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Analysis of LTE network RF performance in a dense urban environment

Nicholas Krawczeniuk
B.S., Computer Science

Advised by

Miguel Mosteiro, Ph.D.
Department of Computer Science
Seidenberg School of Computer Science and Information Systems

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Abstract

The issue of interference in LTE networks and wireless networks, in general, is an important one. Wireless is a finicky paradigm to operate communications in when compared to wired networks. There are issues of loss, reflection, timing, and interference within all networks however, wireless adds a randomness to communications that makes it challenging to control. For mobile networks like LTE to reach their goal of true mobility, service must be nearly everywhere and be able to operate even in the worst possible case. Examining the literature, I found many sources of possible interference in both FDD and TDD-LTE networks. I also examined how these causes of interference can affect mature heterogeneous LTE networks especially those in urban areas that have been designed to support large amounts of traffic. These materials perfectly outline the problems faced in the urban networks of the four carriers in New York City. The tools I used to create this analysis were comparable to those used by radio frequency engineers at the major wireless carriers. I also tapped my experience in one of these roles (in an internship capacity) to make recommendations as to what the carriers could do to improve their networks. My findings concluded that in areas of high population density, the four carriers still need to further optimize their networks signal-wise in order to deliver high performing wireless services where users concentrate. Future research would include making improvements and then testing the impact they have on key performance indicators within the networks.

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Introduction

It should be noted that I will be approaching network performance as a fully external, third-party analyst. To perfect this report, it would be necessary to have network configuration and key performance indicator information which is only available to the network engineering employees at each network operator. This information is not shared with third parties including professional auditors like RootMetrics, who is contracted to report network performance data and regularly consults with the network teams at each operator on performance. The wireless industry in the US is very secretive and for good reason. Operators rarely directly collaborate on shared infrastructure projects and maintaining their own networks in such a way as to outshine the others is a wonderful game of cat and mouse. Network optimization, especially when it comes to coverage and quality of service, is a key differentiator in keeping subscribers happy and loyal.

New York City being the largest market in the United States as well as the location of the corporate headquarters of Verizon Communications is one of the most important places for wireless networks in the country and requires network performance to act like it. Technologies that sometimes hit other parts of the country years later are deployed here first without hesitation. Operators regularly boast about their performance in New York through press releases and news snippets on industry blogs. Third party companies like RootMetrics and Nielsen regularly drive and walk-test the market with off-the-shelf devices to audit network performance here and create reports for both consumers and network engineering teams alike.

The trouble with these reports is typically granularity. While these third parties release the routes they walked or drove and the venues they visited, they do not repeat these examinations at different times of day to confirm consistent performance. Especially during times of peak network load in areas of high population density. This analysis aims to fix that by using population density data to select locations for closer examination. Unlike the third party companies, the report will also be providing specific recommendations on network adjustments rather than just presenting the findings and leaving it up to the reader to make up conclusions about how to improve service with interference analysis being the key topic examined due to its never-ending prevalence in the world of wireless.

Literature Review

In my research, I focused my attention towards more advanced interference studies in LTE networks that used propagation models and data from live networks. Using these papers as guidebooks, I tailored my methodology to fit the tools I had at my disposal. In Chamorro et al., (Chamorro et. al. 2018) the authors focus on issues related to interference within heterogeneous LTE networks, or LTE networks that have more than one type of cell site/transmitter involved in them. Specifically, they hone in on the issue of home femtocells and their interactions with macro cell sites at the cell edge. Home femtocells are commonly used in the US by all four carriers and are usually the main option for customers who find that coverage is lacking in their home. Often they are right on the edge of service, at the cell edge of two different cell sites, or are in an area where there is simply no coverage at all.

Chamorro et al. examine the issue of a femtocell at the cell edge and use the ICS Designer tool to create coverage plots of a mock network in Barcelona, Spain. The mock network contains 11 femtocells and one macro cell site. The macro cell site is sectored using antennas with a beamwidth of 120° while the femtocells utilize a much less efficient omnidirectional antenna (Chamorro, Reyes, & Paredes-Paredes, 2018). Such a configuration is not uncommon among live networks especially those using LTE UE Relay technology where the goal is to specifically enhance coverage. The authors focused only on downlink scenarios due to the limitations of their design tool (Chamorro et al., 2018). By comparison, my work avoids this all together by examining a live network and its uplink traffic using a spectrum analyzer. Chamorro et al. focus on three measurements: RSSI (Reference Signal Strength Indicator), RSRQ (Reference Signal Received Quality), and SINR (Signal to Interference plus Noise Ratio). RSSI, while used in other technologies, is helpful in LTE for measuring the signal strength across an entire channel instead of only the resources allocated to a device. RSRQ and SINR are measures of the quality of the signal being received by a device. SINR is particularly important in heterogeneous networks as discussed later on in this thesis.

Because of the high variability of radio frequency environments, models for propagation of wireless signals are standardized and used to design and construct wireless networks. These models are composed of terrain maps as reported by various governments as well as other GIS data sourced from the appropriate entities. Models for "clutter" are also used to simulate certain environments like urban, suburban, and rural spaces. The International Telecommunications Union as well as the 3rd Generation Partnership Project have both defined models that Chamorro et al. use in their paper. Specifically, ITU 525, a free space attenuation model and the 3GPP LTE

Urban Propagation model were used (Chamorro et al., 2018). The authors virtually simulate an environment where the femtocell is very close to the center of the cell site just a few hundred meters away.

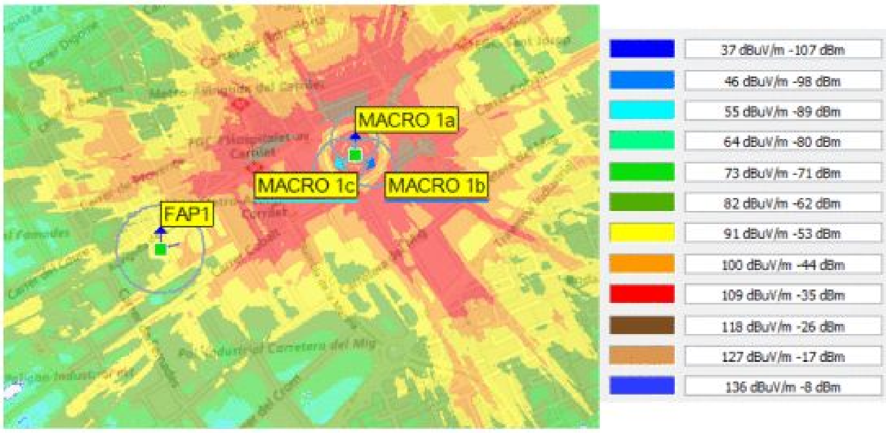

Fig. 1. FAP1 defines the femtocell site while MACRO 1a, 1b, and 1c define each sector of the macro cell site. The legend defines radiated power measurements as well as the RSSI at those radiated powers. (Chamorro et al.)

This first scenario in Chamorro et al. examines a femtocell overlapping a macrocell causing interference on the downlink at a device connected to the femtocell. The signal strength of the macro cell is so large that it inadvertently drowns out the femtocell causing its coverage to vary. SINR on the macro cell site sector directly facing the femtocell experiences the greatest loss in performance because of its orientation. Femtocell performance is also poor in this area. However, when moving further away from the macro cell site while still remaining within the coverage of the femtocell, the authors found that SINR improves greatly. RSSI, however, stays relatively constant and at reasonable levels due to this coverage overlap. RSSI is the only thing that won't perform well in such a situation (Chamorro et al., 2018). The second scenario tested includes a femtocell installed at the edge of the macro cell (much farther away than the first). This would be an optimal case for installation of a femtocell as the user's coverage from the macro network would be relatively weak. However, issues with clingy devices do plague operator's networks and this scenario takes this into account by having a device stay connected

to the far away macro cell even when it comes within coverage of the femtocell. The result is poor signal quality and SINR when connected to the macro cell site (Chamorro et al., 2018). These three scenarios are the most relevant to my examination of service in high-traffic locations because they are the most likely to occur in a dense urban environment like Manhattan with certain effects even being amplified due to small cell/femtocell locations sometimes being within line of sight to the nearest macro cell site(s). Such a scenario is present in two of the locations I cover in my examination and is likely a key issue causing unstable performance at one in particular.

Černý and Masopust (Černý and Masopust 2017) discuss the interference mitigation techniques that have been developed for the LTE standard in their paper *Interference optimization and mitigation for LTE networks*. The techniques covered in this paper are very commonly used in commercial LTE network development. Specifically, the authors cover adaptive frequency reuse, power control, MIMO, and beamforming. All are currently in use by AT&T, Sprint, T-Mobile, and Verizon in Manhattan in some form. One common issue that has plagued cellular wireless networks has been the issue of frequency reuse. In the era of AMPS, and later GSM, each sector of a cell site used a specific wireless frequency to communicate with each user. Cell sites would commonly have three sectors each of which would have its own frequency. Because each had their own frequency, site 1 with sector 1 with frequency A could overlap the coverage of site 2 with sector 2 with frequency B without any interference happening as illustrated with the diagram below:

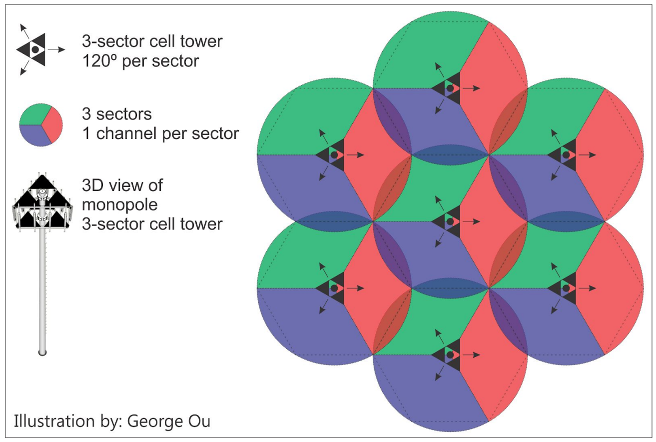

Fig. 2. The "Cellular" model, illustrated by George Ou

This model was fine for older technologies in times when cellular devices were less common and certainly less traffic-intensive. However, as the number of cellular users grew, so did the need to use allotted channels more efficiently. Today, LTE has revolutionized this with adaptive frequency reuse. Rather than have a channel, or path for transmitting or receiving data, dedicated to each sector of a cell site, LTE cell sites use all channels on all sectors at every cell site. This presents an issue of interference however, if all sites in a network are using the same channel to transmit. The problem becomes even more important if they are in close proximity to one another or, in the case of modern day urban networks like the ones examined in New York, transmitting inside the coverage areas of one another. Adaptive frequency reuse combats this issue by adjusting the network to more accurately accommodate individual devices. As Černý and Masopust state, *"The network can dynamically adjust to any situation... When the eNodeB receives information about mobiles located near the cell borders with low SNR on the downlink, the eNodeB changes the frequency reuse scheme and gives information about it to neighboring cells to do the same... It means that the whole frequency band is used to cover the centre of the*

cell ensuring maximum data rate. The problematic areas around cell borders are served by a part of the frequency band, which is different in each of 3 neighborhood cells." (Černý & Masopust, 2017) The authors state that this kind of reuse can improve SINR even in high-density areas by as much as 10 dB (Černý & Masopust, 2017).

Power control is another technique often used to adjust coverage and optimize performance in LTE networks. Černý and Masopust examine two techniques of power control that aim to help device battery life as well as conserve energy. Open and Closed Loop Power Controls are algorithms on the device-side that determine the correct transmission power to use based on situational conditions like path loss. They also take regular measurements of the device's SINR conditions and report it to the eNodeB every 20 milliseconds and then tell the device to adjust its power accordingly. A fractional power control scheme is also implemented to allow device transmission power to be lower than needed even in situations of path loss. Using fractional power control schemes can allow throughput of a cell to increase by up to 40% especially for cell edge users (Černý & Masopust, 2017).

MIMO, or multiple-input multiple-output, is another technique mentioned by Černý and Masopust that helps combat interference within the network. Not only does it help with interference but it also greatly increases throughput even in good network conditions. MIMO allows for multiple data streams to flow through multiple antennas on either side of the connection creating a more robust signal and drastically improving throughputs.

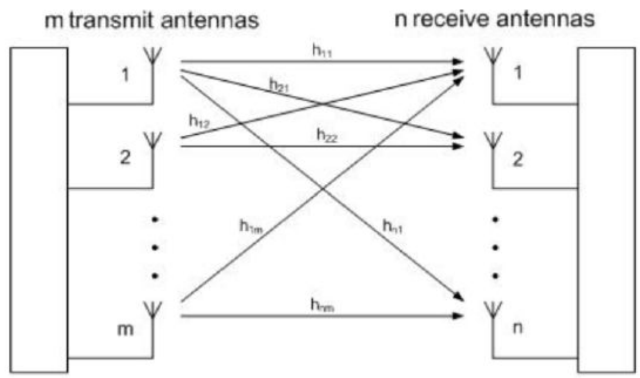

Fig. 3. (Černý and Masopust) The connectivity between a transmitter and a receiver in a typical MIMO setup up to n antennas where, to reap the full benefits of MIMO, m and n are equal. Each h in the diagram is a separate spatial stream being received/transmitted.

The benefits of higher-order MIMO on a network are numerous as it allows carriers to offer better service even to older devices further increasing network efficiency. Initial LTE networks offered a “2x2” setup indicating two antennas were dedicated to transmission and two were dedicated to reception. This was also the case on the device side. Now, with today’s networks and devices, “4x4” MIMO is a more common capability. 4x4 MIMO installation and activation can improve service for 2x2 MIMO cell edge users because, even though such devices are older or more limited, having four antennas to receive signals on the macro cell site side means device uplink transmissions are more likely to be received, and a device is able to stay connected to the network and receive some form of service, rather than be left with an unstable connection or being forced to fall back to an older technology. For devices that have 4x4 MIMO capability, service in areas of high interference is improved for the same reasons a cell site is able to better “hear” a 2x2 MIMO device transmitting.

As mentioned in my methodology, I will be using the Moto X4 which is 2x2 MIMO-capable. While many higher end devices today are compatible with 4x4 MIMO today, it

is important to note that a majority of devices on the market are still using 2x2 MIMO. Real world testing must reflect this as it leads to an inefficiency in the use of network resources and a notable loss of performance compared to if all devices on the network were using 4x4 MIMO.

The possibility of network interference and performance issues at the air interface permeate throughout. This is shown specifically in *Interference analysis and performance evaluation for LTE TDD system*. While most operators in the United States don't currently utilize a TDD-LTE system in most of their markets, its use is becoming more prevalent as network needs change and the FCC distributes spectrum in new ways that depart from the common block-pair system with TDD becoming more important in upcoming 5G mmWave and high-midband networks. TDD offers increased spectral efficiency to the more commonly used FDD standard and one operator in the US, Sprint, does use it quite heavily due to the breakdown of their 2.5 GHz EBS/BRS spectrum holdings. The authors explore TDD interference issues from a network design perspective in section two of their paper. They outline intra-cell interference, inter-cell interference, self-noise, and crossed timeslot interference as the biggest threats to TDD-LTE systems. TDD systems require great precision in their timing of transmissions over a slice of spectrum because their spectral efficiency comes from using one channel to both transmit and receive data from the device and the cell site. These transmissions are separated in time. This is in contrast to FDD networks which use separate channels for downlink and uplink transmissions allowing a device to transmit at the same time it is receiving data from a cell site and vice-versa.

The authors discuss the issue of self-noise in TDD systems as being caused by timing problems. LTE uses the OFDM digital signal modulation scheme to maximize efficiency and

create as many subcarriers as necessary for data to be transmitted on. These subcarriers are spaced at 15 kHz each. Each subcarrier overlaps; however, this overlap does not cause interference within the system. Instead, the overlapping portion of the subcarriers cancels each other out leading to lower interference while gaining higher network performance. This overlap "at right angles" is the source of the O in OFDM which stands for orthogonal. When using a real world system, the authors note there are likely to be slight issues in timing of the TDD system leading to issues with synchronization and channel estimation (when the eNodeB is able to "guess" the channel conditions based on that of the device's uplink channel conditions) (Pei Chang et. al., 2010) (Lauro 2019). This failure in timing leads to subcarriers overlapping each other more than they should causing them to become less orthogonal and leading to worse network performance. This is, of course, worsened in conditions of poor SINR (Pei Chang et. al., 2010).

Intra-cell interference is also a major issue relating to the design of LTE networks. Within a common macro cell site, there are multiple sectors installed. Each sector is designed to provide coverage in the general direction it is pointing. This direction is determined by an azimuth set when designing the site in either an area gaining new coverage or fitting the site into an existing network for the purposes of adding capacity. Cell sites can have many sectors in order to create added capacity, guarantee coverage in specific locations, or both. As network usage grows, a cell site with three sectors might grow to have six or more depending on its location. Multi-sector designs are becoming increasingly common in urban areas where capacity is needed. While the boost in capacity is great, the issue of interference becomes more and more prevalent as the authors note. Intra-cell interference does exist in real world systems when

orthogonality is broken (as with the timing issues in self-noise). Having resource blocks shared among devices in multi-user MIMO schemes also causes intra-cell interference to become a greater concern (Pei Chang et. al., 2010). The other issue of inter-cell interference is also common within TDD systems and the authors note four scenarios in which inter-cell interference would occur and cause performance to worsen: when a device receives interference from a neighboring eNodeB, when an eNodeB receives interference from a device, when a device receives interference from another nearby device, and when an eNodeB receives interference from another eNodeB (Pei Chang et. al., 2010). Problems of received interference continue to plague TDD networks and improvement in the design of networks where these are common issues will result in lessened interference.

The final interference issue the authors discuss is the problem of cross timeslot interference. As previously stated, TDD-LTE divides transmissions in time so timeslots dedicated to downlink and uplink. There is also a special slot dedicated to transmissions of control data which facilitates device handoffs within the cell site and between cell sites as well as requests and receives data on the device's current network conditions. A table of the seven different configurations is shown below:

Uplink-downlink configuration	Downlink-to-Uplink Switch-point periodicity	Subframe number									
		0	1	2	3	4	5	6	7	8	9
0	5 ms	D	S	U	U	U	D	S	U	U	U
1	5 ms	D	S	U	U	D	D	S	U	U	D
2	5 ms	D	S	U	D	D	D	S	U	D	D
3	10 ms	D	S	U	U	U	D	D	D	D	D
4	10 ms	D	S	U	U	D	D	D	D	D	D
5	10 ms	D	S	U	D	D	D	D	D	D	D
6	5 ms	D	S	U	U	U	D	S	U	U	D

Figure 4. TDD frame configuration options (Keysight Technologies)

Cross timeslot interference occurs when uplink and downlink transmissions collide. A device might be attempting to uplink on the same timeslot as a neighboring TDD cell site is trying to downlink resulting in a collision and strong interference. This issue can be exaggerated when using multiple frame configurations for the network in the same locale. Neighboring cell sites with different configurations will have different downlink and uplink timing leading to near unavailability of the network. As Wang et al. conclude, demodulation is impossible because SINR becomes even worse than -20 dB. Devices are no longer able to use the network at such a level of SINR. These three possible sources of interference in TDD systems are crucial to evaluating the performance of the networks I will be examining. Specifically the Sprint 2.5 GHz LTE band 41 network. Evaluating the performance of this part of the Sprint network keeping in mind these sources of interference is crucial. Examining network performance while only considering FDD interference factors would not be proper methodology when viewing a TDD system.

Methodology

For this project, I used a software-defined radio as a spectrum analysis tool to view downlink and uplink transmissions of the four major LTE, or Long Term Evolution, networks in New York City. These networks are built and managed by AT&T, Sprint, T-Mobile, and Verizon along with partner organizations like Transit Wireless. A software-defined radio approach was chosen for this project rather than using a conventional off-the-shelf WiFi network because of the flexibility they provide. Software-defined radios - or SDR's - do what their name implies and provide a radio that can transmit and receive signals based on the software applied to them. The

SDR literature has a vast number of projects that can allow a user to run nearly any wireless technology from their radios. SDR's are able to receive many different kinds of signals and utilize many different technologies because of their capabilities in a wide range of the radio frequency spectrum. The radio used for this project is the Ettus Research USRP-B210. It is rated for use on all frequency bands from 70 MHz to 6 GHz. Such a range covers everything from the FM band, used for audio broadcasting, to 6 GHz, which is home to fixed wireless connections. It was coupled with two Ettus Research VERT2450 omnidirectional antennas. Using two antennas to search for spectrum is optimal because it best simulates the setup of a consumer device capable of 2x2 MIMO as nearly all LTE devices are.

The SDR will be driven by software running in a Ubuntu virtual machine environment within macOS Mojave. The spectrum analysis software I have chosen for the project is the Osmocom Spectrum Browser. It provides a set of capabilities comparable to a typical real-time spectrum analyzer that one might find available to carrier's radio frequency engineering teams as well as in radio and communications research laboratories. Osmocom Spectrum Browser allows for adjustment of gain, sampling rate, bandwidth, as well as center frequency. I also used a newly purchased Android device, the Motorola Moto X4, as a network testing device.

The Moto X4 is a low-cost Android device running Android 9.0 Pie. It is built on the Qualcomm Snapdragon 630 processor and uses 3GB of RAM. The Snapdragon system-on-a-chip is important to this project because of its LTE modem. The X12 modem used by the Moto X4, while slightly dated, is more than capable of accessing all of the necessary frequencies that modern day LTE networks in the United States use. It is also capable of aggregating up to three LTE carriers at once allowing for theoretical download speeds of 600 Mbps (assuming 256

QAM). This modem also has all of the primary 3GPP frequency bands for the four national carriers in New York. Using this device, I conducted measurements of various LTE reference signal performance indicators to show radio frequency performance on each network at a given time of day.

Measurements were taken using the Network Signal Guru app from QtRun Technologies. Network Signal Guru, when combined with root access to control a device's Qualcomm modem, is an incredibly useful tool equivalent to the industry-standard TEMS Pocket, Accuver XCAL Solo, and Rohde & Schwarz QualiPoc tools used by RF engineering teams at all four major carriers. I will be looking at three main measurements in this thesis - RSRP, SINR, and RSSI. Each has its own specific use in LTE networks. RSRP, or Reference Signal Receive Power, is the measured received power across the bandwidth of an LTE carrier allocated to a specific device in the form of resource blocks. RSRP is the most accurate measurement of LTE "signal" in a given location. It's accuracy comes from measuring based on allocated resource blocks at a given location during a given time gives an accurate representation of service with multiple users on a network. Resource blocks, or groups of frequency resources assigned to devices, are allocated dynamically in LTE on a per-frame, or per-time period, basis and are only allocated if a device is using them. Therefore, taking a measurement of received power of only the resource blocks allocated to a device at a given time is a more accurate measurement relative to performance.

The second measurement I looked at is SINR. SINR is a measure of the amount of interference that the network causes to itself as well as the general electromagnetic noise floor present on the frequency bands it is running on. SINR is a key performance indicator in LTE

because a network that has an high SINR in a majority of its coverage area will subsequently perform well both coverage-wise and reliability-wise. Network features like higher-order quadrature amplitude modulation or QAM - a technique used to communicate more bits per transmission - lead to a 33% gain in spectral efficiency over previous QAM, allowing users to be better served while on the network (Howald et. al., 2009). The better the SINR across the network, the higher the number of users using higher order QAM leading to a major gain in network efficiency. SINR optimization is important for the overall health of the network setting aside the benefits that can be gained from QAM. In urban environments, SINR optimization becomes much more difficult because of two main factors: a more dense, often heterogeneous network and more users moving traffic over the network. The networks of the four major carriers in New York are a perfect example of this.

The Manhattan cell grid is hugely dense, along with the rest of the city leading New York to be one of the best-performing cities for wireless infrastructure in the US. Consequently, because of the massive population in the city, carriers have invested heavily in the latest technologies to ensure high quality of service. In particular, this includes small cells and distributed antenna systems. In addition to the rooftop-mounted sites, network infrastructure is also installed on light poles and inside buildings to allow for better capacity and guarantee proper coverage even inside massive steel structures. Controlling the SINR of all of these different elements in the network, especially when coverage between each of the elements often overlaps, is a challenge that engineers are careful not to ignore.

The third and final measurement on the Moto X4 I looked at is the RSSI. The RSSI is a measurement of received power across the entire bandwidth received. Not just a few resource

blocks. Reading RSSI is more of just an exercise in coverage. If the RSSI is low, then RSRP is going to be even worse. Indeed, RSSI is used to calculate the RSRP using the equation RSRP = RSSI - 10log(12N) where N is the number of resource blocks based on the LTE carrier size. The areas where I conducted measurements and analyzed spectrum in are not ones without signal however because RSSI can influence RSRP. It is important to check to make sure that each value is the expected one based on the other.

To choose locations for this project, I used the Manhattan Population Explorer map and data visualization model developed by Justin Fung (Fung 2018). The map displays population density data over the course of a week at specific times of day. This data is sourced from the MTA's free turnstile information database distributed in plaintext format as well as spatial data from the CUNY Graduate Center's mapping and GIS service (Fung 2018). The NYU Wagner Center also contributed estimations on the upper bounds of populations during each time of day. Using this data, I targeted areas that saw the highest change in population based on time of day. With the exception of one, my location choices leaned heavily on stations within the transit system as these tend to concentrate large groups of people at very specific times of day and then are nearly deserted at other times leaving a more noticeable dichotomy when all the data is assembled. The final list of indoor locations included New York Penn Station and the World Trade Center PATH station. Outdoor locations included Union Square and Queensboro Plaza. All four of these locations experience dramatically different network conditions in terms of total tonnage, or traffic carried, on both the downlink and uplink. Each location also has varied network setups causing service to act differently at each. These setups will be covered later in the thesis when detailing the results of my findings.

Using the tools mentioned above, I collected data using screen recording and capture software already installed on each device. I analyzed walk test logs from Network Signal Guru to ensure consistency of the readings I've taken. Use of walk-testing also places my methodology more in line with industry standard practices at the four national carriers. The table below describes the ideal ranges for each of the three aforementioned measurements:

	RSRP (dBm)	**RSSI** (dBm)	**SINR** (dB)
Great	-90 to -30	-85 to 0	15 to 40
Acceptable	-105 to -90	-95 to -85	-3 to 15
Poor	-140 to -105	-130 to -95	-30 to -3

Table 1. Baseline ranges for RSRP, RSSI, and SINR

RSRP and RSSI use dBm or decibel-milliwatts because they are reference signals based on the received power by the device. In fact, dBm measure the number of decibels as a ratio to one milliwatt of power. On the other hand, SINR is measured in decibels alone because it is the difference in decibels between the received signal power and the network interference and noise floor.

Results and Recommendations

My examination of New York's wireless infrastructure across the four major networks yielded somewhat varied results in the way of LTE RF network performance. The locations tested - New York Penn Station, WTC PATH Station, Union Square, and Queensboro Plaza - were all covered by the four major network operators. Covered in this sense means that a

customer would be able to use LTE data and place or receive a VoLTE call as expected. However, all four networks were not equal in these locations. RSRP, RSSI, and SINR all varied from network to network with performance on each being somewhat distinct even in conditions where one might not expect that to be the case.

While it might seem more appropriate to consider this a performance report of wireless service at transit system stations, these four locations are hubs that cater well outside the needs of just local transit riders. Union Square sees foot traffic from shoppers, tourists, office workers, students, residents, and others. Its park hosts events of all kinds during all seasons. All of this in addition to a major hub for the NYC subway on Manhattan's east side. The WTC PATH station is directly underneath 1 World Trade Center and is itself a tourist attraction due to its unusual architecture. It plays host to a high-end mall and connects with the NYC Subway Fulton St Station - another major transit station. An underground pathway connects it to Brookfield Place, a separate high-end mall, food court, and office space for major corporations as well. New York Penn Station serves mostly as a transit hub with a few eateries and stores however its national reach with connections to Amtrak makes it unique. The station is also owned by Amtrak and thus has network infrastructure that is not cohesive with the rest of the transit systems in New York. Queensboro Plaza is another transit hub and a purely local one at that. However, it differs from Penn Station and WTC PATH in that it is fully elevated and the Long Island City neighborhood it serves is in a period of rapid growth and construction. New construction is constantly happening in cities and building materials and locations change how the networks perform in a given area not only by altering the coverage (new buildings block and reflect signal in new ways

not previously accounted for in the network design) but also by creating capacity needs as tenants move from elsewhere into their new spaces.

Penn Station

New York Penn Station is the regional hub for four major transit systems. Locally, it offers subway service on six different lines. Regionally, it is a major station for NJ Transit and Long Island Rail Road commuter trains. Nationally, it offers service via Amtrak with service on one of the nation's only high-speed rail lines. The Regional Planning Authority notes that while Penn Station's original design capacity was for a weekday ridership of 200,000 people, it has far exceeded that reaching an average weekday ridership of 650,000 (Regional Planning Authority 2018). While examining network usage during rush hour inside Penn Station, the results were not unexpected.

The station's location underneath Madison Square Garden means it requires some kind of alternative coverage solution to guarantee service where customers expect it during their journey. Inside, I was able to spot indoor distributed antenna systems (DAS) for three of the four major networks specifically AT&T, Sprint, and Verizon. Each network has designed its own DAS for the station including separate antennas to adequately cover specific areas. Interestingly, the carriers have also taken to labeling their antennas with their logos. A rare move for infrastructure that generally attempts to keep a low profile. Notably absent from Penn Station's main concourse was infrastructure for T-Mobile. Unlike Transit Wireless in the NYC Subway system, Penn Station does not have shared wireless infrastructure leading each carrier to build out their own antennas systems. AT&T and Verizon have opted to use typical omnidirectional ceiling mounted

antennas for their system while Sprint opted to use directional ones leading to indoor coverage being focused in specific areas while still allowing for general coverage throughout the station. The absence of a DAS for T-Mobile is not completely unprecedented as service from outdoor macro sites and the Transit Wireless DAS installed for the NYC Subway stop bring moderate coverage onto the main concourse. However, LTE band 4 service available on T-Mobile's AWS spectrum, falling in the 2100 MHz and 1700 MHz bands is limited compared to the other AWS user in New York, Verizon. The figure below illustrates this weakness even with a heightened gain of 64 dB from the spectrum analyzer.

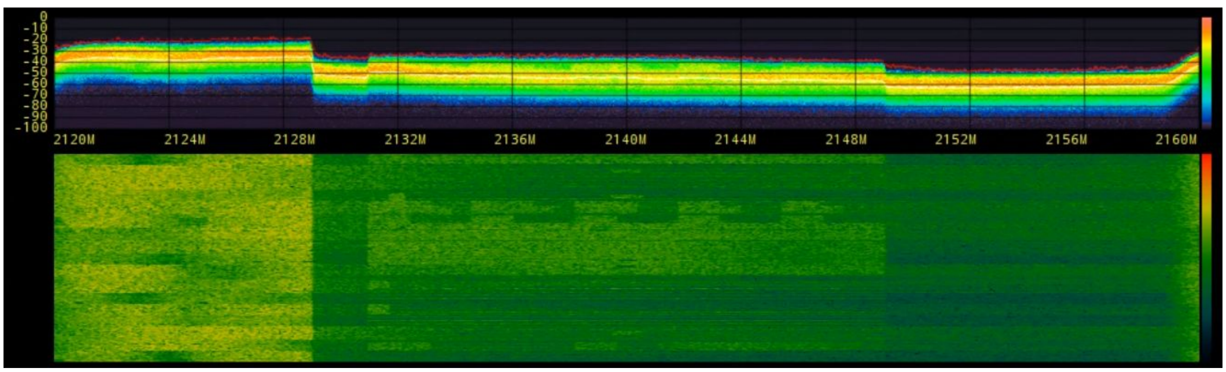

Fig. 5. Verizon (center freq. 2120 MHz) vs. T-Mobile (center freq. 2140 MHz), downlink-only.

RSRP, RSSI, and SINR averages for the carriers with DAS present fell into the "great" range generally. Because of the proximity of the antennas to my spectrum analyzer and test device, RSSI and SINR were especially strong while RSRP was strong but could have been reproducible outdoors with a macro site.

B# denotes 3GPP frequency band number	**AT&T**	**Sprint**	**T-Mobile**	**Verizon**
RSRP (dBm)	B2: -75 to -69 B5: *N/A* B12: -60 to -50	B25: -77 to -69 B26: -60 to -53 B41: -80 to -73	B2: -118 to -112 B4: -114 to -110 B12: -105 to -102	B2: -110 to -108 B4: -78 to -70 B13: -60 to -50
RSSI (dBm)	B2: -35 B5: *N/A* B12: -30	B25: -36 B26: -30 B41: -39	B2: -79 B4: -75 B12: -65	B2: -75 B4: -40 B13: -30
SINR (dB)	B2: 15 to 23 B5: *N/A* B12: 13 to 22	B25: 16 to 25 B26: 12 to 22 B41: 20 to 26	B2: -3.0 to 0.7 B4: -2.6 to 1.0 B12: -2.0 to 0.7	B2: 3.0 to 7.0 B4: 15 to 22 B13: 13 to 20

Table 2. Penn Station recorded RSRP, RSSI, and SINR values by carrier and frequency band

T-Mobile did not perform as well and my test device often fluctuated between LTE band 4 (AWS) and band 12 (700 MHz). Availability of LTE band 2 was limited indoors. Verizon's DAS had LTE band 4 and 13 installed allowing those bands to produce results on-par with Sprint and AT&T however their band 2 network seemed to either be coming from an outdoor macro site or the Transit Wireless DAS resulting in worse performance when compared to its other two frequency bands. AT&T's dual-band DAS produced solid results however LTE band 5 was not yet present at this location. This is either due to the spectrum still being used to support AT&T's 3G HSPA+ network or macro sites outdoors not yet broadcasting the band.

At this location, improving service to keep up with network demand at Penn Station is "easy" for T-Mobile. The best path to improvement with the least amount of design and construction work would be to reach an agreement with Verizon or AT&T to share antennas while setting up separate infrastructure such as eNodeBs and remote radio heads to support their network. However, this could be costly and getting permission from other carriers poses a

problem. It has been done before but, generally, sharing infrastructure with other carriers is best done through a neutral-host vendor that is impartial to competition in the wireless market. Neutral-host vendor agreements mean carriers can share infrastructure owned by the vendor while getting cheaper access to said infrastructure and faster, more consistent maintenance of the equipment. This is to say nothing of the red tape and right-of-way that would be needed from Amtrak in order to add service. T-Mobile's other option would be to construct a DAS on their own as the other carriers have done albeit with more red tape and leasing costs from Amtrak as well as time-consuming design and intrusive construction work. Improving Verizon service is a much more simple project that would require only the addition of new band 2 remote radio heads to their existing DAS. Antenna replacements might be necessary depending on the capabilities of the existing hardware but because hurdles with Amtrak leasing are already cleared, construction aspects of the project could be completed in a matter of hours or days.

World Trade Center PATH Station

The World Trade Center PATH station sees about 62,000 commuters per day (Port Authority of New York and New Jersey 2019). While this is higher than all of the other Manhattan PATH stations combined, it might sound low when compared to Penn Station and even many NYC Subway stations. However, this station has connections to Fulton St as well as the newly reopened WTC-Cortlandt St station. This in mind, transit ridership through this location is much higher than the Port Authority's numbers might indicate. Keeping in mind all the tourist traffic due to the site's unique architecture and high-end mall, it's not hard to see how important wireless service is here. Thankfully, the station and surrounding complex have a

neutral-host DAS in place that is more than capable of handling the large amount of traffic. The DAS was designed and installed by Boingo Wireless as part of the construction of the Oculus complex and PATH station, both of which are owned by Port Authority (Port Authority of New York and New Jersey 2014). Boingo's neutral-host position has allowed all four carriers to install their equipment within the station and share Boingo's antennas seamlessly. The result is consistent, functional service and similar coverage no matter the network. The station is also connected to Brookfield Place (which has its own DAS installed) via an underground pathway. Handoff between the two occurs seamlessly with no performance problems. Given that the station is not completely belowground, the outdoor network did not seem to cause much if any interference. The noise floor remained low according to the spectrum analyzer while the signal was high even with 0 dB of gain applied. Notice even in the crowded PCS band, each carrier is well-defined in this DAS environment with relatively low noise.

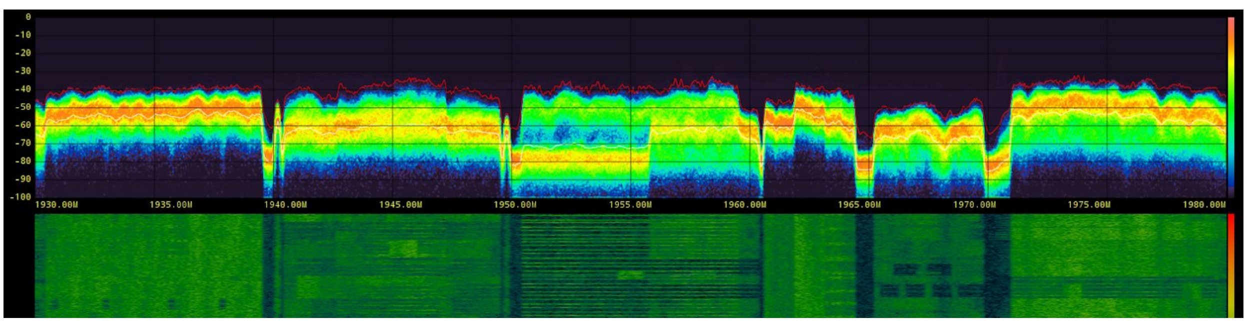

Fig. 6. AT&T (1935 MHz, 1962.5 MHz, 1967.5 MHz), T-Mobile (1945 MHz), Sprint (1955 MHz), and Verizon (1975 MHz). Downlink spectrum only. Also note the T-Mobile GSM carriers (1939 MHz, 1949 MHz) in the guard bands of the LTE carrier.

While the noise floor between 1930 MHz and 1960 MHz was higher, above 1960 MHz noise was low and service was of high quality. It is important to realize that though the shift to LTE has caused capacity reductions for many legacy 2G and 3G services, the PCS band is still

commonly used to offer these services especially for Sprint and T-Mobile. Even with limited amounts of spectrum in this band, the carrier's networks are relatively well-controlled. Carriers in the position of having to run multiple technologies in a limited amount of spectrum are getting creative with its use. T-Mobile's two 200 kHz-wide GSM carriers shouldering its larger, more critical 10 MHz LTE carrier are a testament to this creativity. T-Mobile also employed a dynamic spectrum sharing system from Ericsson in their part of the PCS band several years ago in order to run a 5 MHz 3G HSPA+ carrier and a 10 MHz LTE carrier in addition to two GSM carriers all within the same 10 MHz of PCS spectrum. Meanwhile, AT&T's first 5 MHz LTE carrier operates with a smaller guard band between Sprint's 10 MHz LTE carrier and it than T-Mobile does using LTE and GSM. This raises the noise between AT&T and Sprint's LTE carriers slightly and might point to poor filtering or misconfiguration on AT&T's part.

RSRP, RSRQ, and SINR generally fell within the "great" range for all networks due to the station's DAS. SINR in the PCS band was slightly higher for some carriers due to the aforementioned multi-generational set of networks occupying the band.

B# denotes 3GPP frequency band number	**AT&T**	**Sprint**	**T-Mobile**	**Verizon**
RSRP (dBm)	B2: -74 to -69 B5: -110 to -98 B12: -60 to -50	B25: -79 to -70 B26: -59 to -53 B41: -80 to -73	B2: -80 to -70 B4: -82 to -70 B12: -105 to -101	B2: -81 to -69 B4: -78 to -70 B13: -60 to -50
RSSI (dBm)	B2: -30 B5: -65 B12: -30	B25: -31 B26: -30 B41: -32	B2: -30 B4: -35 B12: -72	B2: -29 B4: -34 B13: -30
SINR (dB)	B2: 10 to 20 B5: -3.0 to 0.5 B12: 9 to 15	B25: 11 to 22 B26: 7 to 14 B41: 20 to 26	B2: 9 to 21 B4: 15 to 25 B12: -2.0 to 0.7	B2: 10 to 23 B4: 15 to 24 B13: 10 to 17

Table 3. WTC PATH Station recorded RSRP, RSSI, and SINR by carrier and frequency band

As previously stated, all networks generally performed well in the PATH station. The only inconsistencies that appear are from LTE bands that were not added to the Boingo DAS specifically AT&T's band 5 (850 MHz) and T-Mobile's band 12 (700 MHz). These bands were absent from the DAS due to either their rollout being limited or the carrier's design decision to exclude it from the system.

Recommendations for future capacity improvements could come from the addition of the two bands mentioned for both AT&T and T-Mobile. AT&T might be wise to adjust the frequency of their 5 MHz LTE carrier at 1962.5 MHz so as to further reduce noise for both Sprint and themselves. It would also be beneficial to consider upgrades in which the 5 MHz carriers centered at 1962.5 MHz and 1967.5 MHz are combined into a single 10 MHz carrier centered around 1965.2 MHz. Because AT&T isn't currently already doing this, I suspect that an equipment limitation is preventing them from expanding capacity this way. As generations of mobile wireless technology push forward into 5G, T-Mobile should look to shut down their 2G GSM services completely so as to lower noise in their portions of the PCS band specifically in high-traffic locations such as this were the performance benefits of LTE are greater than the cons of leaving a location without GSM. Sprint should look to activate 256 QAM here especially on band 41 to take advantage of the great SINR conditions the DAS provides for its customers. This would result in up to 33% more network capacity assuming otherwise ideal conditions.

Union Square

Union Square's hustle and bustle does tone down late at night as I discovered while examining conditions during peak time midday and late at night around 2:00 AM. Union

Square's setting is unique as it is fully outdoors and fully mixed-use. The network at Union Square is fully heterogeneous as one might expect from networks in an urban core of a large city. Macro cell sites for each carrier surround the Square from rooftops and downtilt to focus coverage on this busy area. Carriers are also using multi-sector cell sites to serve the Union Square area while meeting capacity needs. The area is also dotted in nodes for a neutral-host outdoor DAS created by NextG Networks, now part of Crown Castle. Some of these have been converted into small cells and separate small cells mounted on buildings are also present. The result is an incredible tapestry of network gear all hidden in plain sight and quickly serving customers with the connections they need no matter the situation in the surrounding area.

My goal in examining service at both peak times and off-peak was to view the change in SINR between the two. I expected SINR levels to be worse during peak time due to the amount of traffic being transmitted in a heterogeneous network environment with multiple sources of interference. This turned out to be true but most of the time did not have the dramatically different results I expected. Because of Union Square's importance and population density, all networks were running using all available spectrum allocated to them to offer superior capacity. It is important to note that not all bands were active on all cell sites (macro/small/DAS) in the area. This led to better SINR on some bands and slight differences in RSSI and RSRP within the networks of each carrier. Often, small cells and outdoor DAS might only be single-band or dual-band leading to less interference (and therefore improved SINR) on the bands not on every site. At Union Square, this was the case with some of the macro cell sites on AT&T's band 2 and 5 network.

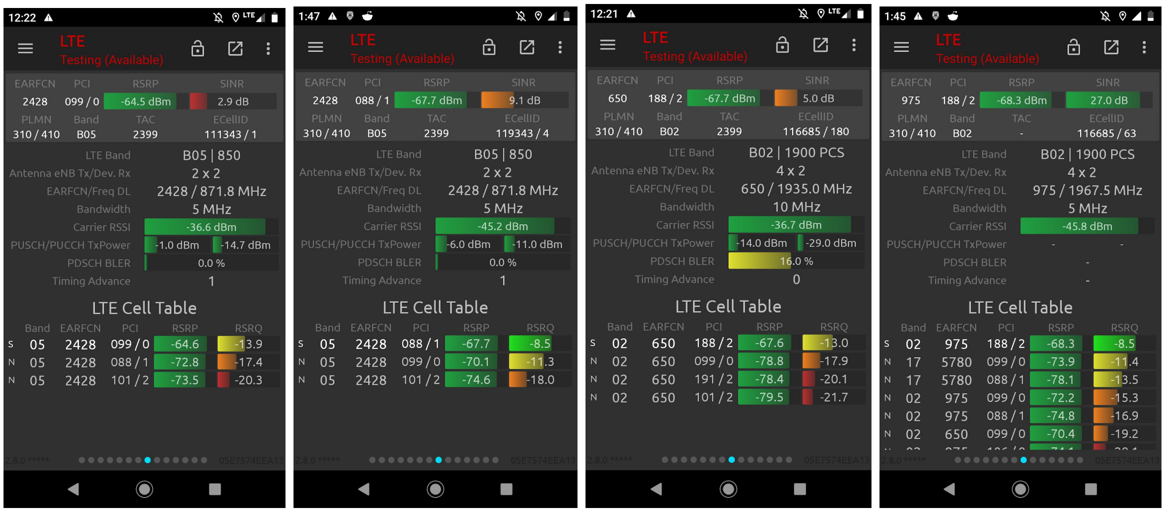

Fig. 7. AT&T B5 (left) and B2 (right) at peak time (12:22 PM) versus off-peak (1:47 AM), please note the PCI and ECellID pattern on B5 implies service is coming from the same site but not necessarily the same sector. B2 carriers are different carriers but coming from the same sector and are subject to similar interference and noise conditions.

AT&T's band 2 and 5 network examined above showed improved SINR in peak versus off-peak hours especially on band 2. The band 2 network showed improvements in SINR for service from the same sector as well as improvements in RSRP for the same exact carrier as can be seen in the LTE cell table of the second screenshot. Band 5 showed a slight loss of RSRP and RSSI but saw gains in RSRQ for the same sector and carrier as well as a noticeable SINR improvement off-peak for the band.

Other carriers saw similar changes in SINR and minor fluctuations in RSRP and RSSI as illustrated below. SON, or self-optimizing network, functions might alter network performance to optimize service based on conditions such as number of connected devices and the channel conditions for each. As of writing, all carriers have implemented some features of SON in their LTE networks (Parker 2014) (Alleven 2017) (Dano 2016) (Goldstein 2013).

B# denotes 3GPP frequency band number, formatted peak/off-peak	**AT&T**	**Sprint**	**T-Mobile**	**Verizon**
RSRP (dBm)	B2: -67 / -68 B5: -64 / -67 B12: -66 / -71	B25: -78 / -71 B26: -57 / -65 B41: -84 / -84	B2: -62 / -63 B4: -73 / -69 B12: -54 / -59	B2: -60 / -59 B4: -66 / -65 B13: -78 / -78
RSSI (dBm)	B2: -36 / -45 B5: -36 / -45 B12: -36 / -42	B25: -52 / -48 B26: -31 / -41 B41: -52 / -57	B2: -28 / -35 B4: -32 / -40 B12: -27 / -39	B2: -31 / -30 B4: -36 / -35 B13: -46 / -46
SINR (dB)	B2: 5.0 / 27 B5: 2.9 / 9.1 B12: 4.7 / 2.7	B25: 12.4 / 27 B26: 12.5 / 18 B41: 6.0 / 17	B2: 0.9 / 10.4 B4: -5.9 / 8.2 B12: 20.2 / 24.3	B2: 9.6 / 19.2 B4: 8.5 / 18.3 B13: -3.5 / -1.4

Table 4. Union Square RSRP, RSSI, and SINR values by carrier and frequency band

In the figure above, the difference between peak time and off-peak SINR is typically very great with only minor outlying degradation for AT&T band 12. In some cases such as T-Mobile band 4, the change in SINR could mean the difference between dropping or continuing a VoLTE call. RSRP between the four carrier's sub-1 GHz networks was also noticeable and reflects the greater network density T-Mobile and Sprint originally designed their networks for in Manhattan. The near-1:1 overlay of band 26 and band 12 on Sprint and T-Mobile's PCS networks respectively shows in the high RSRP the test device received at Union Square both during peak time and off-peak. These values are especially good when compared with AT&T band 5 and 12 as well as Verizon band 13. All of these bands fall into the same 700 MHz and 800 MHz ranges.

The networks at Union Square were able to handle traffic well and reacted to different conditions as expected in terms of SINR. Changes in RSRP and RSSI were not expected

however. RSSI degradation off-peak was a surprising discovery and of interest to the analysis in this paper. Recommendations for Union Square can't really be made because carriers are already maximizing their existing resources in this location and trying to add new cell sites, small cells, or DAS nodes might only cause the law of diminishing returns to kick in and ultimately not be worth the cost. The addition of LAA-LTE technology (LTE service using the unlicensed 5 GHz band) might help ease network congestion and improve RF performance on certain carriers if only due to a lightened network load. Given Union Square's size as well as the unlicensed nature of the band - which necessitates sharing spectrum with all of the 5 GHz WiFi networks in a given area - this might not be an optimal solution. Continuing to obtain spectrum licenses in the mid-band as well as mmWave range would be the best way to grow capacity for all networks in this area.

Queensboro Plaza

Queensboro Plaza might initially seem like a strange choice for an analysis of network performance on first glance. The station is 118th in ridership out of 472 stations within the NYC Subway system (Metropolitan Transit Authority 2019). Not one of the most pressing places to address network performance issues. However, the growth of the area around Queensboro Plaza has it rapidly rising as a transit hub for far-west Queens. Development in the Long Island City area has been exploding since 2015. Between July 2017 and 2018, the NYC Department of Buildings approved some 1,436 new residential housing units for the neighborhood (Localize Labs 2018). Placing it as far-and-away the most under-development neighborhood across the whole city including the newly-opened Hudson Yards. All of the new development leaves the

networks in Long Island City in a major predicament. A formerly low-rise neighborhood with a network built to cover low-rise buildings and streets has started to become a major center of skyscraper development leading to new signal-blocking materials being used and new reflections causing signals to attenuate and network interference to rise. Often, engineers in large urban markets have to make major changes to the network because of new development and other issues outside of their control such as lease expirations. Queensboro Plaza is one such example in which new development and growth have outpaced the redesign process of the networks.

Queensboro Plaza's network performance issues have existed for a long time and the addition of alternative coverage solutions like Transit Wireless haven't helped the situation like one might expect. Upon further inspection, it would appear as though all carriers either have elected not to activate service on the DAS at this station or have not optimized handoff settings in such a way that allows devices at the station to use it (such as the scenario in Chamorro et al. describes, leading to interference). Verizon was the only network that recorded acceptable SINR performance on bands 2 and 4 at the station. Even though performance was acceptable, SINR levels would fluctuate by up to 5 dB quite often. AT&T, Sprint, and T-Mobile recorded SINR of less than 1 dB for each of the frequency bands within their networks (with the exception of Sprint's B25). This poor performance on AT&T and T-Mobile was in spite of their activation of 4x2/4x4 MIMO support.

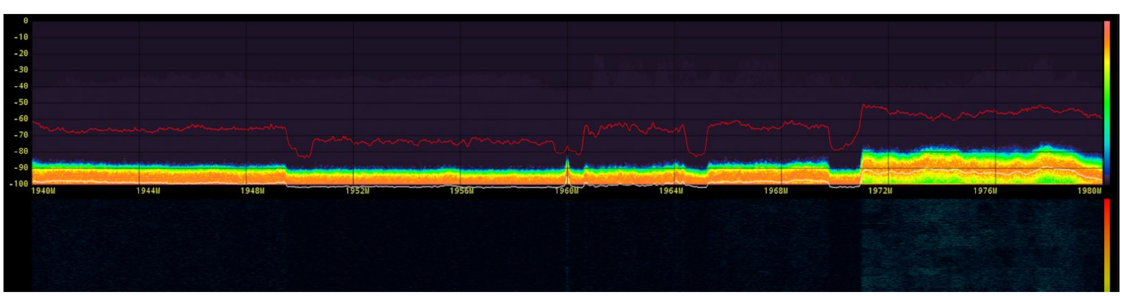

Fig. 8. PCS band spectrum analysis at Queensboro Plaza. Downlink only.

Notice in Figure 11 with 0 dB gain applied, each carrier is barely visible with Verizon being only marginally stronger at 1975 MHz. This severe disparity, when compared to the other locations tested, is even more obvious when you look at the RSRP and RSSI values at Queensboro Plaza. Both of these values are quite strong and even comparable to the other locations tested indicating received power and signal are good however, in Fig. 11, interference keeps a clear signal from being easily found. This is also indicated in the SINR values in Fig. 12. Due to this issue, the carriers might have opted not to activate service on the Transit Wireless DAS for fear that it would only add to the issue.

B# denotes 3GPP frequency band number	**AT&T**	**Sprint**	**T-Mobile**	**Verizon**
RSRP (dBm)	B2: -90 to -83 B5: -83 to -78 B12: -92 to -79	B25: -89 to -84 B26: -89 to -80 B41: -110 to -103	B2: -92 to -91 B4: -96 to -92 B12: -87 to -84	B2: -80 to -74 B4: -80 to -67 B13: -79 to -73
RSSI (dBm)	B2: -54 B5: -49 B12: -45	B25: -57 B26: -55 B41: -70	B2: -53 B4: -51 B12: -53	B2: -46 B4: -43 B13: -45
SINR (dB)	B2: -1.0 to -0.1 B5: -4.9 to -1.2 B12: -4.0 to 0.3	B25: 1.0 to 7.1 B26: -5.3 to -4.9 B41: -3.4 to -0.9	B2: -9.5 to -6.4 B4: -7.4 to -5.5 B12: -5.0 to -3.0	B2: 8.5 to 18.1 B4: 10 to 18 B13: 5.0 to 7.0

Table 5. Queensboro Plz recorded RSRP, RSSI, and SINR values by carrier and frequency band

What's interesting here is that, unlike the issue of service in suburban and rural areas where a device might be on the edge of multiple very weak signals causing interference and making it difficult to latch onto just one, the issue at Queensboro Plaza appears to be the opposite issue yet with the same effect. Too many strong sectors for each network all overlap at this one location leading to good availability of signal (RSRP, RSSI) but incredibly poor SINR resulting

in poor network performance overall. SINR seemed to be further compounded when two trains were pulled into the station at the same time creating a temporary wall and further interfering with service. Users commonly complain about dropped, robotic, and generally, near-failing VoLTE calls as well as slow data speeds.

Queensboro Plaza is a very tricky problem to solve and has been for several years now for engineers at the major carriers. Verizon's design seems to have resulted in a solid level of service at the station and surrounding area. With the rapid development happening in Long Island City, any recommendations might become outmoded quickly. However, a proliferation of DAS in the large new developments going up might be the key to serving the rest of Long Island City with fewer issues. More indoor DAS in these buildings means less of a need to try to cover them with macro cell sites and more of a focus on outdoor neighborhood coverage areas for said sites. While on-platform at Queensboro Plaza, applying downtilting to certain sectors would reduce interference. This would have to be done in a balancing act to avoid making capacity suffer due to only one or two sectors serving the station. Much more drastic measures could be taken in the form of site relocation. This would also be a step in redesigning the network to accommodate the new development in the neighborhood. Carriers should also work with Transit Wireless to test their DAS at the station itself. Creating a high-power DAS to overpower the macro sites would at least provide users at the station with good service. There is potential for that to come at the expense of users on the macro network however.

Conclusion

While wireless carriers continue the endless process of network improvement and optimization to keep pace with the exploding demand for wireless services, it is clear that areas of high-traffic and high population density still pose somewhat of a problem in the nation's largest market. Service across New York is quite good and rarely are any of the carriers without service while aboveground. The findings and recommendations in this report show simply that it could potentially be even better. Interference problems will always be a sticking point for operators as their networks grow. With 5G, density of the sites in a network will become even greater issue for carriers and New York's already dense, heterogeneous network is a sign of what is to come to smaller cities and suburbs across the nation. Controlling interference and coverage of the network is key to creating networks that everyone can access and share without concerns of data slowdowns or dropped calls. These networks are critical infrastructure and will become an even more primary source of communications as time goes on. Carriers should realize the position they are in and optimize the networks in New York to reflect that by whatever means necessary.

References

Alleven, M. (2017, December 08). Sprint achieves 120-140 Mbps in LAA deployment with SpiderCloud, says LAA on long-term road map. Retrieved from https://www.fiercewireless.com/wireless/sprint-achieves-120-140-mbps-laa-deployment-spidercloud-says-laa-long-term-roadmap

Cerny, J., & Masopust, J. (2017). Interference optimization and mitigation for LTE networks. *2017 International Conference on Applied Electronics (AE)*. doi:10.23919/ae.2017.8053579

Chamorro, L., Reyes, A. F., & Paredes-Paredes, M. C. (2018). Interference Evaluation in LTE Heterogeneous Networks. *2018 IEEE Third Ecuador Technical Chapters Meeting (ETCM)*. doi:10.1109/etcm.2018.8580332

Chang, P., Chang, Y., Han, Y., Zhang, C., & Yang, D. (2010). Interference analysis and performance evaluation for LTE TDD system. *2010 2nd International Conference on Advanced Computer Control*. doi:10.1109/icacc.2010.5487076

Dano, M. (2016, November 15). Verizon testing SON, cognitive radio as part of network densification efforts. Retrieved from https://www.fiercewireless.com/tech/verizon-testing-son-cognitive-radio-as-part-network-densification-efforts

Fung, J. (2018). Manhattan Population Explorer. Retrieved from http://manpopex.us/

Goldstein, P. (2013, January 23). Cisco targets AT&T's SON technology with $475M purchase of Intucell. Retrieved from https://www.fiercewireless.com/wireless/cisco-targets-at-t-s-son-technology-475m-purchase-intucell

Hesham, A. (n.d.). LTE DT Parameters. Retrieved from https://www.academia.edu/31434500/LTE_DT_Parameters

Howald, R. L., Vieira, A., & Aviles, M. (2009). NEW MEGABITS, SAME MEGAHERTZ: PLANT EVOLUTION DIVIDENDS. *2009 NCTA Technical Papers*.

Keysight Technologies. (n.d.). LTE TDD Frame Configuration. Retrieved from http://rfmw.em.keysight.com/wireless/helpfiles/n7625b/Content/Main/3_LTE_TDD_Frame_Configuration.htm

Lauro. (n.d.). LTE-FDD vs. LTE-TDD (a.k.a LTE-TD) - Lauro - Expert Opinion - LTE University. Retrieved April 21, 2019, from http://lteuniversity.com/get_trained/expert_opinion1/b/lauroortigoza/archive/2012/06/12/lte-fdd-vs-lte-tdd-a-k-a-lte-td.aspx

Li, Y., Niu, C., Ye, F., & Hu, R. Q. (2016). A universal frequency reuse scheme in LTE-A heterogeneous networks. *Wireless Communications and Mobile Computing,16*(17), 2839-2851. doi:10.1002/wcm.2731

Localize Labs. (n.d.). The Neighborhoods Developers Have Their Eyes on Now. Retrieved from http://labs.localize.city/the-neighborhoods-where-developers-have-their-eyes-on-now/

Ou, G. (2015, March 23). 28 Years of American Cellular Phone Service. Retrieved from https://hightechforum.org/28-years-of-american-cellular-phone-service/

Parker, T. (2014, June 23). T-Mobile to use Eden Rock's SON to reduce dropped calls, increase throughput. Retrieved from https://www.fiercewireless.com/tech/t-mobile-to-use-eden-rock-s-son-to-reduce-dropped-calls-increase-throughput

Port Authority of New York and New Jersey. (2014, August 11). *PORT AUTHORITY ANNOUNCES CELLULAR AND WI-FI SERVICES AT WORLD TRADE CENTER*[Press release]. Retrieved from https://www.panynj.gov/press-room/press-item.cfm?headLine_id=2048

Port Authority of New York and New Jersey. (2019). Traffic & Volume Information. Retrieved from https://www.panynj.gov/path/statistics.html

Regional Planning Authority. (2018, October 11). Public for Penn Station: Clock is Ticking to Make Drastically Needed Improvements. Retrieved from http://www.rpa.org/article/public-for-penn-station-clock-is-ticking-to-make-drastically-needed-improvements

Ryu, J. (n.d.). LTE Quick Reference - RSRP, RSRQ, RSSI, SINR Interplay. Retrieved from http://www.sharetechnote.com/html/Handbook_LTE_RSRP_RSRQ_SINR_Interplay.html

Wang, Q., & Li, X. (2016). Analysis of LTE FDD and TD-LTE combination networks interference. *2016 2nd IEEE International Conference on Computer and Communications (ICCC)*. doi:10.1109/compcomm.2016.7925116

Wang, W., Zhou, K., Zhang, Y., & Shen, S. (2008). Effects of synchronization errors on the performance of TDD/OFDMA crossed timeslot. *2008 Third International Conference on Communications and Networking in China*. doi:10.1109/chinacom.2008.4685162