDD/FDD network with the LTE TDD network (presumably deployed in a higher band) providing the downlink capacity and the LTE FDD network (presumably deployed in a lower band) providing the uplink capacity.

As network traffic increases we believe the transmit power levels in the Tokyo network will drop and the instances of the Power Headroom being negative will increase.

Figure 15 provides the probability distribution plots for the Power Headroom for the LTE TDD and LTE FDD networks. The Power Headroom KPI is a great means of identifying a constraint in the uplink coverage – if the value is negative than the network is uplink limited. The figure indicates that an uplink constraint only existed in the LTE TDD network for 10.1% of the time during the uplink throughput tests. Although it isn't entirely clear in the figure, for all other tests + network configurations the Power Headroom was negative for only a fraction of a percent.

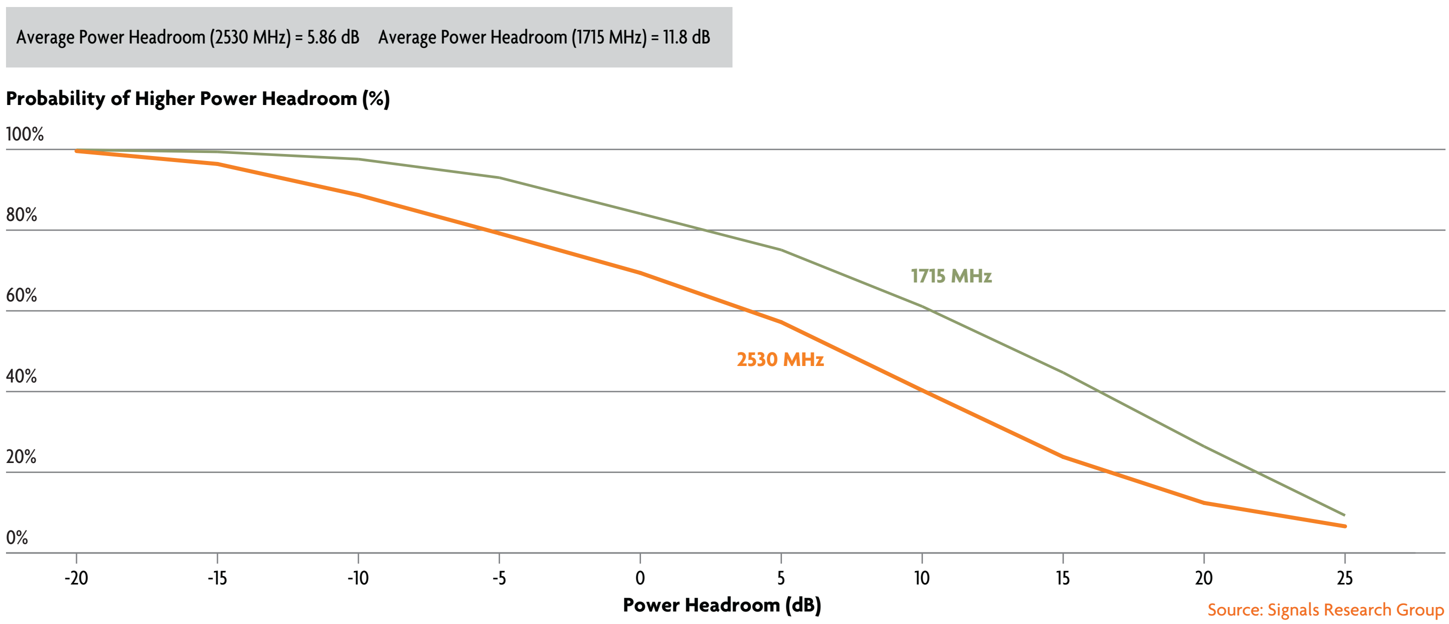
Figure 15. Power Headroom for LTE TDD and LTE FDD during Downlink and Uplink Throughput Tests – probability plots



Source: Signals Research Group

For comparison purposes we are including combined results from two uplink drive tests that we did in Vancouver (reference Figure 16). In this case the Power Headroom was negative in both bands for a much higher percentage of the time. In the case of Band 7 with a full 20 MHz of spectrum used for the uplink transmission the Power Headroom was negative for 30.6% of the time. We expect that over time and as network traffic increases the transmit power levels in the Tokyo network will drop and the instances of the Power Headroom being negative will increase.

Figure 16. Power Headroom for Band 7 and Band 4 in the Rogers Wireless Network – probability distribution plots



Source: Signals Research Group

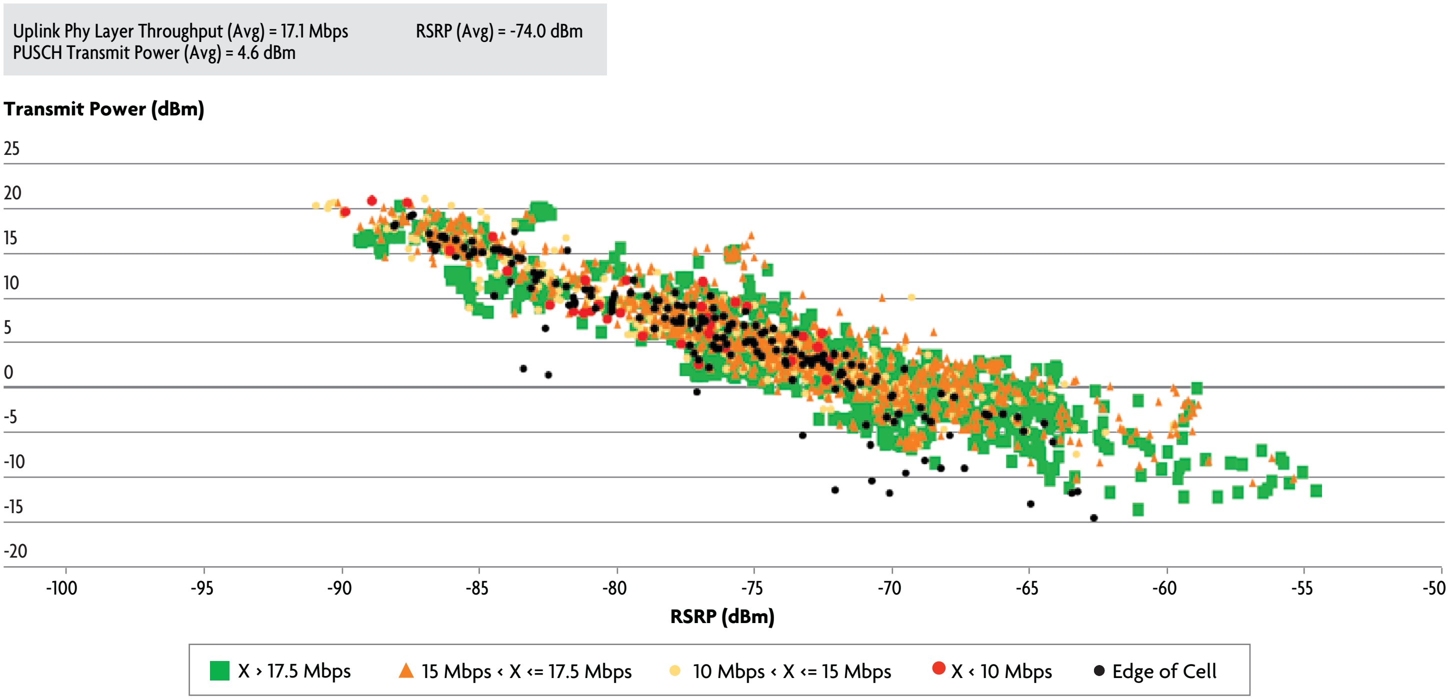
Figure 17 through Figure 19 provide insight into how the transmit power levels varied as a function of the RSRP, and how the combination of these two parameters impacted the corresponding uplink throughput. We note that other factors, such as the uplink SINR, can also influence the transmit power levels but we can only include so many variables in one figure.

At a certain point, the transmit power levels can't increase and at a certain point the uplink throughput for the LTE TDD device starts to decline.

To varying degrees, the uplink throughput declined with lower RSRP. This situation is most evident in the LTE TDD results (Figure 19) and least evident in the LTE FDD 10 MHz results (Figure 17). Interestingly, the figure shows that the device was able to achieve an uplink throughput in excess of 17.5 Mbps across virtually the entire range of RSRP and transmit power levels. It is also evident that the lower RSRP values result in higher transmit power levels. In the case of LTE TDD, the maximum transmit power level starts appearing with a corresponding RSRP value of ~-90 dB. At a certain point the transmit power level can't be increased and the uplink throughput starts to decline.

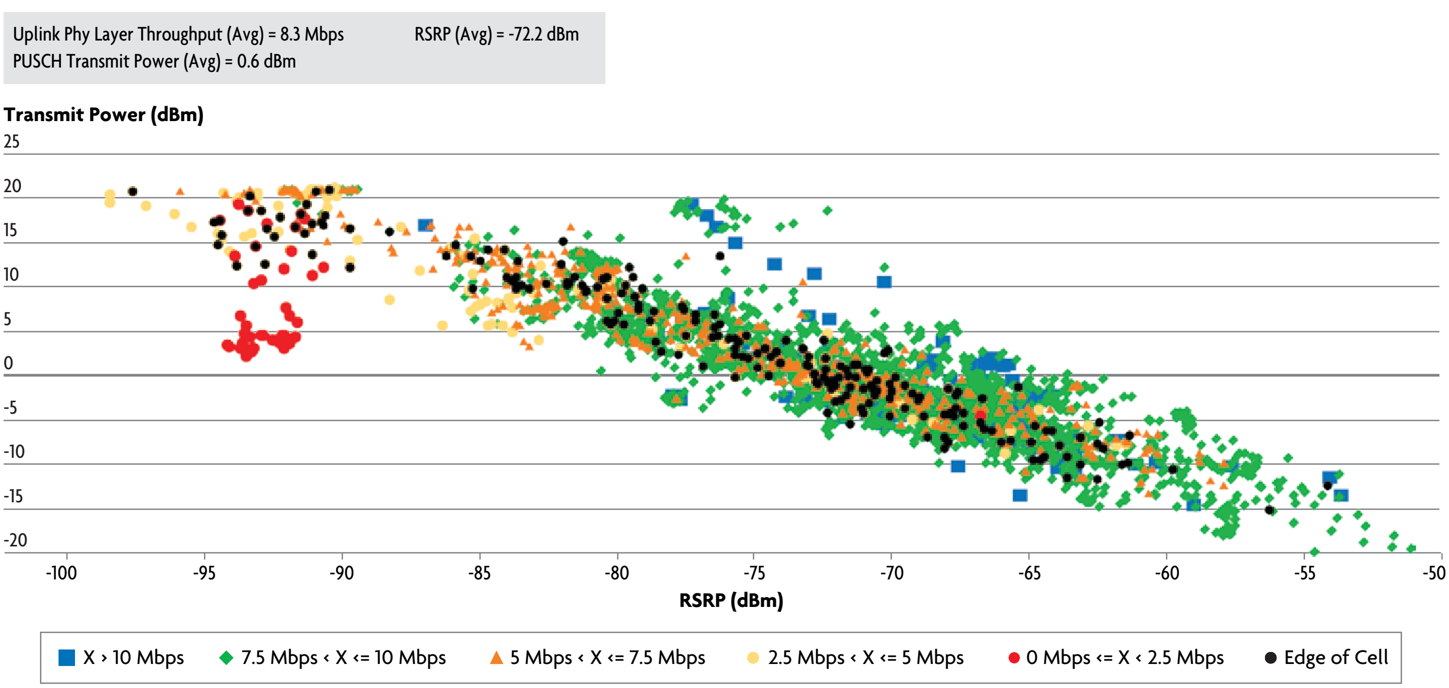
These three figures also include the edge of cell throughput. We didn't include the uplink throughput values in this figure but they are provided in three backup figures that we include in the appendix (Figure 44 through Figure 46).

Figure 17. Transmit Power as a Function of RSRP with Corresponding Throughput Values of LTE FDD 10 MHz – scatter plot



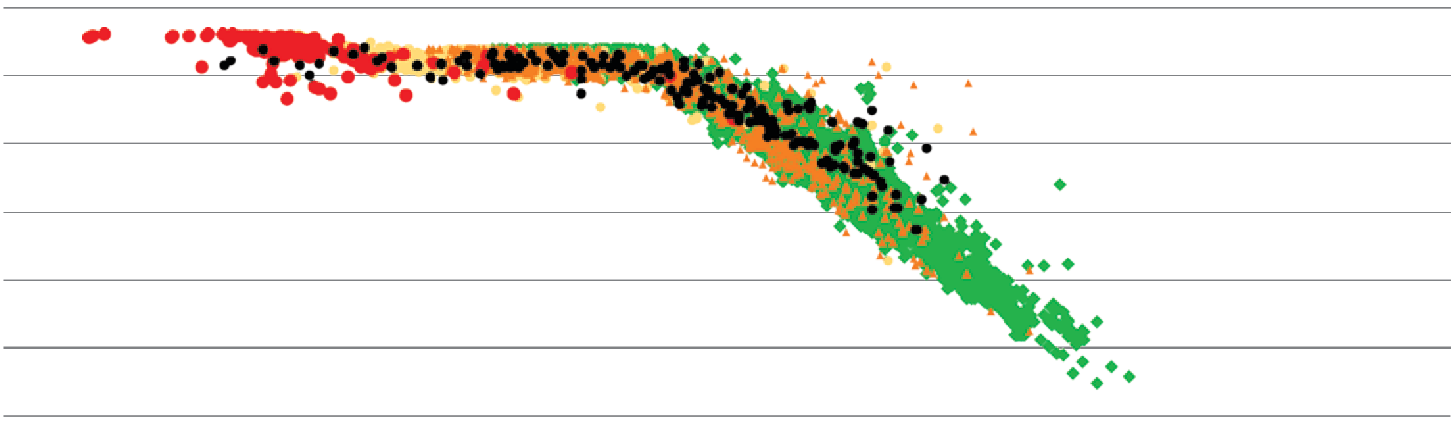
Source: Signals Research Group

Figure 18. Transmit Power as a Function of RSRP with Corresponding Throughput Values of LTE FDD 5 MHz – scatter plot



Source: Signals Research Group

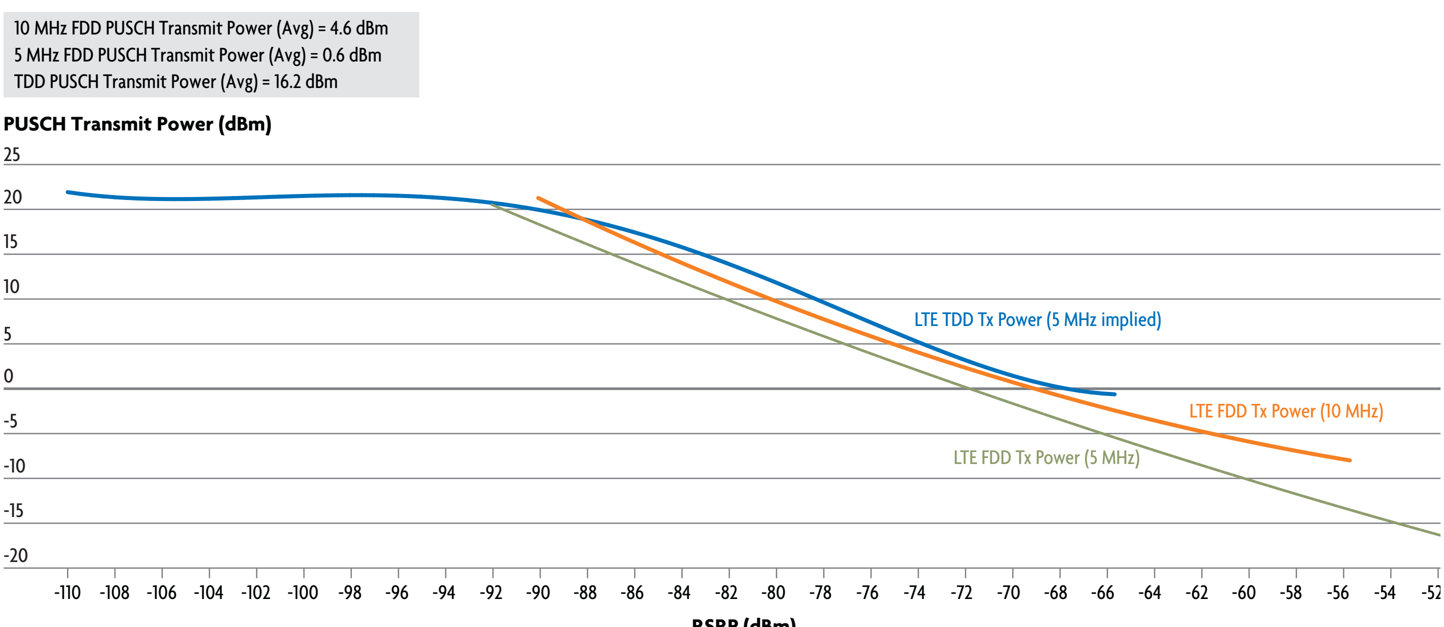
Figure 19. Transmit Power as a Function of RSRP with Corresponding Throughput Values of LTE TDD – scatter plot



Source: Signals Research Group

After creating the scatter plots, we calculated a "best fit" line for each set of data. The results are shown in Figure 20. We remind readers that the two LTE FDD results were obtained in different parts of the network and that the LTE TDD results cover all of the tests.

Figure 20. Transmit Power as a Function of RSRP for LTE TDD and LTE FDD – best fit plots

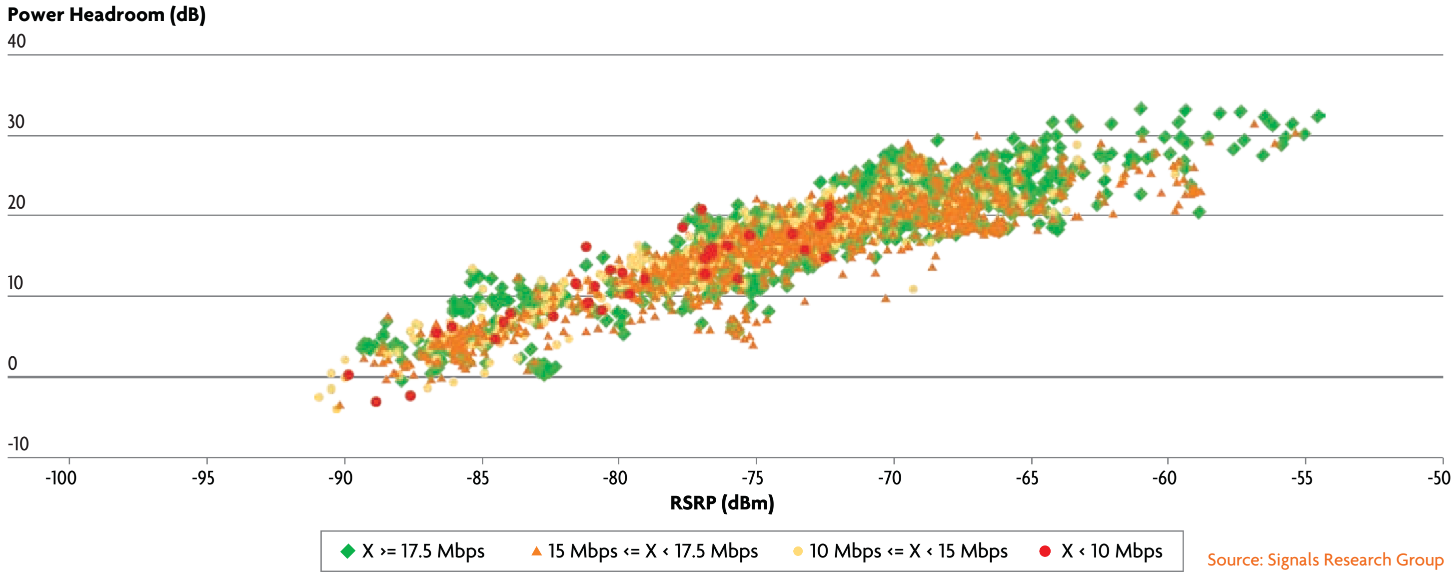


Source: Signals Research Group

Figure 21 through Figure 24 adhere to a similar methodology used to create the previous four figures, but in this case we are using Power Headroom for the Y axis. The impact of an uplink coverage constraint is most evident in Figure 23. We believe the grouping of dots in Figure 22 showing low throughput, higher Power Headroom, and low RSRP values stem from instances when the mobile device, for whatever reason, wasn't transmitting any data and it was only using a few resource blocks. Looking at the data, these instances typically occurred during cell handovers.

Figure 21. Power Headroom as a Function of RSRP with Corresponding Throughput values for LTE FDD 10 MHz – scatter plots

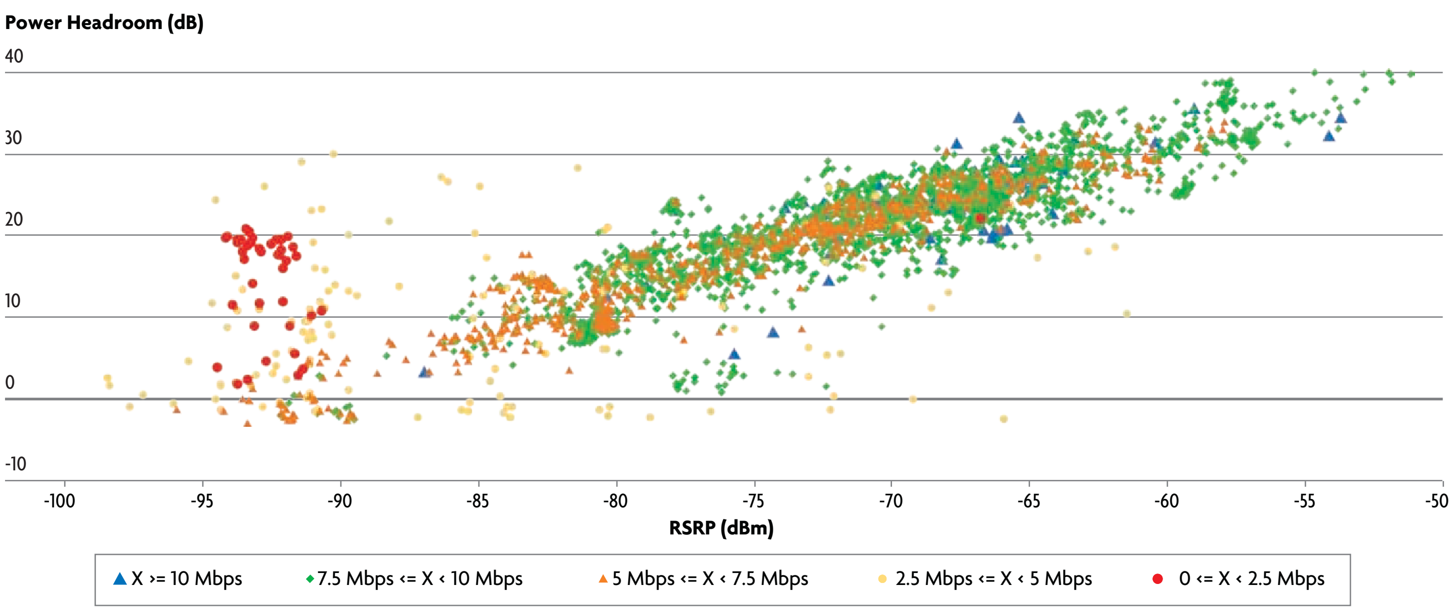
Uplink Phy Layer Throughput (Avg) = 17.1 Mbps   RSRP (Avg) = -74.0 dBm
Power Headroom (Avg) = 16.6 dB



Source: Signals Research Group

Figure 22. Power Headroom as a Function of RSRP with Corresponding Throughput values for LTE FDD 5 MHz – scatter plots

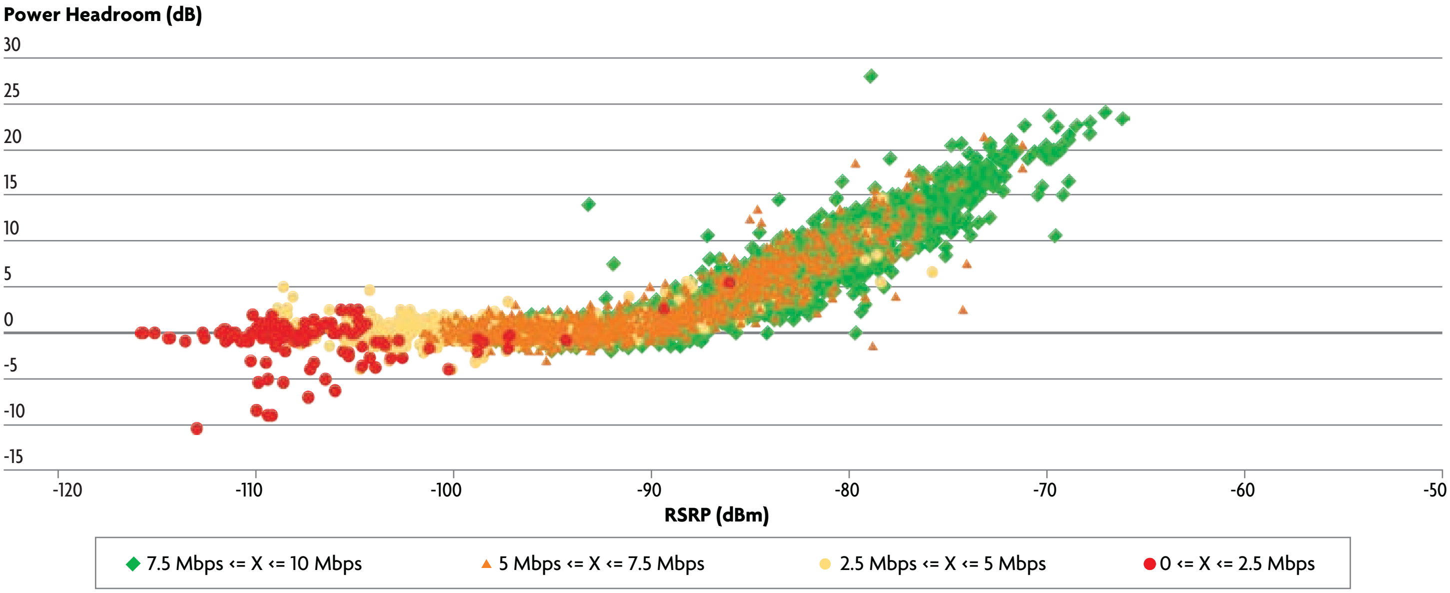
Uplink Phy Layer Throughput (Avg) = 8.3 Mbps   RSRP (Avg) = -72.2 dBm
Power Headroom (Avg) = 20.6 dB



Source: Signals Research Group

Figure 23. Power Headroom as a Function of RSRP with Corresponding Throughput values for LTE TDD – scatter plots

Uplink Phy Layer Throughput (Avg) = 7.6 Mbps   RSRP (Avg) = -86.9 dBm
Power Headroom (Avg) = 5.3 dB

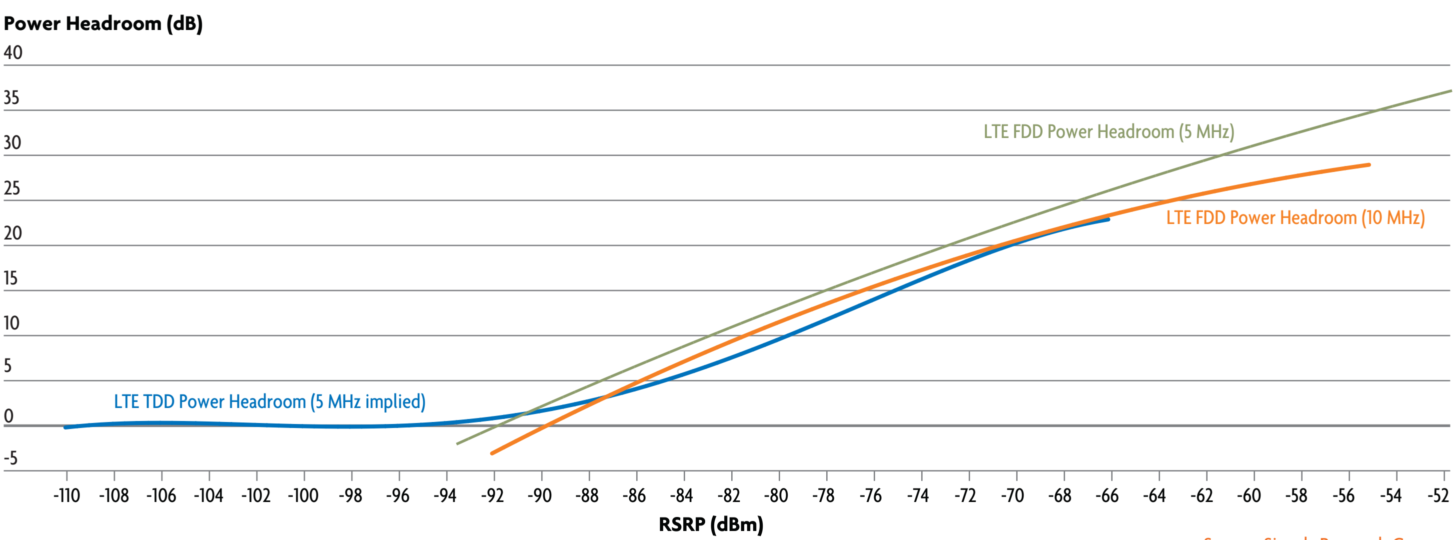


Source: Signals Research Group

Figure 24 provides best fit plots using the information provided in Figure 21 through Figure 23.

Figure 24. Power Headroom as a Function of RSRP for LTE TDD and LTE FDD – best fit plots

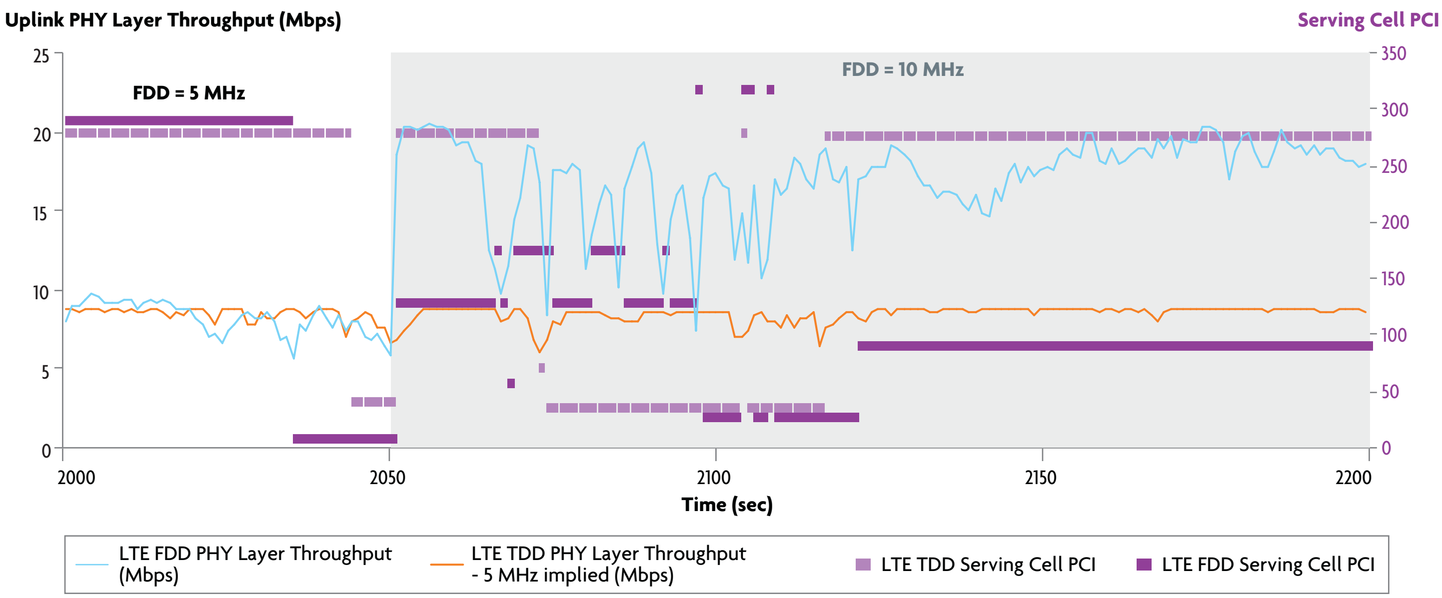
10 MHz FDD Power Headroom (Avg) = 16.6 dB
5 MHz FDD Power Headroom (Avg) = 20.6 dB
TDD Power Headroom (Avg) = 5.3 dB



Source: Signals Research Group

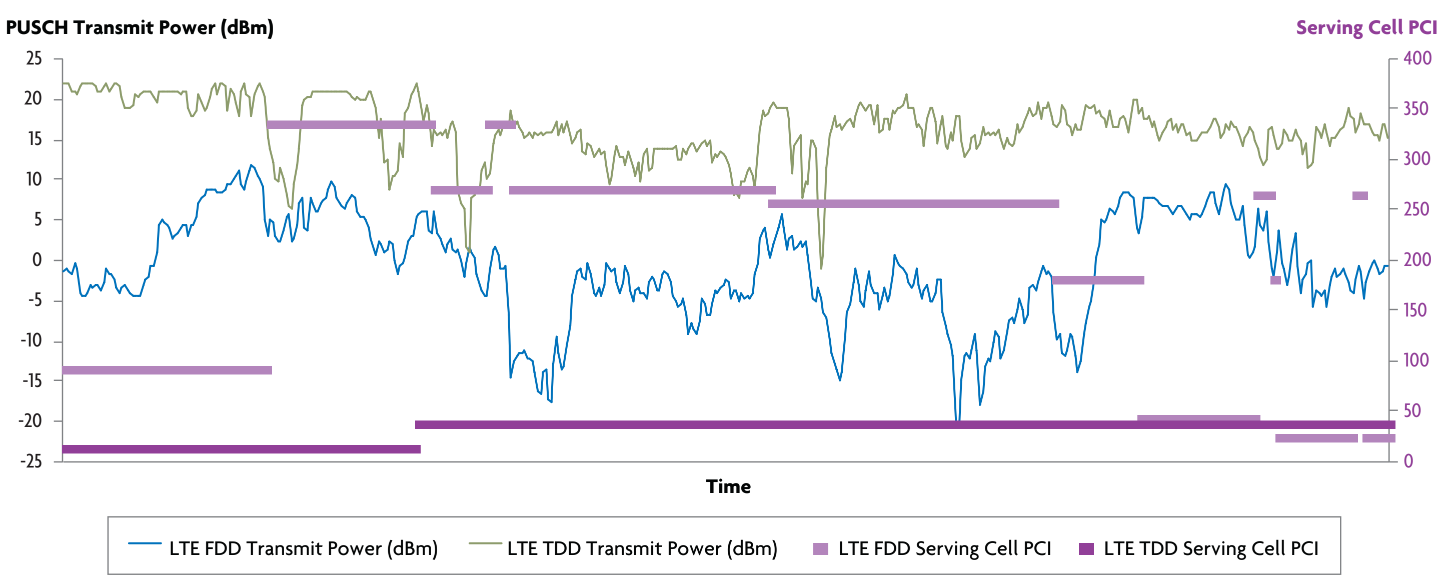
The last two figures show time series plots that pertain to uplink performance. Figure 25 plots the uplink Physical Layer throughput and the Serving Cell PCI values (secondary Y Axis) as a function of time. It shows how throughput varies during cell handovers, as well as a jump in the uplink throughput when the LTE FDD mobile device switched from a 5 MHz channel to a 10 MHz channel. Figure 26 shows comparable information for the uplink transmit power. In the appendix we include two comparable figures which show the same information over an extended period of time (Figure 47 and Figure 48).

Figure 25. Uplink Physical Layer Throughput for LTE TDD and LTE FDD versus Serving Cell PCI Values – time series plots



Source: Signals Research Group

Figure 26. Transmit Power for LTE TDD and LTE FDD versus Serving Cell PCI Values – time series plots



Source: Signals Research Group

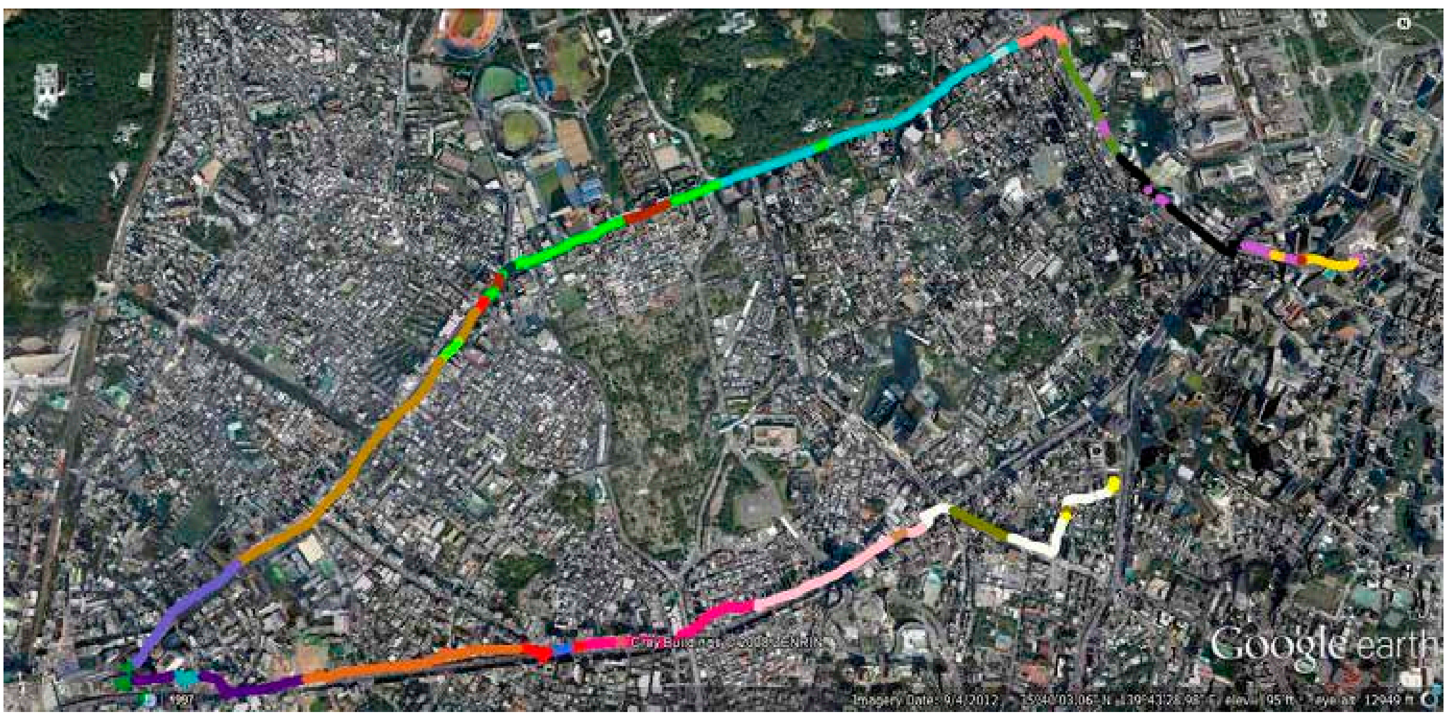
6.0 Skype Video Call – Comparing and Contrasting LTE TDD and LTE FDD

In our forthcoming LTE-Advanced Carrier Aggregation report we will sacrifice a lot of fallen trees to the performance of Carrier Aggregation with typical user behavior and not the contrived maximum throughput testing that we normally do, but which does not necessarily reflect user behavior. In this report we are looking at one particular application – namely, Skype Video between two notebook computers.

While the LTE TDD network is fairly dense, the LTE FDD network seemingly has a higher density of cell sites.

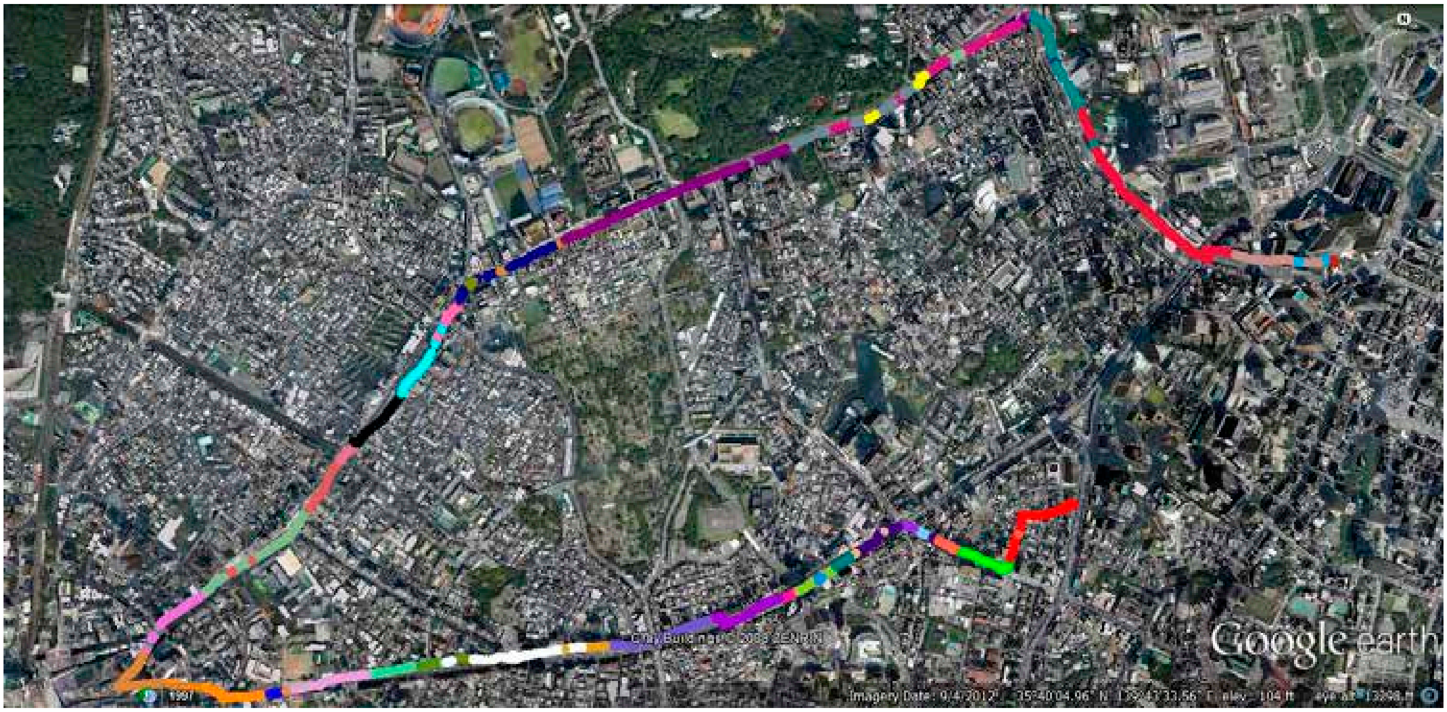
During the 29.1 minute video we transferred an impressive 1.2 GB of data based on summing the downlink and uplink data transfers from the LTE TDD and LTE FDD devices. We've included Figure 27 and Figure 28 for two reasons. First, the figures show the 5.6 mile drive route that we followed, but more importantly the figures provide a sense of the absolute and relative cell densities in the operator's networks. In the case of the LTE TDD network the mobile device used 29 unique PCI values and the mobile device using the LTE FDD network used 46 unique PCI values. Each PCI value identifies a unique cell sector in the area. We assume the operator has deployed three-sector cell sites but we have not confirmed this view. A comparison of these two values provides good anecdotal evidence that while the LTE TDD network is fairly dense, the LTE FDD network seemingly has a higher density of cell sites. This observation isn't surprising given the capacity requirements of the network and the result is generally consistent with the findings that we made in the previous two chapters.

Figure 27. LTE TDD Serving Cell PCI Values during Skype Video Drive Test – geo plot



Source: Signals Research Group

Figure 28. LTE FDD Serving Cell PCI Values during Skype Video Call Drive Test – geo plot

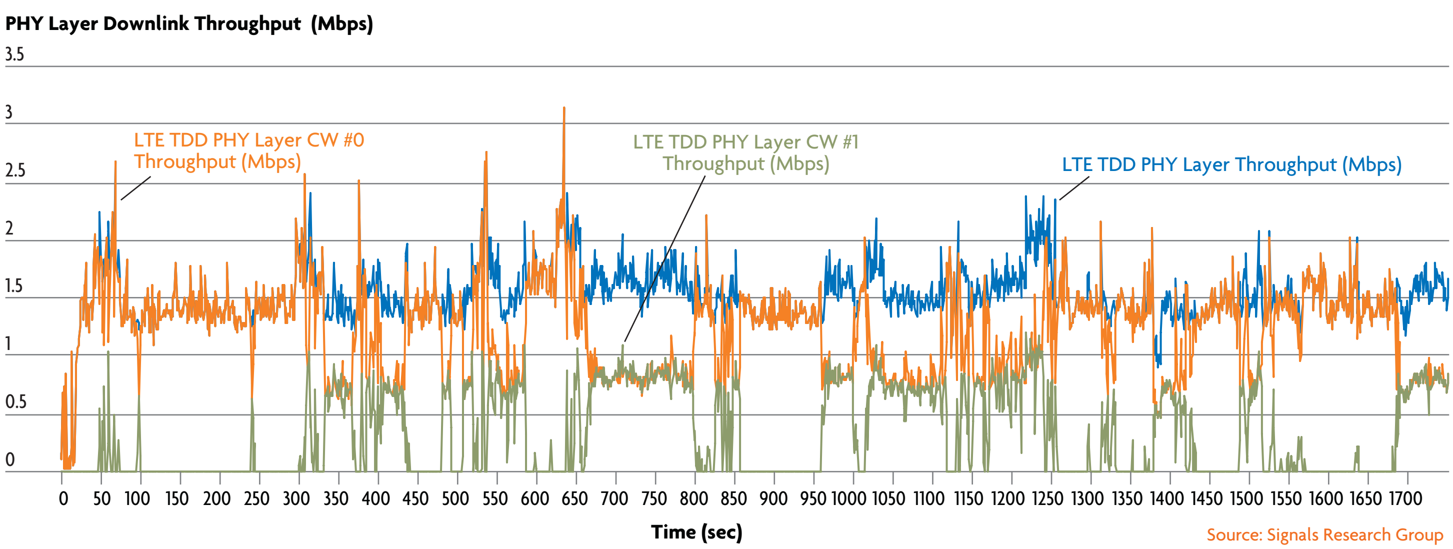


Source: Signals Research Group

Figure 29 through Figure 31 provide some insight regarding the downlink and uplink throughput while doing a Skype video. During the 29.1 minute test we transferred an impressive 1.2 GB of data based on summing the downlink and uplink data transfers from the LTE TDD and LTE FDD devices. There is a modest difference in the downlink throughput and it is also evident that the LTE FDD network made greater use of MIMO than the LTE TDD network. However, the reported SINR in the LTE FDD network was on average 1.8 dB higher than the reported SINR in the LTE TDD network and both averages were in the range where we have found that MIMO doesn't have a material benefit on user throughput although it could still provide an efficiency benefit.

Figure 29. LTE TDD Aggregate Downlink Throughput and by Individual Code Word during a Skype Video Call – time series plot

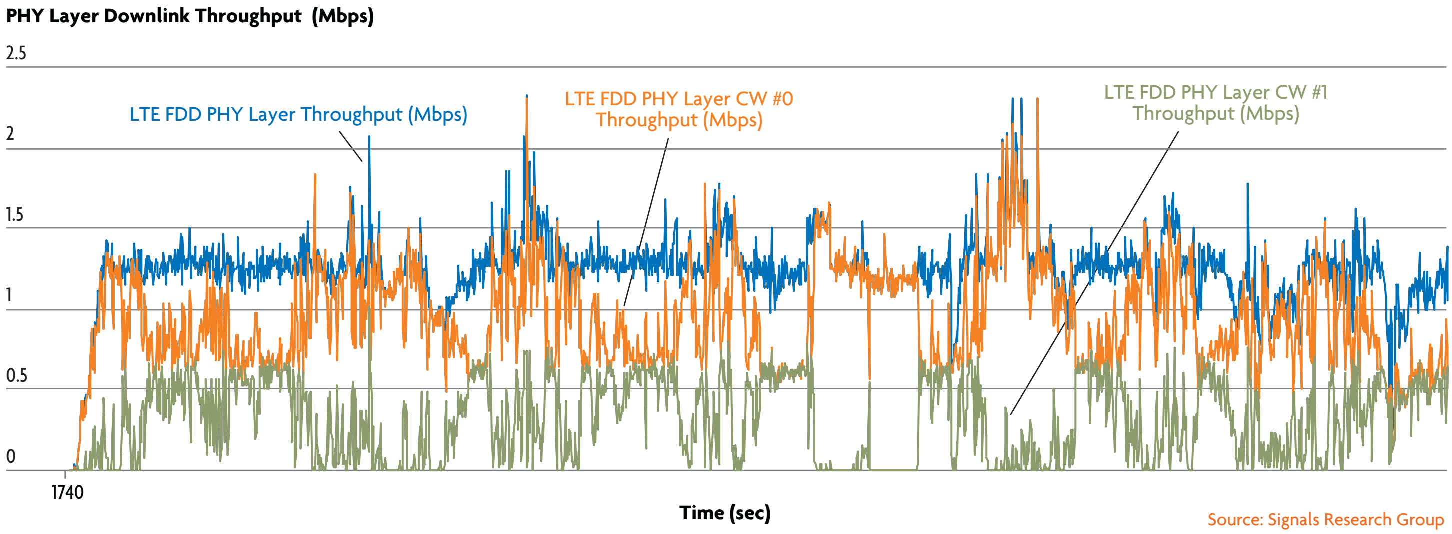
LTE TDD Physical Layer Throughput (Avg) = 1.52 Mbps LTE TDD Physical Layer CW #0 Throughput (Avg) = 1.20 Mbps LTE TDD Physical Layer CW #1 Throughput (Avg) = 0.32 Mbps



Source: Signals Research Group

Figure 30. LTE FDD Aggregate Downlink Throughput and by Individual Code Word during a Skype Video Call – time series plot

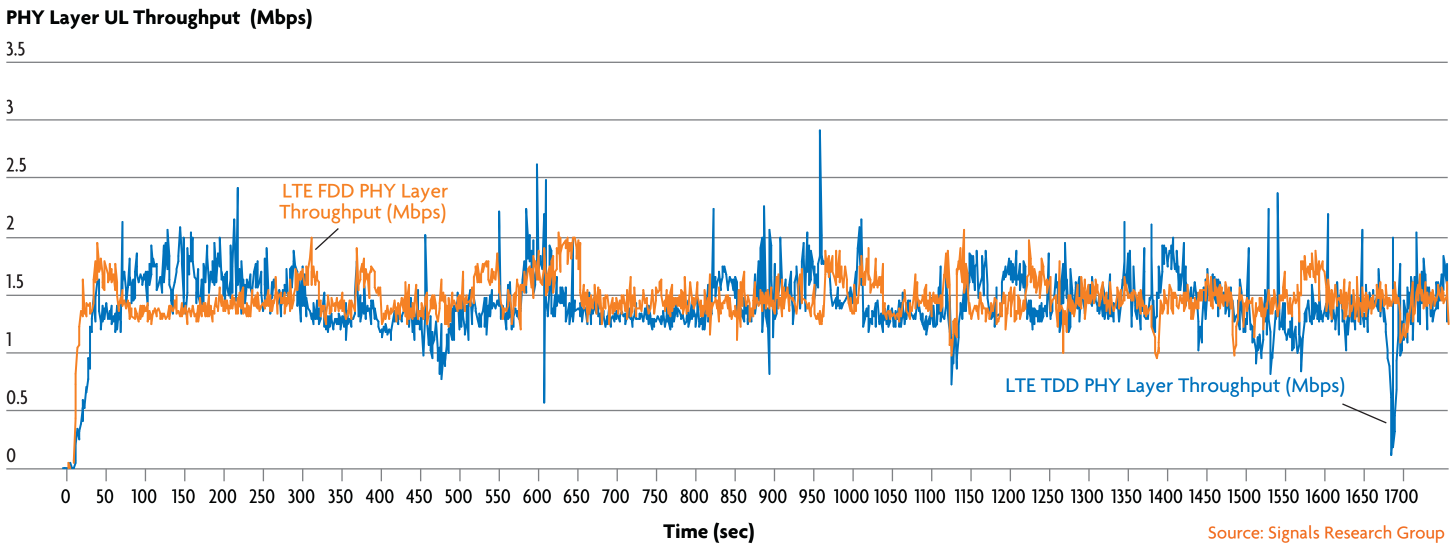
LTE FDD Physical Layer CW #0 Throughput (Avg) = 0.93 Mbps
LTE FDD Physical Layer CW #1 Throughput (Avg) = 0.31 Mbps



Source: Signals Research Group

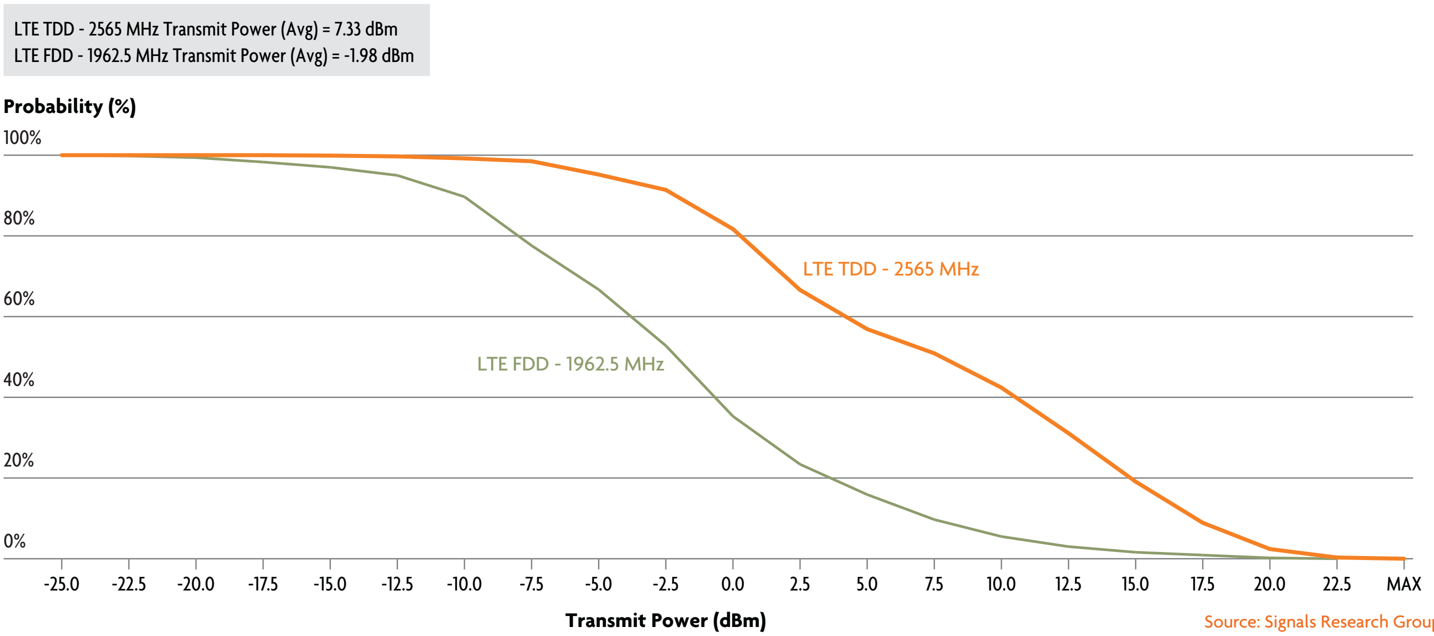
Figure 31. LTE TDD and LTE FDD Uplink Throughput during a Skype Video Call – time series plot

LTE TDD Physical Layer Throughput (Avg) = 1.39 Mbps
LTE FDD Physical Layer Throughput (Avg) = 1.46 Mbps



Source: Signals Research Group

Figure 32. Transmit Power for LTE TDD and LTE FDD during a Skype Video Call – probability plots



Source: Signals Research Group

The transmit power of the LTE TDD device was 9.3 dB higher than the transmit power of the LTE FDD device during the Skype Video test.

Figure 32 provides probability distribution plots of the transmit power for the two mobile devices. This figure is relevant because it stems from network usage that is more typical of a mobile data consumer. For this application, and over the same drive route, the transmit power of the LTE TDD device was 9.3 dB higher than the transmit power of the LTE FDD device. Again, this difference is primarily due to the higher frequency band and the less densely deployed LTE TDD network.

While not shown in this report, we did a similar test involving Skype Voice. During that lengthy test, which was also conducted while driving around central Tokyo, there was a 7.5 dB difference in the average transmit power between the LTE TDD device (average = -3.2 dB) and the LTE FDD device (average = -10.7 dB).

7.0 MIMO Usage and Category 4 Device Implications

When we were conducting the drive testing, we frequently noticed in the XCAL display that the downlink throughput was using transmit diversity instead of MIMO.

We included this chapter at the end of this report because we wanted to highlight a couple of observations that are somewhat tangential to the analysis of the LTE TDD network. When we were conducting the drive tests, we frequently noticed in the XCAL display that the downlink throughput was using transmit diversity instead of MIMO. In poor SINR conditions, the mobile device + network should default to transmit diversity and as we discussed in the last report (*SA* 08/10/13, "Fifty Shades of MIMO"), we believe that sometimes MIMO gets used when it probably shouldn't be used – the end user throughput ends up being lower with MIMO than without it.

In Tokyo, when we were collecting the data we frequently monitored the throughput, the presence or absence of MIMO, and the reported SINR. We almost immediately observed that MIMO was used far less frequently than we have normally observed. In one case, we were stopped at an intersection and the reported SINR was above 20 dB, suggesting pretty favorable network conditions. However, MIMO generally wasn't being used. On occasion, and at this same intersection, when MIMO was briefly activated the throughput increased considerably, or roughly 25%, before immediately dropping once the network stopped using MIMO. During these instances the reported SINR remained the same.

Throughput from the second transmission path (code word #1) is only present when MIMO is being used.

Figure 33 provides three figures which highlight this issue. The figures plot the Physical Layer throughput as a function of time. We've plotted the total throughput, which is the sum of the throughput from the two individual transmission paths, and the throughput from the second transmission path (e.g., code word #1), or the throughput that is only present when MIMO is being used. In order to avoid having a thoroughly messy and unreadable figure, we didn't plot the throughput from the first transmission path (e.g., code word #0), although its contribution can be derived from the differences between the total throughput and the throughput from the second transmission path. We also plotted the reported SINR values along the secondary Y axis. Although it isn't evident in the figure, the time scale is roughly three minutes in the top figure, four minutes in the middle figure, and five minutes in the bottom figure.

With similar SINR conditions, the set of three figures show that the total throughput increases materially when MIMO is used.

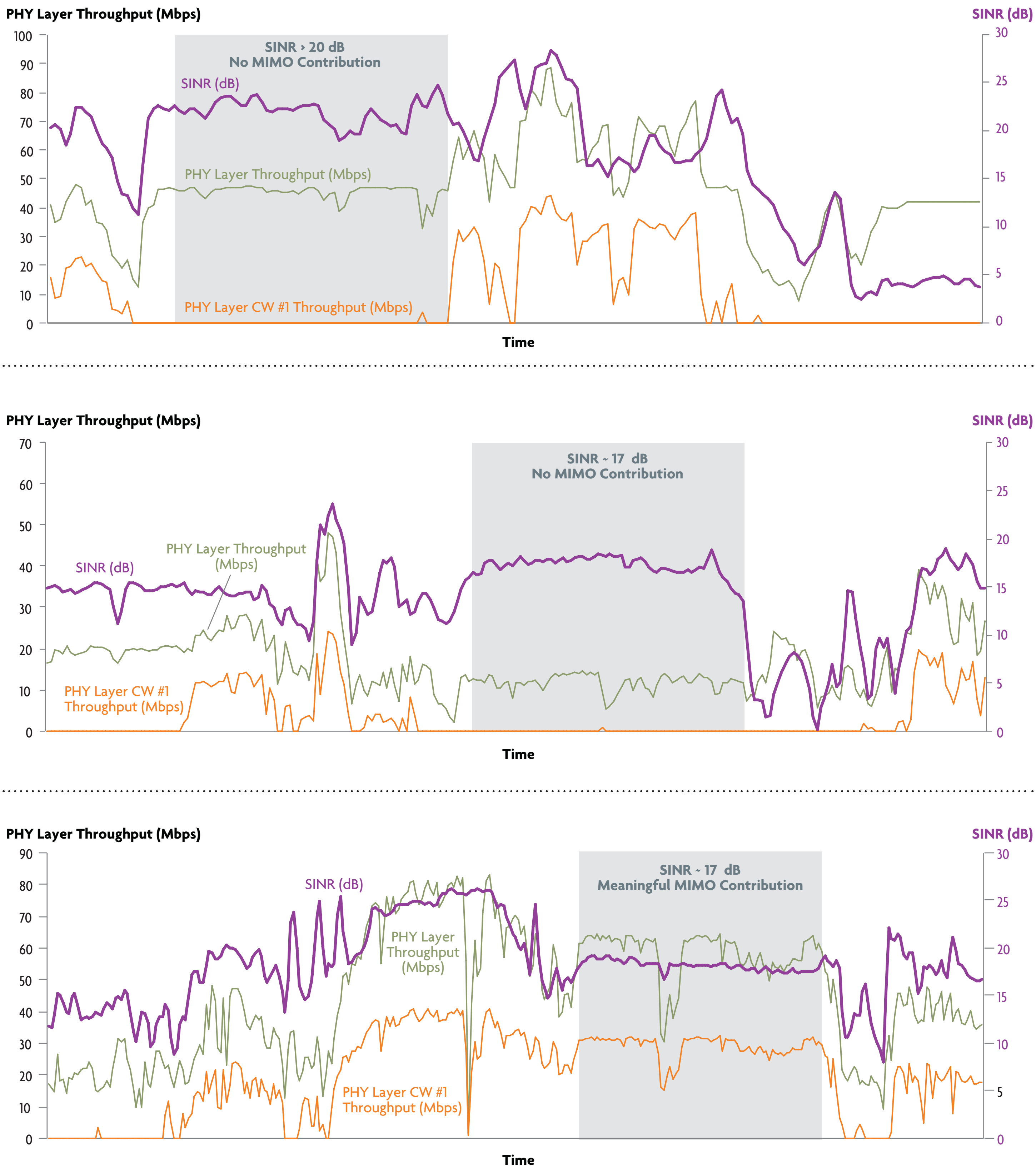
In the top figure we have highlighted a sixty second region when the SINR was above 20 dB yet MIMO wasn't being used – the mobile device wasn't even requesting it. Immediately after this highlighted region, the figure indicates that the mobile device started to request MIMO, MIMO was enabled, and the throughput increased. We recognize the figure shows that the SINR values also increased, at least initially, but then they returned to similar values obtained in the highlighted region. However, MIMO remained enabled and the throughput was higher than it was during the time period shown in the highlighted region.

In the middle and bottom figures we have highlighted two regions with very similar SINR conditions. In the middle figure, it is evident that MIMO wasn't used since there isn't any contribution from the code word #1 throughput in this region. Based on our analysis of the log file, the mobile device didn't request MIMO. In the bottom figure there is a throughput contribution from code word #1 so it is evident that MIMO was used. As a result, the throughput displayed in the highlighted region in the bottom figure is meaningfully higher than the throughput shown in the highlighted region in the middle figure – both highlighted regions have comparable SINR values.

There were opportunities when MIMO could have, and probably should have, been used.

Our view, based in part on data that we reviewed in the log files but also based on what we observed while collecting the data, is that there were opportunities when MIMO could have, and probably should have, been used. For reasons that we don't fully understand, the mobile device didn't request MIMO and the network didn't assign it. In addition to the LTE TDD mobile device not requesting MIMO when we believe it probably should have requested it, we also observed that the network infrastructure didn't always assign MIMO when the mobile device requested it. This outcome isn't necessarily bad if the mobile device is taking an overly-aggressive approach to requesting MIMO, but our analysis suggests otherwise in at least some instances.

Figure 33. MIMO Utilization versus SINR and its Impact on Aggregate Downlink Throughput and for each Individual Code Word – time series



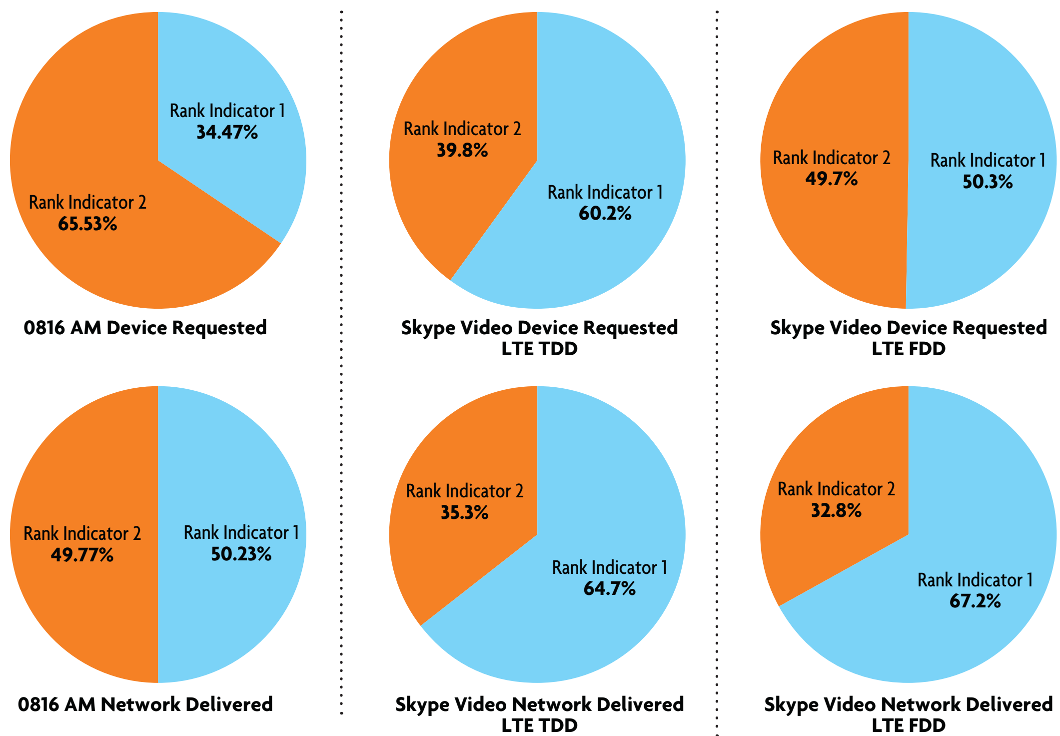
Source: Signals Research Group

Figure 34 shows results from two different drive tests, the "0816 AM" drive test and a Skype Video drive test – for the latter we include both LTE TDD and LTE FDD information. For each test configuration the figure provides two pie charts. The top pie chart in each column shows the percentage of time the mobile device requested Rank Indicator 1 (transmit diversity) and Rank Indicator 2 (Open Loop MIMO). The bottom pie chart in each column shows the percentage of time the network assigned Rank Indicator 1 and Rank Indicator 2.

There seems to be a disconnect between the mobile device and the network regarding requests for MIMO and the actual use of MIMO.

Looking at the results for the "0816 AM" drive test, which was a downlink throughput test, it is evident that the network assigned the mobile device Rank Indicator 2 far less frequently than it was requested. Although we are not providing figures to back up our analysis in this report, we went back and reviewed the log file and we observed fairly lengthy periods when the SINR was favorable (>20 dB), the mobile device was requesting Rank Indicator 2, but the network wasn't assigning it. There could be other factors at work which justify why MIMO wasn't used when it was requested or why MIMO wasn't requested when we think it should have been requested, but based on the information we've reviewed there seems to be a disconnect between the mobile device and the network regarding requests for MIMO and the actual use of MIMO. The differences between the device requested and network delivered results for the Skype video test are not surprising since the relatively low throughput required by the application meant there wasn't always enough data in the scheduler's buffer to justify the use of MIMO.

Figure 34. Distribution of Rank Indicator Requests versus MIMO Utilization for LTE TDD and LTE FDD – pie charts



Source: Signals Research Group

A Category 4 device can support peak data rates of up to 150 Mbps with a 20 MHz FDD channel while a Category 3 device is limited to 100 Mbps.

When we tested the LTE TDD network it was our first time using a Category 4 device. Category 4 devices have just started coming on the market with virtually all commercial LTE devices currently limited to Category 3 functionality. A Category 4 device can support peak data rates of up to 150 Mbps with a 20 MHz FDD channel while a Category 3 device is limited to 100 Mbps. With a 10 MHz FDD channel the Category 4 device doesn't provide any incremental benefits while with a 20 MHz LTE network and Configuration 2, the theoretical peak data rate is close to 120 Mbps.

The higher possible data rates associated with a Category 4 device are due to more memory and processing capabilities. Even in a 20 MHz FDD network the Category 4 device doesn't provide any incremental benefit unless the network conditions are good enough to support the higher data rates.

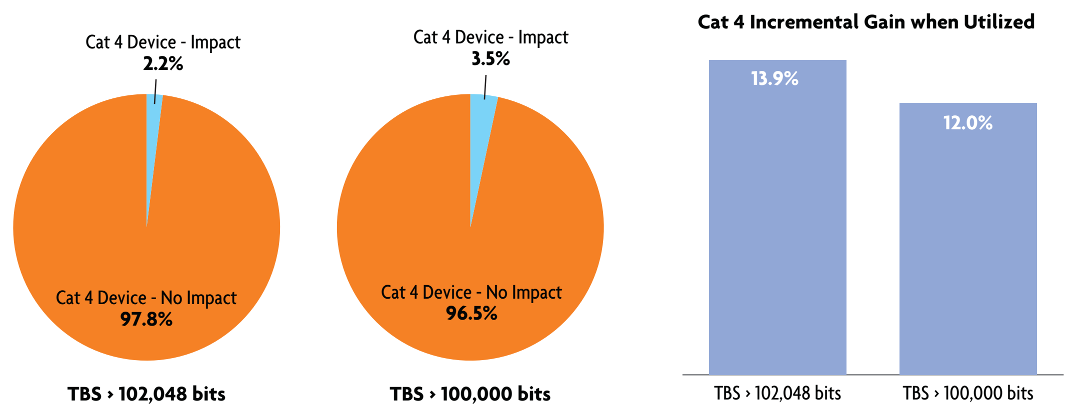
A TBS of 102,048 bits is the theoretical maximum size that a Category 3 device can support.

In order to determine the incremental throughput gains associated with using a Category 4 device we analyzed two lengthy downlink drive test files. Using XCAP, we post-processed the files so that we could analyze the transport block size (TBS) in each one millisecond sub-frame. We then sorted the results so that we could count the number of sub-frames with a TBS higher than 102,028 bits, which is the theoretical largest TBS that a Category 3 device can support. Since it wasn't clear to us if a TBS of 102,028 bits is easily achieved with a Category 3 device, or if some of those instances actually required Category 4 capabilities, we also repeated the analysis with a TBS of 100,000 bits. Given that a 45 minute log file would result in 2.7 million lines of results, it was no small feat!

The results from our LTE TDD testing indicate that the Category 4 device capabilities had virtually no impact on the throughput.

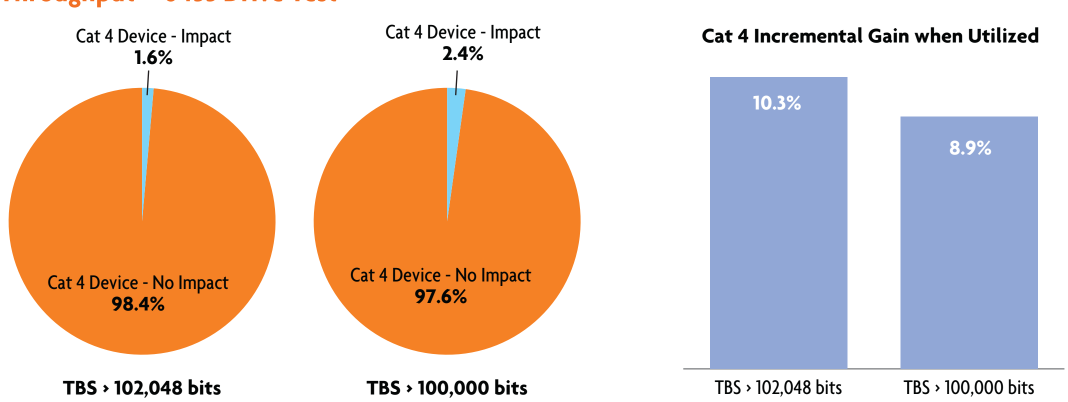
Figure 35 and Figure 36 show the results from two downlink drive tests. The results indicate that the Category 4 device had very little impact on the results that we obtained. With a TBS of 102,048 bits, the Category 4 device functionality was utilized for barely 2% of the time. Lowering the TBS to 100,000 bits hardly has any impact on the percentages. The bar charts show the average incremental throughput achieved by the Category 4 device relative to a Category 3 device, but only when the Category 4 functionality was most likely being used. Although the average incremental throughput gains are encouraging, or in the very low double-digits, the gains are so infrequently realized that the net benefit over the entire test period is negligible. Fortunately, we'll demonstrate in our Carrier Aggregation report that Category 4 devices can still have a material impact on throughput in a commercial LTE network.

Figure 35. Estimated Category 4 LTE TDD Device Utilization and its Impact on Overall Throughput – 0816 Drive Test



Source: Signals Research Group

Figure 36. Estimated Category 4 LTE TDD Device Utilization and its Impact on Overall Throughput – 0455 Drive Test

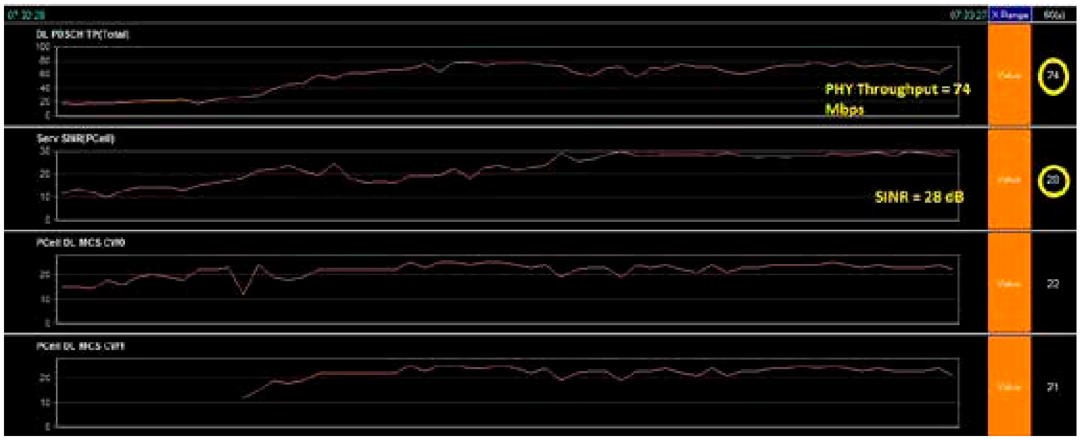


Source: Signals Research Group

8.0 Test Methodology

For the LTE TDD 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 37 shows a screen shot of the XCAL tool in action. Although the information is difficult to see in the figure, the top line shows the Physical Layer downlink throughput, the second line shows the reported SINR, and the bottom two lines show the MCS (Modulation and Coding Scheme) values for each transmission path. The absence of a data point in the bottom figure indicates a point in time when MIMO wasn't used.

Figure 37. XCAL in Action



Source: Accuver and SRG

As is the case with all *Signals Ahead* reports, this entire endeavor was self-funded. Softbank did supply us with test SIMs and access to a high bandwidth FTP server. Qualcomm also supplied us with two test mobile devices. We elected to use test devices, which have a comparable form factor to a commercial smartphone, because we had concerns about using a commercial smartphone with a user interface in a language that we cannot read.

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.

We also could not have done this report without the support of Accuver.

All of our testing took place from a moving vehicle, unless we were stuck in traffic or at a traffic light.

All of our testing took place from a moving vehicle, unless we were stuck in traffic or at a traffic light. We tested at all hours of the day, from 0400 in the morning until 1700 in the evening. The drive routes that we selected were entirely random, in fact, we were hopelessly lost most of the time until we switched on our navigation system so that we could get back to our hotel. Testing indoors would have produced different results and we know that building penetration loss would have degraded the signal over what we observed. However, we also know that merely testing in a few in-building locations would result in statistically meaningless results. We believe it is better to obtain statistically meaningful results and then let readers apply their own adjustments to compensate for in-building performance.

The LTE TDD and LTE FDD devices were tethered to notebook computers. Both devices were fixed to the dashboard of our vehicle with approximately 12 inches of separation in between them. Since we were constantly moving throughout the network and since the operator's LTE TDD and LTE FDD cell sites are not necessarily co-located, neither device had an inherent advantage regarding its location in the vehicle.

The results that we present in this report stem from combining multiple log files into a single log file. This approach ensures that our analysis and conclusions are based on the representative performance of the network. We did, however, focus our analysis on isolated results in order to illustrate interesting findings that we observed in the data.

Since LTE TDD and LTE FDD are almost identical in nature from a standard's perspective, we didn't have to make any adjustments to how we analyzed the data. Further, the "go-to" KPIs that we frequently use when analyzing LTE network performance are the same so it made it easy to do the analysis and to make the comparisons.

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

For the scatterplots, we linked the two applicable KPIs together and then did the necessary averaging. For example, for the SINR versus RSRP versus Physical Layer throughput plots, we averaged all reported SINR and RSRP values plus or minus one second from the reported throughput value in order to obtain the corresponding SINR and RSRP values. We also sorted the throughput values into discrete buckets in order present color coded information that shows how throughput varies as a function of SINR and RSRP. 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.

For the Rank Indicator and Category 4 analysis, we post-processed the log files so that information from every 1 ms subframe was present in the log file.

For the Rank Indicator and Category 4 analysis, we post-processed the log files so that information from every 1 ms subframe was present in the log file. We could then determine the Rank Indicator value that the network assigned the mobile device and compare it to the value that the mobile device requested – this information is found elsewhere in the log file. Similarly, by having information for every single subframe we could see the exact TBS value that the mobile device used versus an average over a one second increment. Our approach was more precise since a one second average could mask those brief instances when the TBS value was greater than what a Category 3 device could support.

9.0 Final Thoughts

We are presently in Singapore where we are getting ready to attend the LTE Asia event, including the pre-conference Signaling Workshop. Fortunately, the Singapore Grand Prix doesn't start until after we leave Singapore and head for home. Now that we are done with the LTE TDD report it is time to move onto the LTE Advanced Carrier Aggregation report, which we hope to have published sometime next month. 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.

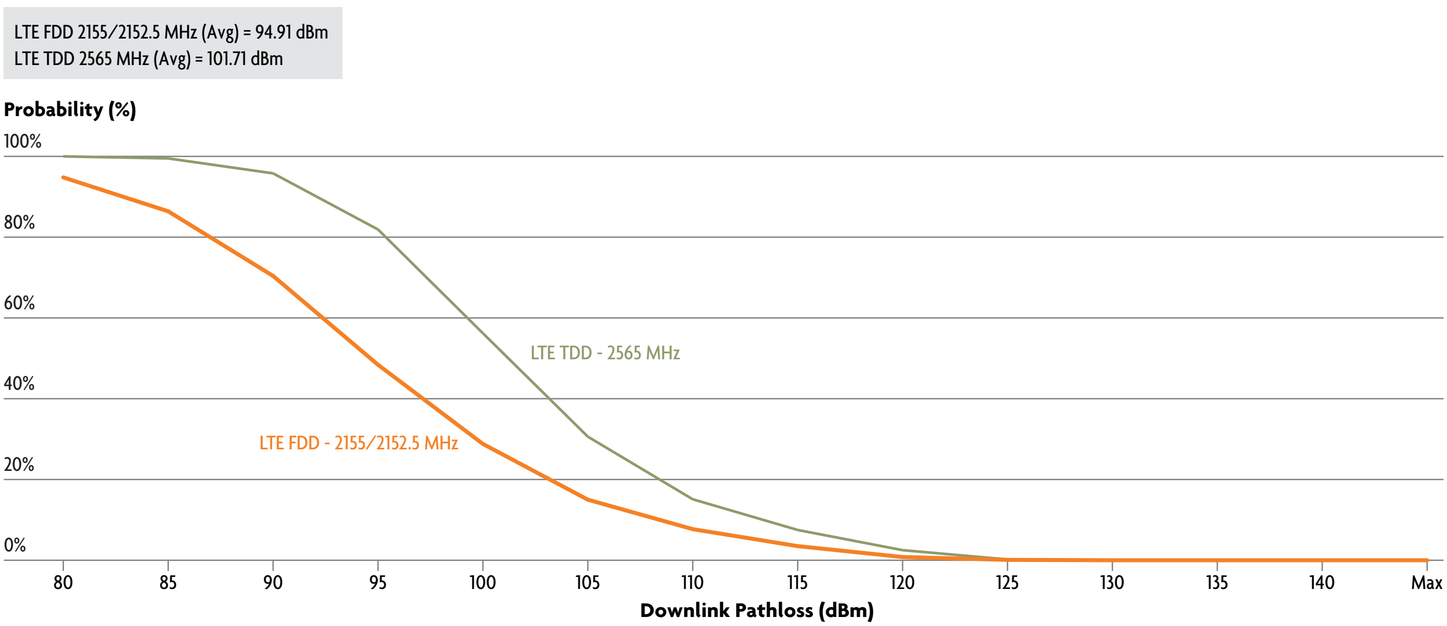
Previously, Mr. Thelander was an analyst with Deutsche Bank Equity Research. Prior to joining Deutsche Bank, Mr. Thelander was a consultant with KPMG (now known as BearingPoint) and a communications officer with the United States Army. Mr. Thelander has also published numerous articles for leading trade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

10.0 Appendix

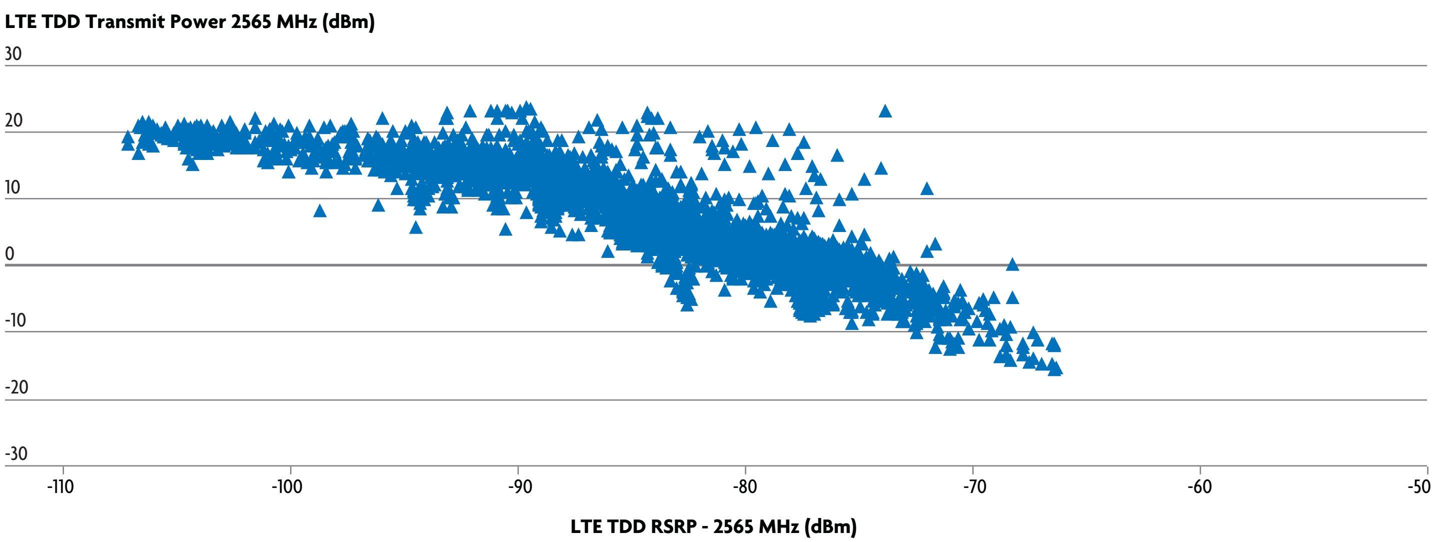
The appendix includes a number of figures that we didn't include in the main body of the report. We are providing these figures without any text or analysis. However, we generally referenced them in previous chapters.

Figure 38. Downlink Pathloss for LTE TDD and LTE FDD – probability plots



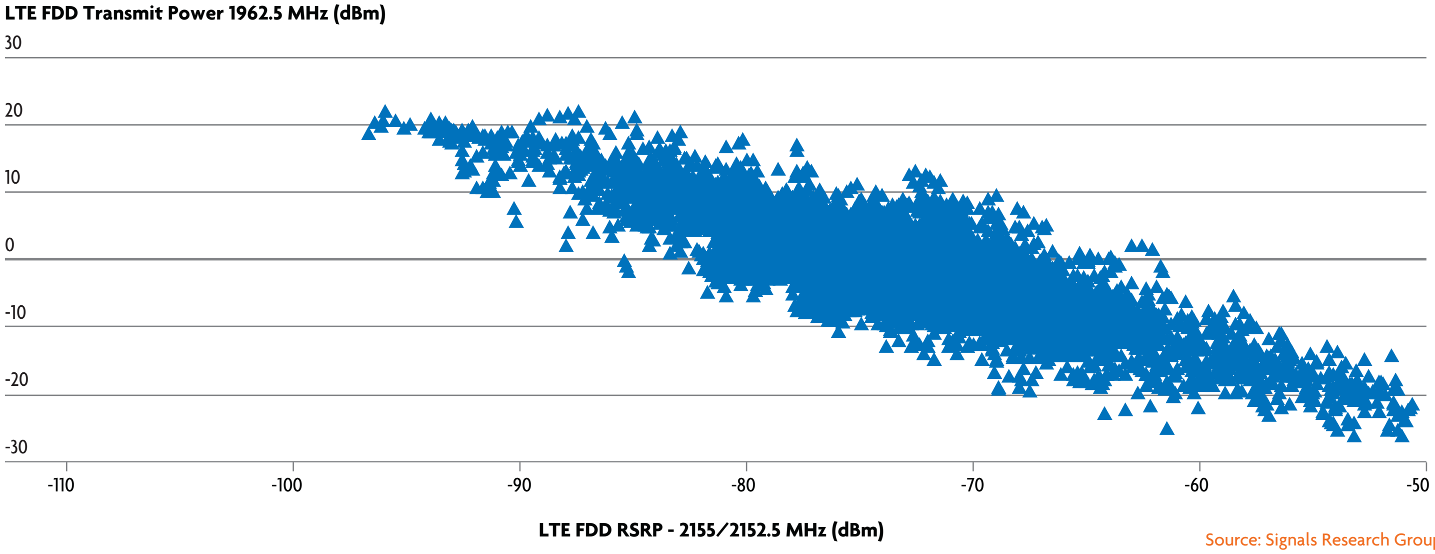
Source: Signals Research Group

Figure 39. LTE TDD Transmit Power versus RSRP during a Skype Video Call – scatter plot



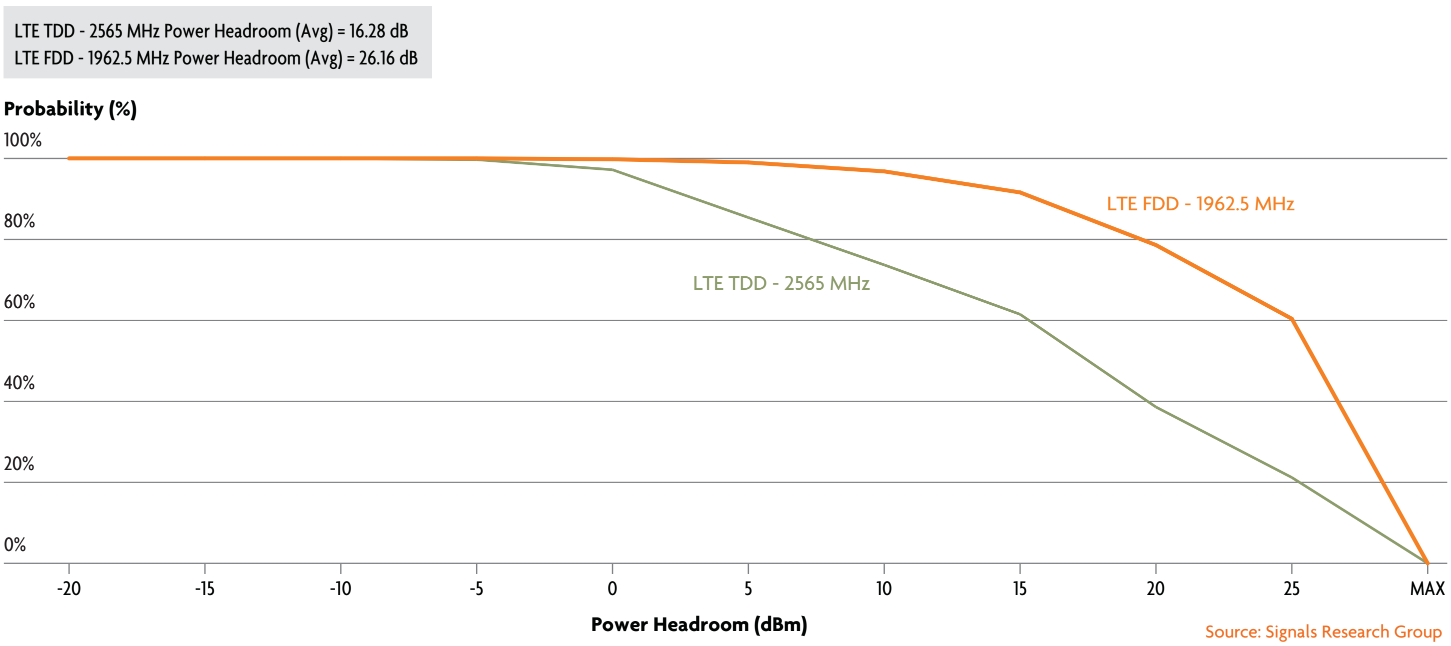
Source: Signals Research Group

Figure 40. LTE FDD Transmit Power versus RSRP during a Skype Video Call – scatter plot



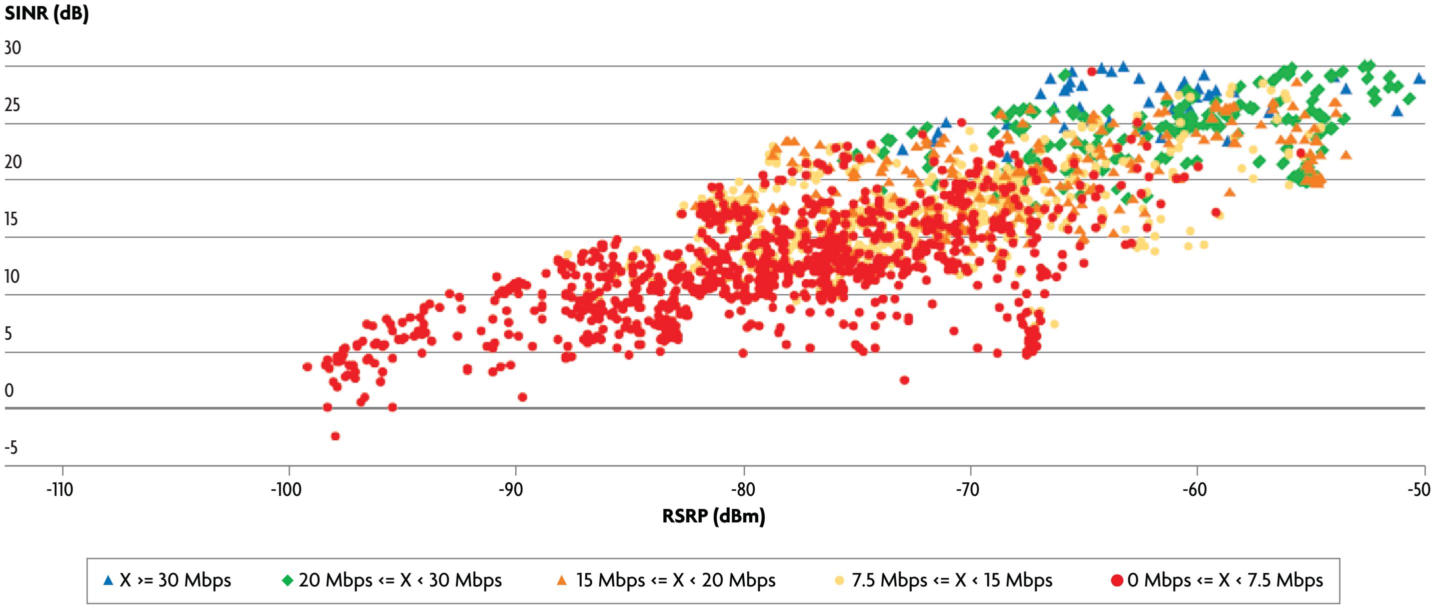
Source: Signals Research Group

Figure 41. Power Headroom for LTE TDD and LTE FDD during a Skype Video Call – probability plots



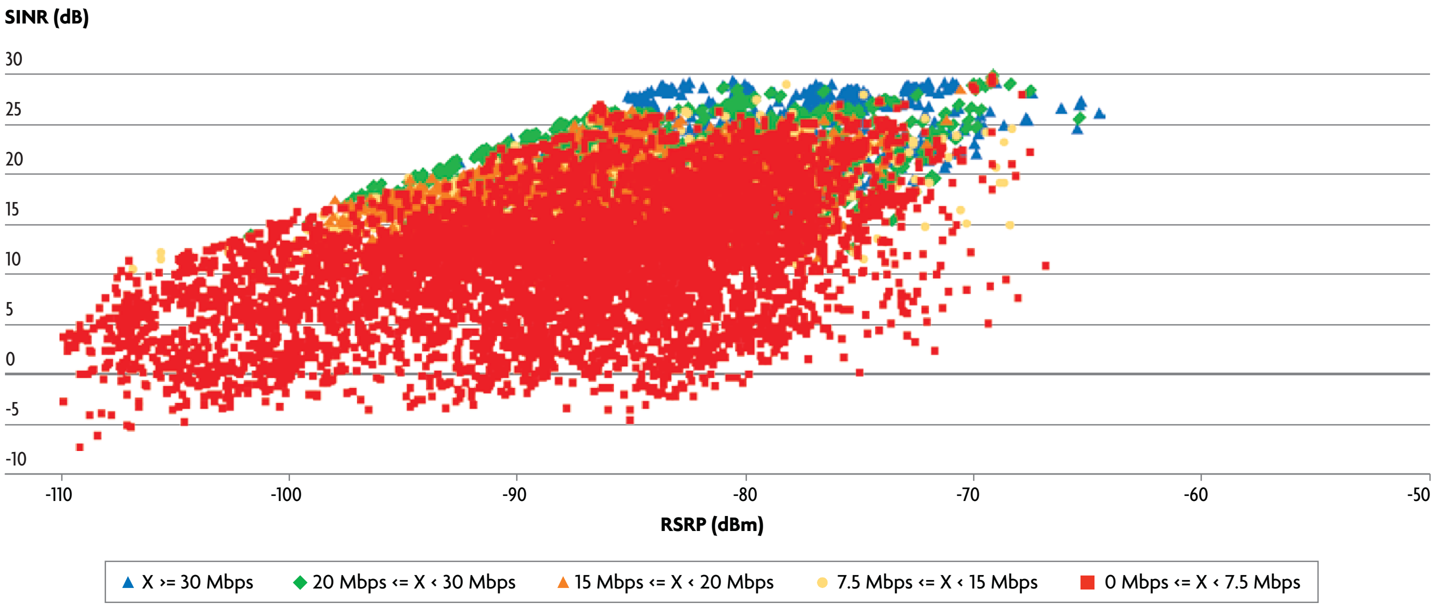
Source: Signals Research Group

Figure 42. LTE FDD 10 MHz RSRP Versus SINR Versus Code Word #1 Throughput – scatter plot



Source: Signals Research Group

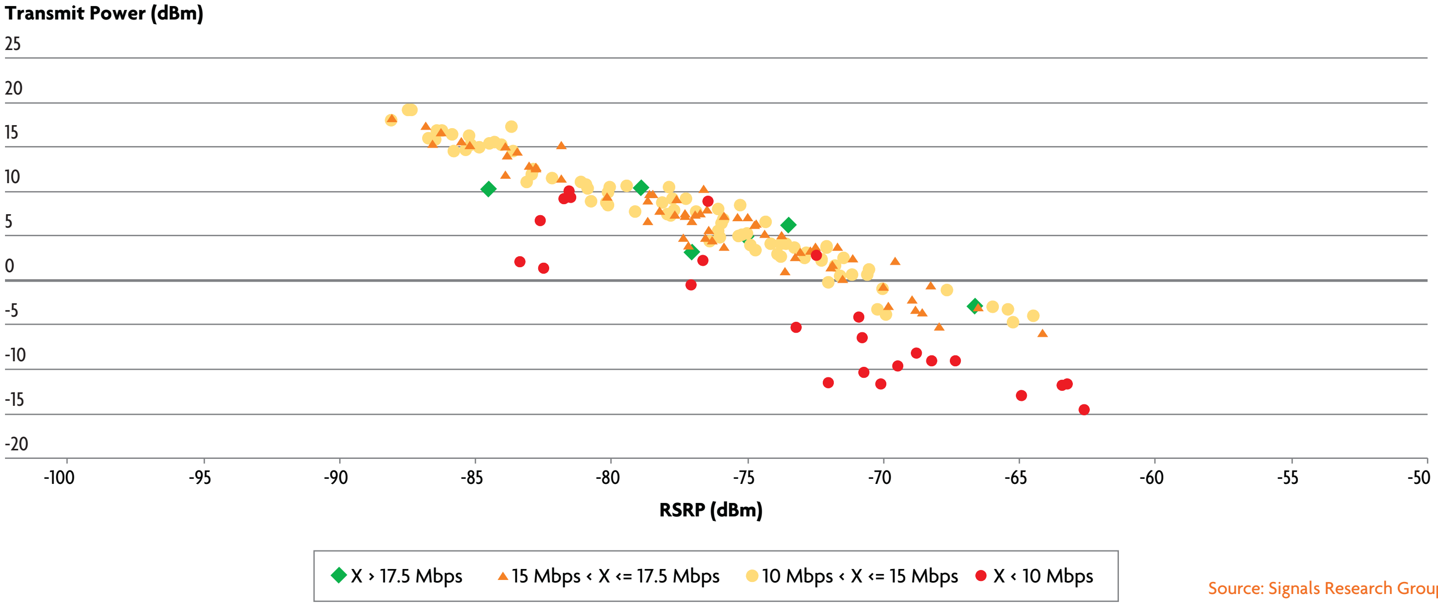
Figure 43. LTE TDD RSRP Versus SINR Versus Code Word #1 Throughput – scatter plot



Source: Signals Research Group

Figure 44. Transmit Power as a Function of RSRP with Corresponding Throughput Values of LTE FDD 10 MHz during Cell Handovers – scatter plot

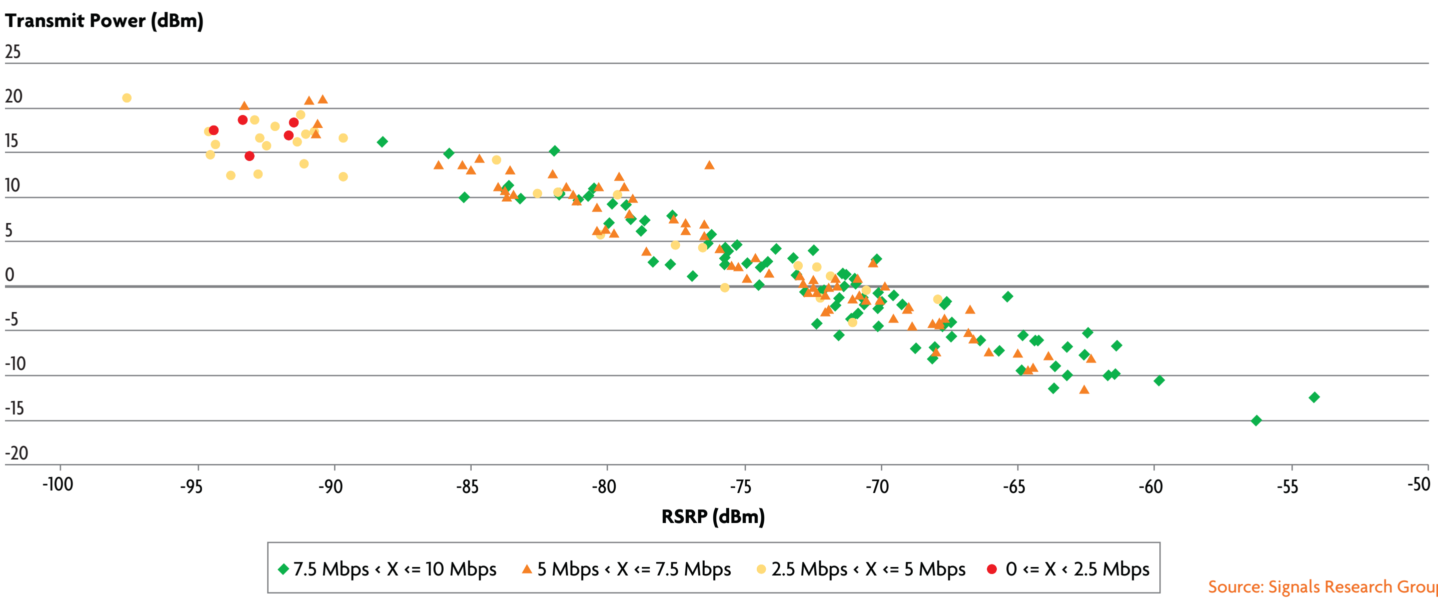
Uplink Phy Layer Throughput (Avg) = 12.8 Mbps
PUSCH Transmit Power (Avg) = 5.7 dBm
RSRP (Avg) = -76.5 dBm



Source: Signals Research Group

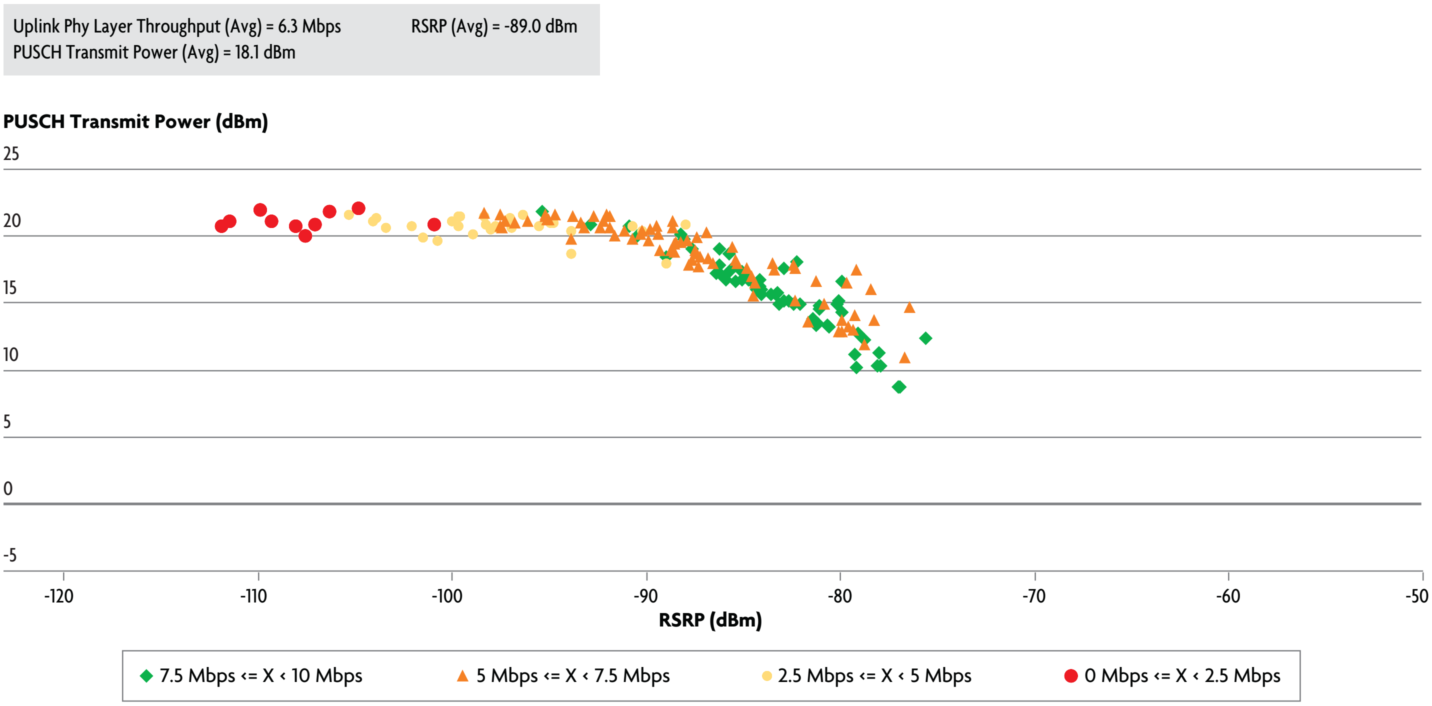
Figure 45. Transmit Power as a Function of RSRP with Corresponding Throughput Values of LTE FDD 5 MHz during Cell Handovers – scatter plot

Uplink Phy Layer Throughput (Avg) = 6.8 Mbps
PUSCH Transmit Power (Avg) = 3.5 dBm
RSRP (Avg) = -75.8 dBm



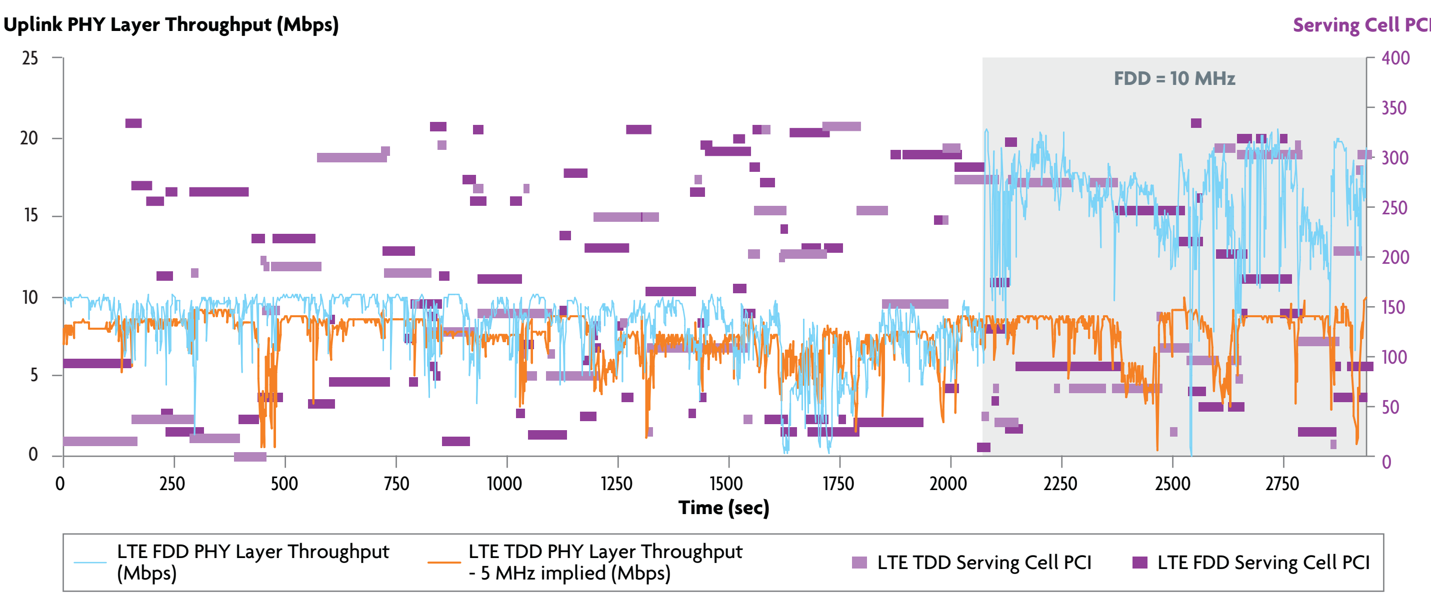
Source: Signals Research Group

Figure 46. Transmit Power as a Function of RSRP with Corresponding Throughput Values of LTE TDD during Cell Handovers – scatter plot



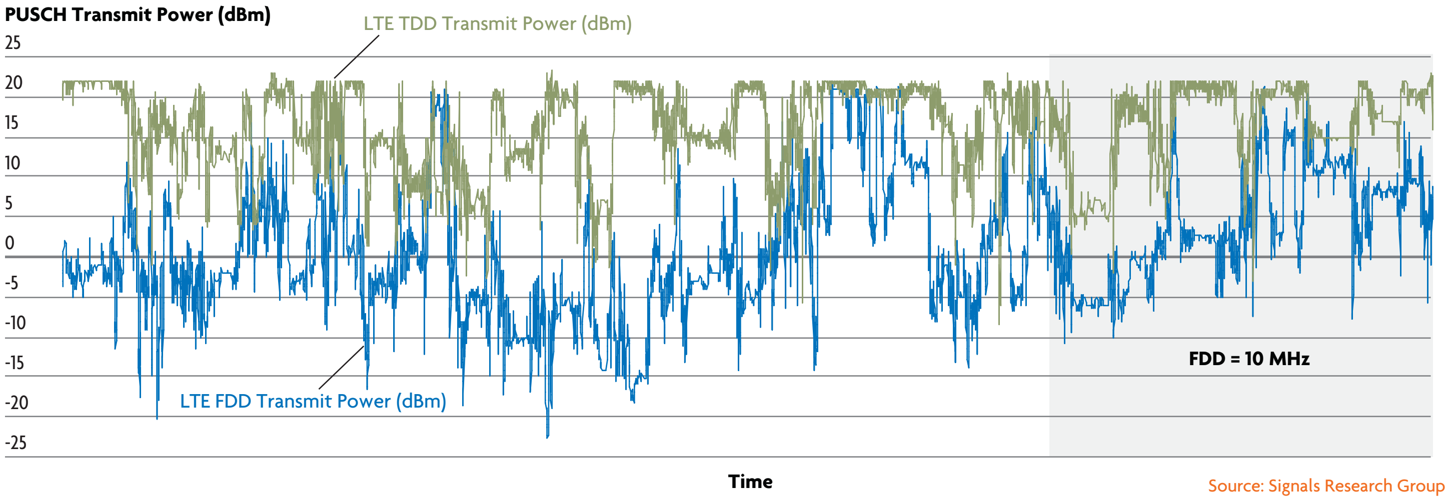
Source: Signals Research Group

Figure 47. Uplink Physical Layer Throughput for LTE FDD and LTE TDD versus Serving Cell PCI Values – time series plots



Source: Signals Research Group

Figure 48. Transmit Power for LTE FDD and LTE TDD versus Serving Cell PCI Values – time series plots



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