Real-World Performance of 5G

A Technical Paper prepared for SCTE•ISBE by

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Introduction

5G is progressing rapidly from technical trials to initial commercial deployments. As of August 2019, thirty nine mobile network operators around the globe had already launched commercial standardized 5G networks, including AT&T, Verizon, T-Mobile and Sprint in the U.S. [1]. While these initial deployments are important milestones in the development of 5G, most deployments in North America are still very limited in scope and scale. For example, Verizon's initial 28 GHz 5G deployment in late 2018 was based on a pre-3GPP 5G standard known as 5GTF and supported fixed wireless access only. Verizon has since launched mobile 5G based on the 3GPP standard and currently offers service in just four cities: Chicago, Minneapolis, Denver and Providence, R.I. AT&T was the first U.S. operator to offer mobile 5G in late 2018 and has since expanded to 20 cities. Unlike Verizon, AT&T is using 39 GHz spectrum in all its launch cities. T-Mobile and Sprint have also recently launched 5G in a handful of cities. Sprint is using 2.5 GHz mid-band spectrum, while T-Mobile is using a combination of 39 GHz and 28 GHz [2].

5G device availability has also been a limiting factor for initial 5G deployments. Most operators only have a few devices that support 5G. For example, T-Mobile only recently demonstrated 5G at 600 MHz because first generation 5G modems did not support the 600 MHz band [3]. Although 5G standards, devices, and commercial networks are maturing quickly, further development and trials are required to fully realize 5G's potential.

This paper presents the results of pre-commercial 5G field trials conducted by Freedom Mobile and its strategic network partner, Nokia. Freedom Mobile is a wholly owned subsidiary of Shaw Communications Inc. and currently Canada's fourth-largest mobile network operator. The pre-commercial trials were carried out at Freedom Mobile's production cell sites in Calgary, Canada on two 5G frequency bands: 3.5 GHz and 28 GHz. These field trials were completed over a 3-month period from June to August 2019.

In this paper, we provide an overview of 5G trial system configuration, including the high-level network architecture, the core network, and the radio access network. We also discuss the test methodology, key results and findings, and other practical considerations in deploying and operating 5G networks. Detailed results from actual drive test data comparing system performance across both bands is also presented. The findings within this paper will be of value to MSOs planning to deploy 5G wireless networks.

System Overview

The pre-commercial trial was conducted at three existing Freedom Mobile cell sites in Calgary, Alberta (see Figure 1). The sites are in a suburban neighborhood with a mix of commercial and residential areas. The area has a population density of roughly 2,000 persons/sq. km (5,178 persons/sq. mi) and dwelling density of 685 dwellings/sq. km (1,773 dwellings/sq. mi.).

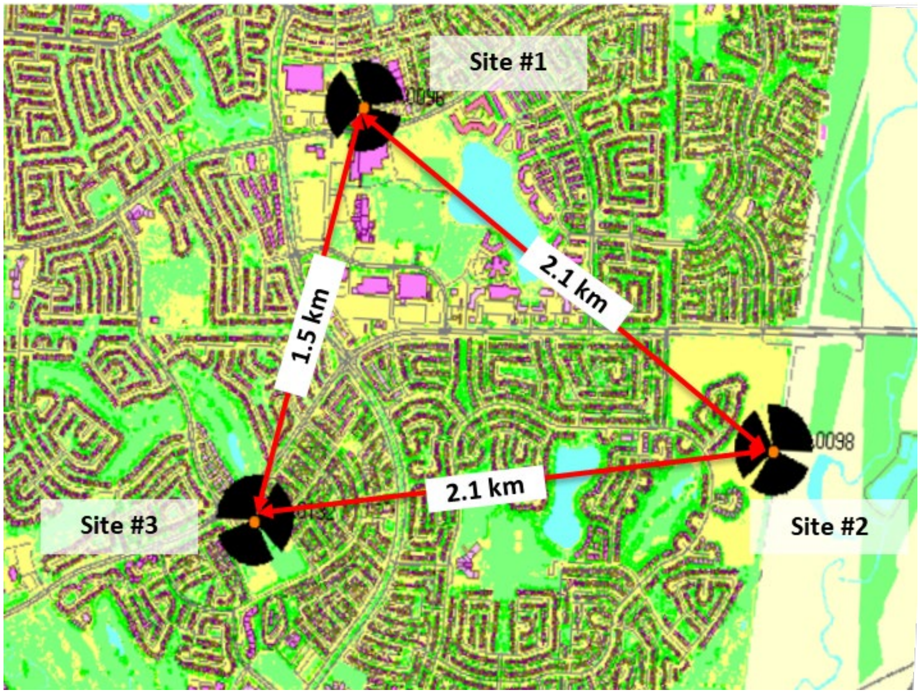


Figure 1 - Pre-Commercial Trial Area

These sites were selected, in large part, because they are owned and controlled by Freedom Mobile. As such, the installation and modification of the 5G base stations and associated equipment could be made without the involvement of another operator or landlord. Another important criterion for selecting these sites was the availability of fiber backhaul facilities capable of supporting multi-gigabit per second 5G data rates. Because the sites are adjacent to one another, we were also able to test call handovers between the sites.

Using existing sites also gave us an opportunity to test 5G in a real-world environment with typical inter-site distances. As shown in Figure 1, the inter-site distances between the three sites ranged from 1.5 km (0.9 miles) to 2.1 km (1.3 miles). The terrain between the sites is moderately hilly with differences in elevation between the sites of up to 60 m (197 feet).

1. Network Architecture

A high-level block diagram of the trial network architecture is shown Figure 2. The trial network consisted of a local core network and a radio access network (RAN) with 3 cell sites. Further details on the LTE core network and RAN are provided in the sections below.

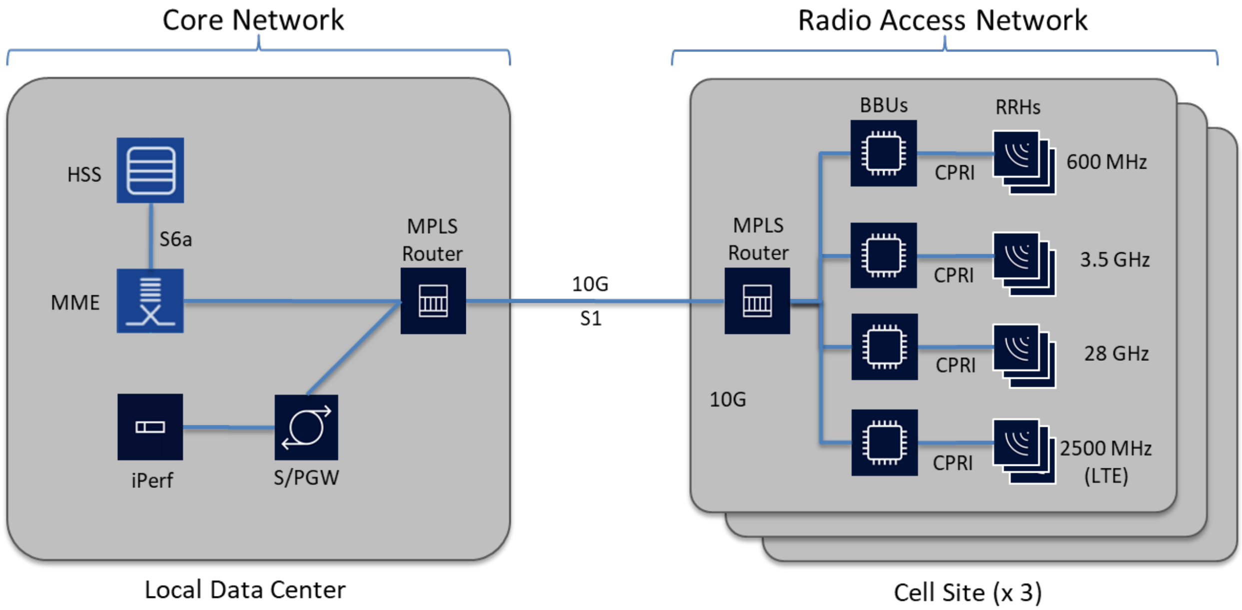


Figure 2 - 5G Trial Network Architecture

1.1. Core Network

The LTE core network, also known as the evolved packet core (EPC), consisted of a serving gateway and packet data network gateway (S/PGW), a mobility management entity (MME), and home subscriber system (HSS) function. An iPerf server was also co-located with the EPC for performance testing. All core network functions and the iPerf server were implemented as virtual network functions (VNFs) on an x86-based server.

For the trial, we used the non-standalone (NSA) Option 3X architecture shown in Figure 3. NSA Option 3X was standardized in 3GPP Release 15 and allows operators to use their existing LTE core networks to support 5G traffic. This simplifies the initial roll-out of 5G networks since the entire core network does not need to be replaced.

With Option 3X, the 5G user equipment (UE) connects simultaneously to an LTE base station, referred to as an evolved node B (eNB), and a 5G new radio (NR) base station (or gNB). As shown in Figure 3, all control plane traffic between the UE and core network is sent through the eNB via an LTE “anchor” carrier. Data plane traffic, on the other hand, is carried simultaneously by both the eNB and gNB. This mode of operation is known as evolved universal terrestrial radio access – NR dual connectivity (EN-DC) and is discussed further in section 1.3.

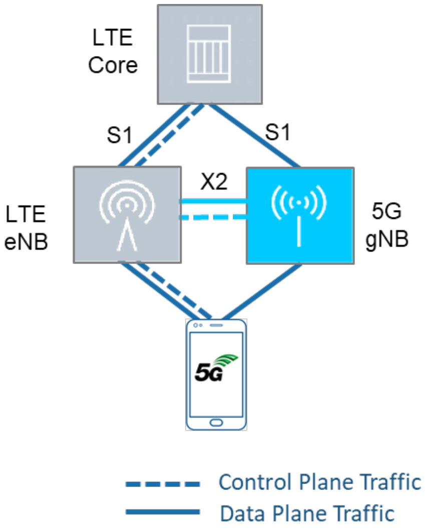


Figure 3 - Non Standalone Architecture (NSA) Option 3X

1.2. Radio Access Network

As shown in Figure 2, four frequency bands were deployed at each cell site. This included three 5G gNBs (i.e., 600 MHz, 3.5 GHz and 28 GHz) and one LTE eNB (i.e., 2.5 GHz), which provided the required LTE anchor carrier for the trial. The 600 MHz band was not tested as part of this trial because 600 MHz UEs were not available in time for the testing.

Each eNB and gNB is comprised of a base band unit (BBU) and a remote radio head (RRH). The BBU is responsible for baseband signal processing, coding, encryption, resource scheduling, and interfacing with the core network and other eNBs/gNBs. The BBU was connected to a cell site router, which in turn was interconnected to the local S/PGW via 10G MPLS links over fiber. In a separate trial, we also used DOCSIS to backhaul traffic from the cell site to the local S/PGW. The results of that trial will be reported in a future paper.

The RRH is a remote radio transceiver that contains the radio frequency (RF) circuitry for up-conversion and down-conversion between the baseband signal and the carrier frequency, signal amplification, and other RF functions. The RRHs are installed on the tower and connect to the BBU, typically located at the base of the tower, via a fiber optic cable using the Common Public Radio Interface (CPRI) protocol. Note that other base station functional splits are possible with 5G but were not tested as part of this trail.

In the case of the 3.5 GHz and 28 GHz gNBs, the RRHs also contain an integrated massive antenna array (MAA). Given the shorter wavelength of the carrier frequency at 3.5 GHz and, particularly 28 GHz, the MAAs contain multiple active antenna elements: 192 in the 3.5 GHz MAA, and 512 in the 28 GHz MAA. This allows very narrow antenna beams to be formed between the gNB and UE, which improves signal reception and reduces interference.

The basic principle behind beamforming is that waves transmitted from multiple antennas will add, either constructively or destructively, in space as they propagate out from the antennas. By changing the phase and amplitude of the signal transmitted by each antenna, it is possible to create narrowly focused beams, as illustrated in Figure 4.

There are two basic types of beamforming: digital beamforming and analog beamforming. In digital beamforming, the transmitted signal is pre-coded in both amplitude and phase during baseband processing before RF transmission. Multiple beams (one per user) can also be formed simultaneously from the same set of antenna elements. This is also known as multi-user MIMO (MU-MIMO). Digital beamforming improves the cell capacity because the same physical resource blocks (frequency-time resources) can be used to transmit data simultaneously for multiple users. Digital beamforming was used by the 3.5 GHz MAA in our trials, however, MU-MIMO was not supported by the software release available at the time.

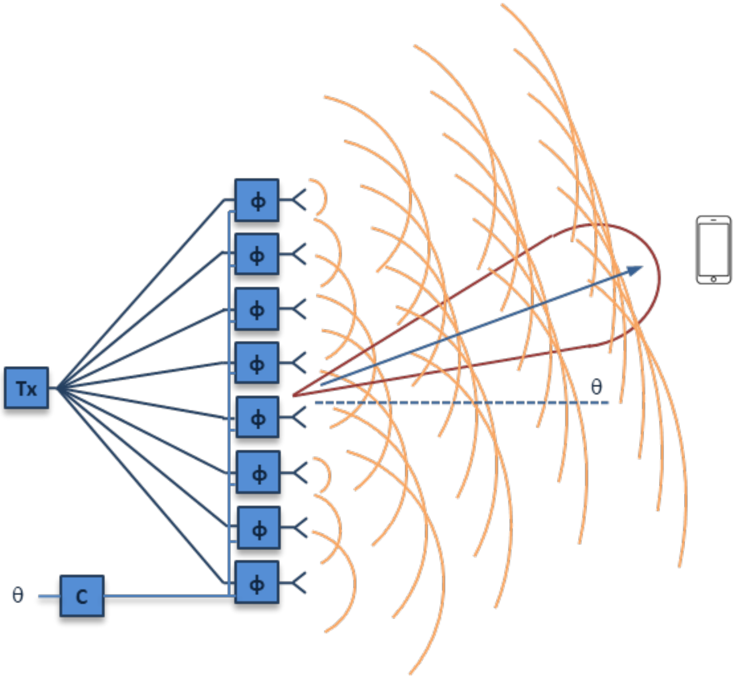


Figure 4 - Beamforming Principle

In analog beamforming, the signals transmitted by the individual antenna signals are adjusted in the RF domain. Unlike digital beamforming, only one beam per set of antenna elements can be formed at any given time. The high antenna gain provided by analog beamforming partially overcomes the higher RF propagation losses associated with mmWave frequencies. It also minimizes interference from other sources. Analog beamforming was used by the 28 GHz MAA in our trials.

With both digital and analog beamforming, individual beams are typically arranged in a pre-defined beam set (or pattern). For example, Figure 5 shows a typical MAA beam set with 2 rows of 4 beams each.

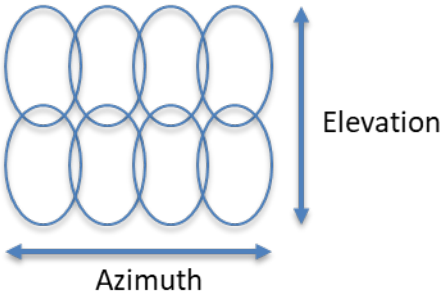


Figure 5 - Typical MAA Beam Set

Both the 3.5 GHz and 28 GHz MAAs used in our trials supported multiple beam sets that can be selected in advance depending on the desired coverage. Unlike the 3.5 GHz and 28 GHz bands, the 2.5 GHz eNB was not equipped with an MAA and was connected to a conventional 12-port, multi-band passive antenna.

Table 1 lists the system parameters for 5G NR and 2.5 GHz base stations.

Table 1 - System Parameters

Parameter	**3.5 GHz**	**28 GHz**	**2.5 GHz (LTE)**
Technology	5G NR	5G NR	LTE
Sectors/Cells	3	3	3
Duplex Mode	TDD	TDD	FDD
DL/UL Split Ratio	8:2	4:1	1:1
Channel Bandwidth	60 MHz	4 x 100 MHz	10+10 MHz
Max. DL Modulation Order	256-QAM	64-QAM	256-QAM
Max. UL Modulation Order	64-QAM	64-QAM	64-QAM
Subcarrier Spacing	60 kHz	120 kHz	15 kHz
BTS MIMO Layers	16	2	2
UE MIMO Layers	1	2	1
Peak UE DL Data Rate	342 Mbps	2.188 Gbps	98 Mbps
Peak UE UL Data Rate	32.5 Mbps	103 Mbps	37 Mbps
TX Power	200 W	8 W	160 W
Antenna Gain	25.5 dBi	29 dBi	18.1 dBi
EIRP	77.5 dBm	57.1 dBm	70.1 dBm

As noted in the table above, three sectors/cells were installed for all three bands at each of the three cell sites. The 3.5 GHz and 28 GHz gNBs operated in time division duplexing (TDD) mode, where the same frequencies are used for both the downlink (DL) between the gNB and UE and the uplink (UL) in the opposite direction. The DL/UL split ratio gives the fraction of time allocated to DL and UL transmissions. For the 3.5 GHz the DL/UL ratio was 8:2 and for the 28 GHz it was 4:1. The 2.5 GHz eNBs, on the other hand, operated in frequency division duplexing (FDD) mode, where the DL and UL transmit simultaneously on different frequencies. As such, the DL/UL split ratio is always 1:1.

The channel bandwidth assigned for each band is also listed in Table 1. In the 3.5 GHz band, the assigned channel bandwidth was 60 MHz and in the 28 GHz band, we were assigned 4 channels, each with a channel bandwidth of 100 MHz. The subcarrier spacing is the frequency offset between adjacent orthogonal frequency division multiple access (OFDMA) subcarriers. The 2.5 GHz bands had a subcarrier spacing of 15 kHz, whereas the 3.5 GHz and 28 GHz bands had a subcarrier spacing of 60 kHz and 120 kHz, respectively.

The number of multi-input multi-output (MIMO) layers (or streams) ranged from 2 layers for 28 GHz to 16 layers for 3.5 GHz. The MIMO layers relates to the number of transmit and receive antennas between the UE and eNB/gNB. Each MIMO layer can carry an independent stream of user data. The channel bandwidth along with the subcarrier spacing and number of MIMO layers determines the peak theoretical data rate for each band. The peak DL and UL data rates, which are only possible under ideal conditions (e.g., short range, no interference, etc.), ranged from 98 Mbps for the 2.5 GHz band up to 2.1 Gbps for the 28 GHz band.

As shown in Table 1, there was a significant difference in transmit (TX) power and antenna gain between the various bands. This resulted in a difference of over 20 dB in the highest and lowest effective isotropic radiated power (EIRP) per eNB/gNB sector. This had a direct effect on the DL coverage area and the RF exposure compliance distances for each band, which are discussed in more detail in section 1.4.

The antenna/MAA height and combined mechanical and electrical down tilts for each band and cell site are listed in Table 2 below. The combined down tilt at 3.5 GHz was 5° at Sites 1 and 2 and 0° at Site 3. At 28 GHz, the combined down tilt was 0° at all three sites. At 2.5 GHz, the combined down tilt ranged from 2° and 7° depending on the site and sector.

Table 2 - Antenna Heights and Down Tilts

	3.5 GHz		28 GHz		2.5 GHz (LTE)	
Site	Antenna Height	Down Tilt	Antenna Height	Down Tilt	Antenna Height	Down Tilt
1	29.0 m	5°	20.0 m	0°	40.2 m	7°
2	20.5 m	5°	18.5 m	0°	29.5 m	4°
3	31.0 m	0°	15.0 m	0°	30.5 m	2-6°

Figure 6 and Figure 7 show the 3.5 GHz and 28 GHz MAAs and the 2.5 GHz antenna at Site 1.

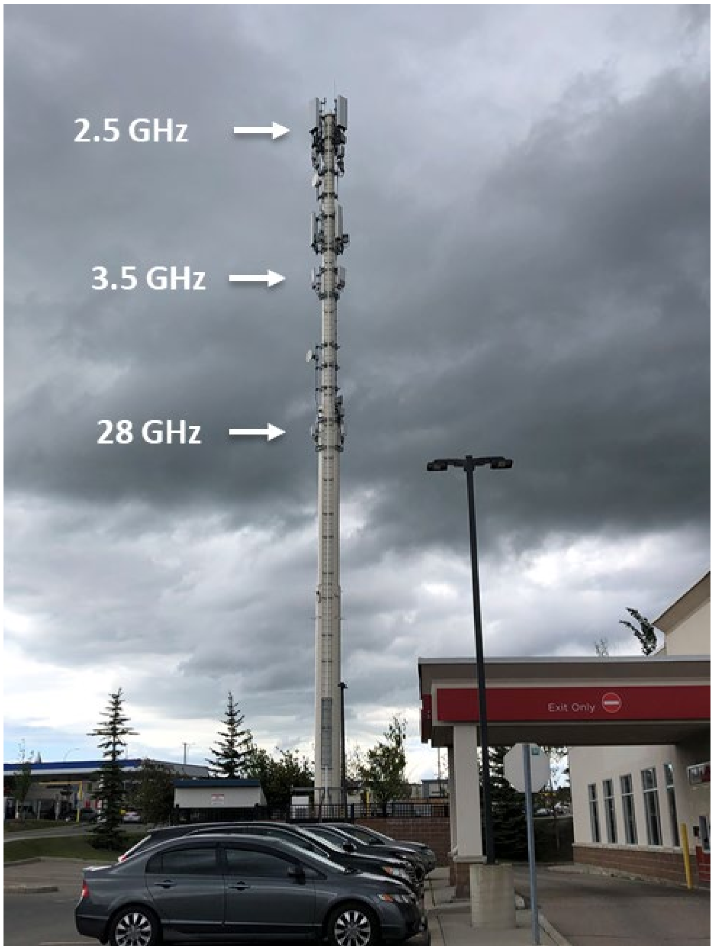


Figure 6 - RRHs/Antennas at Site 1

Figure 7 - 3.5 GHz and 28 GHz Remote Radio Heads

1.3. Dual Connectivity

As mentioned in section 1.1, dual connectivity (EN-DC) allows a UE to simultaneously transmit and receive on multiple component carriers from two cell groups via a master eNB and a secondary 5G gNB. In addition to supporting 5G, EN-DC increases user throughput, provides mobility robustness, and supports load-balancing between the eNB and gNB.

EN-DC band combinations for 5G NR are defined by the 3GPP [4]. The EN-DC combinations that were used in the trial are listed below in Table 1.

Table 3 - Dual Connectivity Combinations

DC Combination	LTE Band	LTE Frequency	LTE Channel Bandwidth	5G NR Band	5G NR Frequency	5G NR Channel Bandwidth
DC_7_n78	B7	2.5 GHz	10+10 MHz	n78	3.5 GHz	60 MHz
DC_7_n257	B7	2.5 GHz	10+10 MHz	n257	28 GHz	4 x 100 MHz

Depending on the EN-DC combination, the 5G coverage area may be affected by the choice of LTE anchor carrier. For example, at 3.5 GHz having an LTE anchor carrier in a lower band (e.g., 2.5 GHz) can potentially improve the 5G coverage. Because the 3.5 GHz band is usually uplink (UL) limited, the 5G downlink (DL) coverage area is typically larger than in the UL direction, as illustrated in Figure 8. As a result, the 3.5 GHz coverage area would normally be limited to the UL cell edge. With dual connectivity, however, the 5G coverage area can extended in the DL because the control and data plane traffic in the UL can still be carried by the 2.5 GHz LTE anchor carrier.

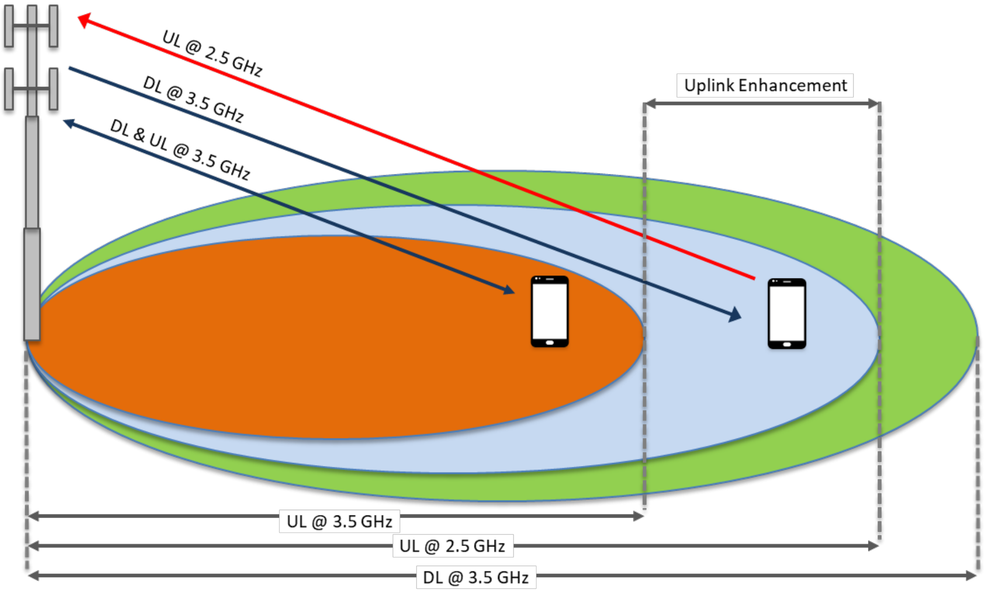


Figure 8 - 5G NR Coverage at 3.5 GHz

1.4. RF Safety

With 4 new bands and 8 existing bands at each of the trial sites, RF safety was an important consideration in planning the trial. As such, RF safety studies were completed for all three cell sites using EMF Visual electromagnetic exposure simulation software. These simulations were performed by constructing a 3D model of the site and then adding all transmitting antennas. Antenna characteristics, such as frequency, radiated power and position were then entered into the software. The simulations provide a representation of the combined radiation pattern for each site and the size of the zones that require restricted access. For example, the simulation results for Site 1 are shown in Figure 9.

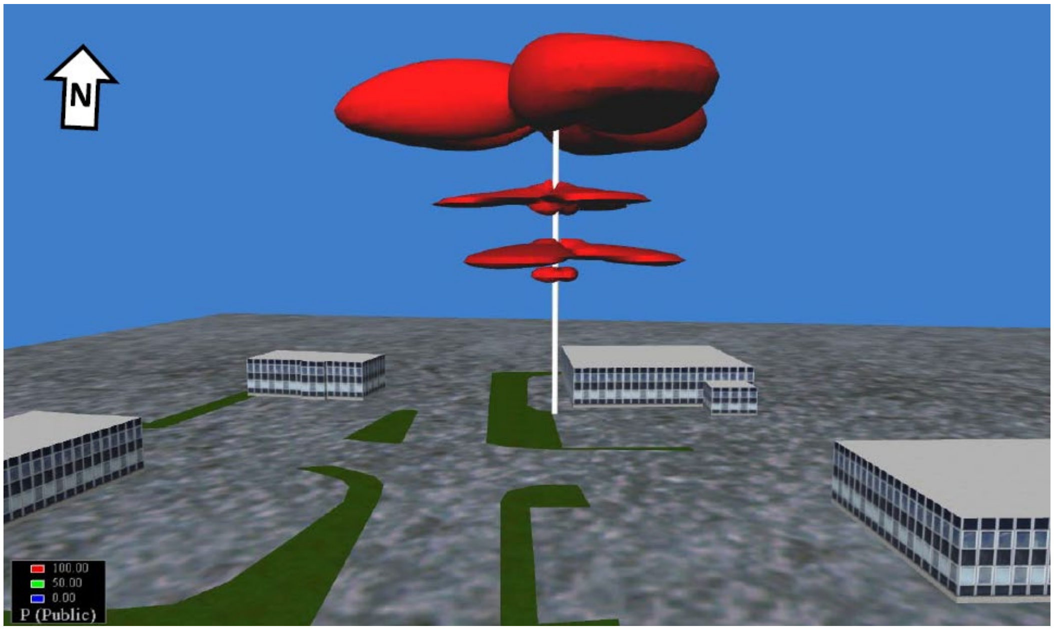


Figure 9 - 3D Electromagnetic Exposure Simulation

The red shapes in the figure above show the boundaries within which the maximum permissible exposure level for an uncontrolled environment is exceeded.

Figure 10 shows a top-down view of the RF exposure levels at 2 m above ground level for the original antenna heights that were proposed for Site 3.

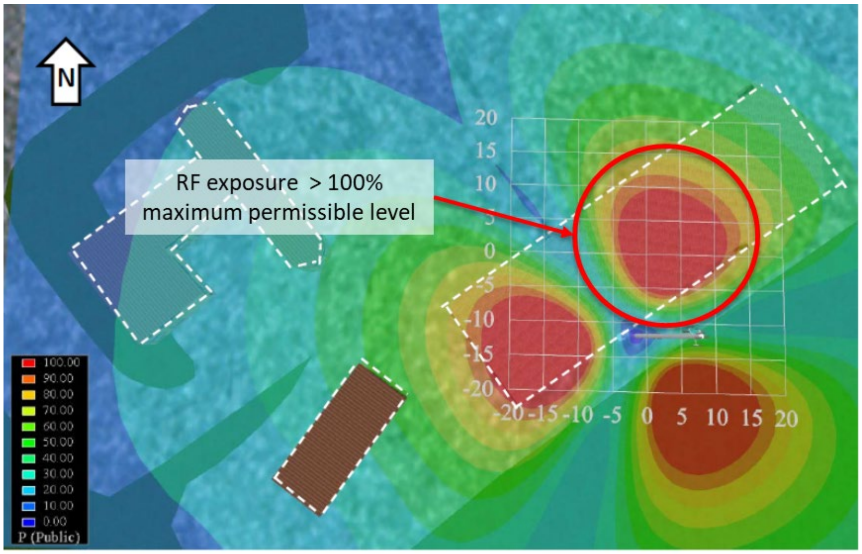


Figure 10 - RF Exposure Level at 2m above ground level

This figure shows that the RF field strength exceeds the Maximum Permissible Exposure (MPE) level for an uncontrolled environment in the area immediately surrounding the site. As a result, the 3.5 GHz RRHs at this site had to be relocated from 15m (50 feet) to 31 m (100 feet) above ground level to meet Canadian safety code requirements [6].

Note that these studies only simulate the propagation of the signal in free space and do not consider surrounding obstacles or the absorption of the signal by these obstacles. In addition, the simulation assumes that all transmitters are operating simultaneously at their maximum power levels. As a result, these simulations represent the worst-case scenario.

2. User Equipment

Two different UEs were used as test devices during the trial. For mobile testing, we used the Qualcomm and Wiston NeWeb Corporation (WNC) mobile test platforms shown in Figure 11. Both mobile test platform (MTPs) are based on Qualcomm's Snapdragon SDX50 5G modem. The technical highlights for the WNC MTP are listed below:

- 5G NR sub-6 GHz NSA
- Max data rate up to 2.22 Gbps based on EN-DC
- 256 QAM, 4x4MIMO, 100MHz bandwidth
- Data interface USB 3.1 Gen 1 Type-C
- 4G LTE CAT 16

The Qualcomm MTP had similar specifications at 3.5 GHz and also supported 28 GHz. The Qualcomm and WNC MTPs were used for both functional and performance testing. Because the SDX50 5G modem does not support the 600 MHz band, we were unable to test the 600 MHz band during this trial.

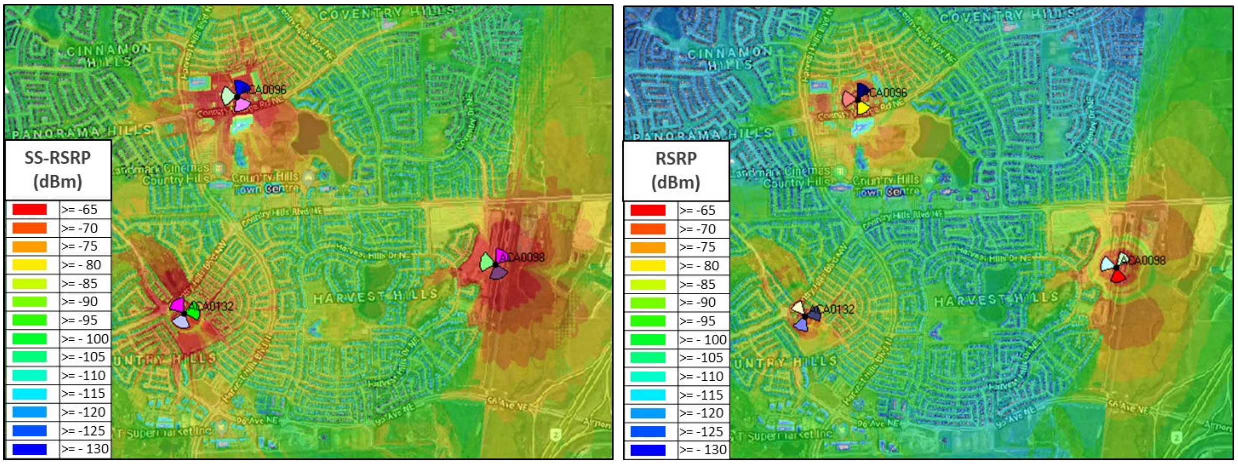
(a) Qualcomm MTP (b) WNC MTP

Figure 11 - Mobile Test Platforms

3. Network Coverage

5G NR network coverage predictions were completed for 3.5 GHz and 28 GHz bands prior to testing. The coverage predictions were generated using Forsk Atoll 5G NR planning software using 2 m resolution geodata except the area immediately east of Site 2, for which only 30 m geodata was available.

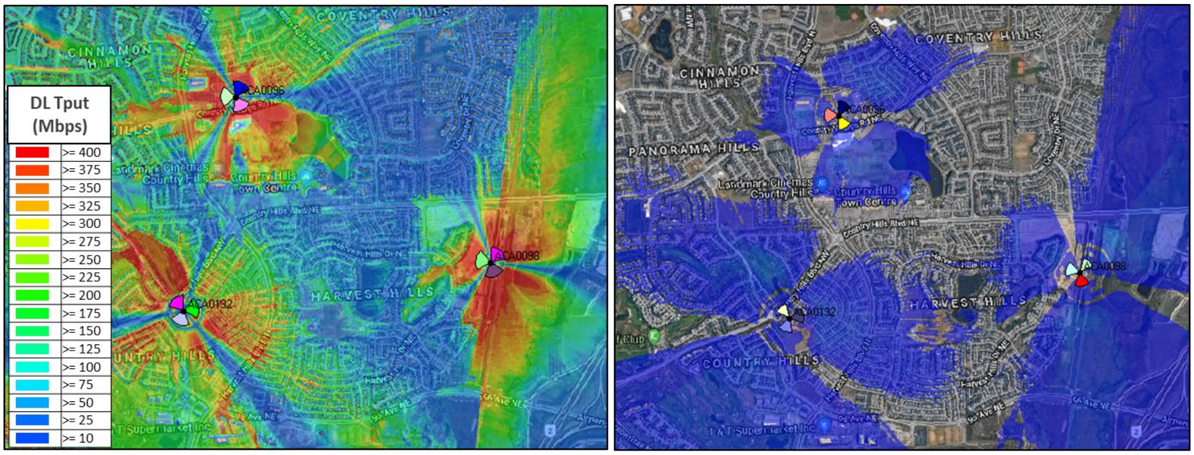
The predicted DL coverage for the 3.5 GHz (5G NR) and 2.5 GHz (LTE) bands are shown in Figure 12. The DL coverage for the 3.5 GHz band is measured by the synchronization signal - reference signal receive power (SS-RSRP) and the 2.5 GHz DL coverage is measured by the RSRP. This figure shows that the predicted 3.5 GHz SS-RSRP is roughly 5-10 dB higher than the 2.5 GHz RSRP over the entire coverage area.



(a) 3.5 GHz (b) 2.5 GHz (LTE)

Figure 12 - Downlink Coverage Prediction

Figure 13 shows the predicted DL throughput for the 3.5 GHz and 2.5 GHz bands. At 3.5 GHz, DL throughput rates of up to 350 Mbps are predicted near the cell sites (i.e., within a couple hundred meters) and rates of 100 Mbps are predicted at distances up to about 1 km. This assumes an 8:2 split between DL and UL time slots.

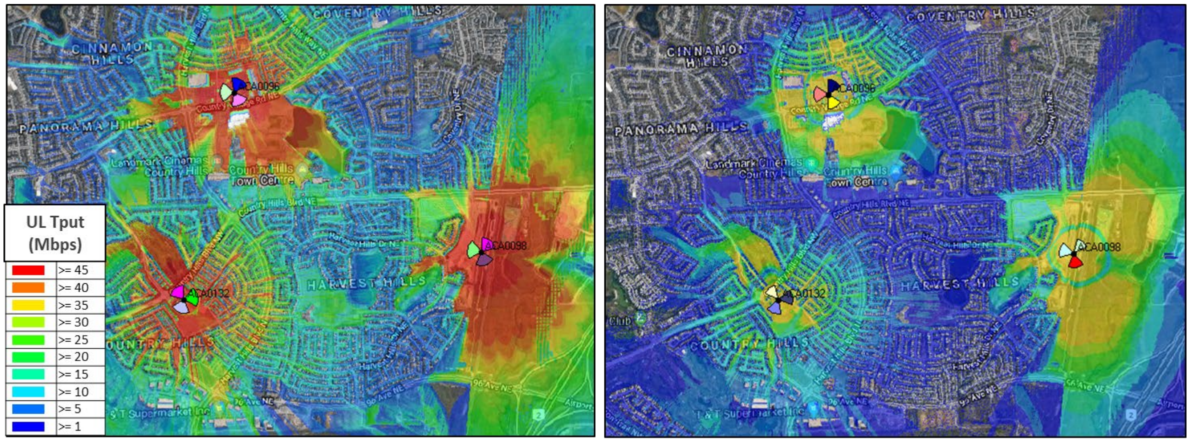


(a) 3.5 GHz (b) 2.5 GHz

Figure 13 - Downlink Throughput Predictions

In contrast, the predicted DL throughput for the 2.5 GHz band are much lower, typically less than 50 Mbps. This is due primarily to the difference in channel bandwidth between the two bands (i.e., 10 MHz vs. 60 MHz) and the lower RSRP at 2.5 GHz.

Figure 14 shows the predicted UL throughput for 3.5 GHz and 2.5 GHz. As shown in this figure, the UL throughput at 3.5 GHz is roughly 1/10th of the DL throughput rates. This is due to the DL/UL split ratio and lower system gain in the UL. There are also some areas where no coverage is available in the UL (e.g., east of Site 1).



(a) 3.5 GHz (b) 2.5 GHz

Figure 14 - Uplink Throughput Prediction

The UL throughput at 2.5 GHz is only marginally lower than at 3.5 GHz. For example, near the cell sites the UL throughput at 2.5 GHz is up to 35 Mbps versus 45 Mbps at 3.5 GHz. This is roughly proportion to the difference in effective UL bandwidth (i.e., 10 MHz at 2.5 GHz vs. 60 MHz /4 = 15 MHz at 3.5 GHz).

The predicted 28 GHz outdoor DL coverage is shown in Figure 15 and Figure 16 for Site 1. In this case, the coverage area is significantly smaller than the 3.5 GHz band. This difference is due to several factors, including lower EIRP (57.1 vs. 78 dBm), lower antenna heights, and higher obstruction (e.g., buildings, foliage) losses. The impact of buildings and other obstructions on the DL coverage is clearly illustrated in Figure 16.

Figure 15 - 28 GHz Coverage Prediction

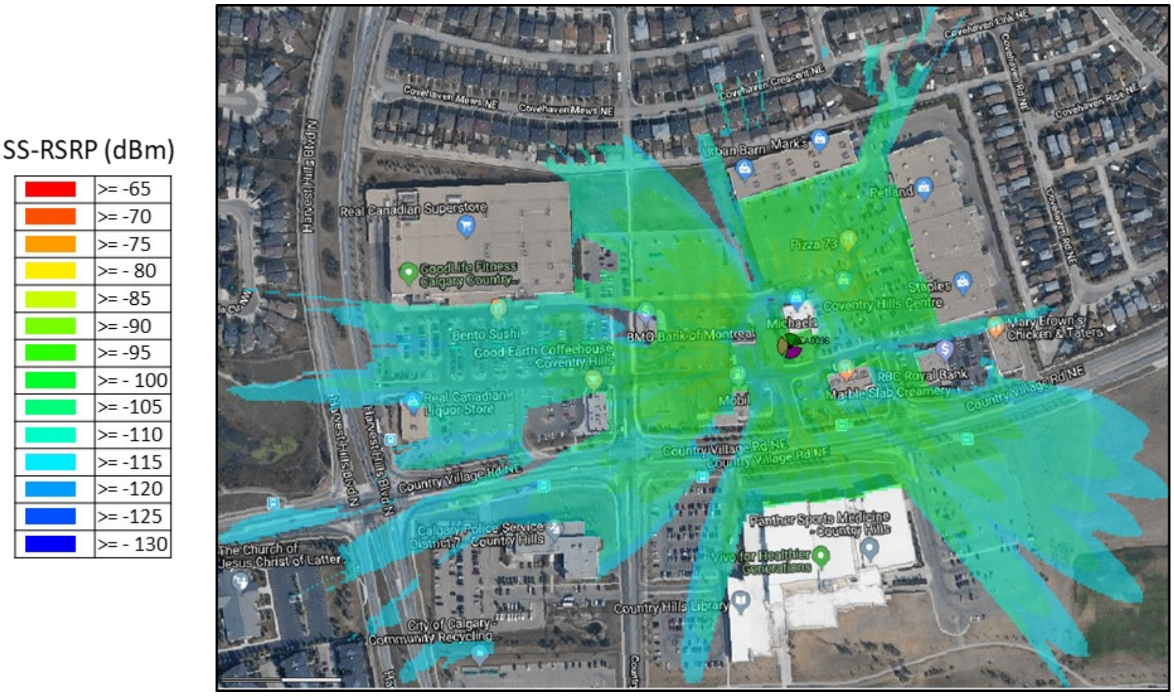
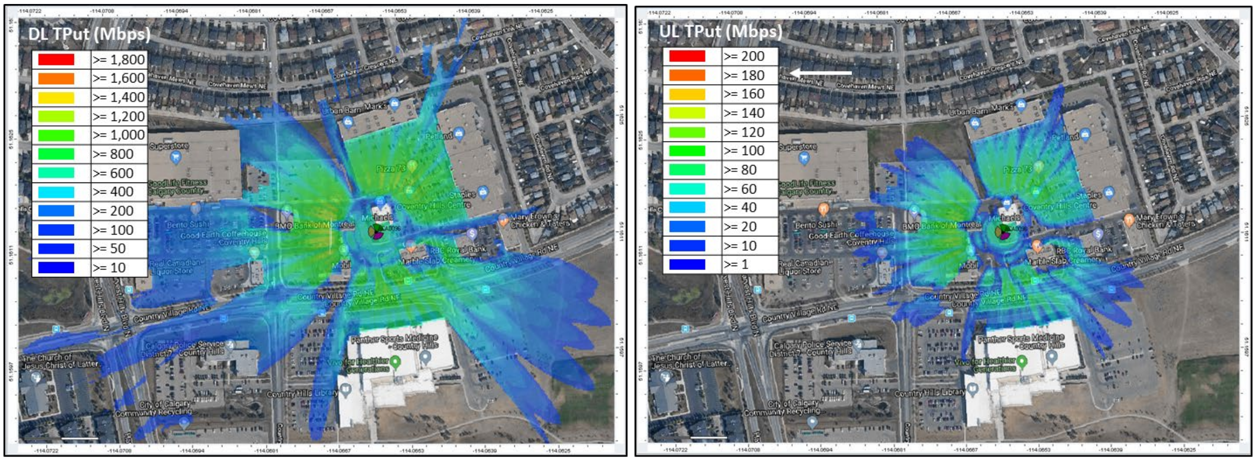


Figure 16 - 28 GHz Coverage Prediction at Site 1

Figure 17 shows the predicted outdoor DL and UL throughput for the 28 GHz band. This assumes a 4:1 split between DL and UL time slots. Although DL data rates of 1 Gbps are predicted at distances of up to 200 meters (660 feet) from the cell site, the DL throughput rate drops quickly beyond this distance. Like 3.5 GHz, the predicted UL throughput rates are roughly 1/10th of the DL throughput rates. Again, this is due to the DL/UL split ratio and the difference in system gain in the UL.



(a) DL Throughput (b) UL Throughput

Figure 17 - Predicted 28 GHz Outdoor Throughput

System Tests

4. Test Methodology

Two types of testing were conducted to verify the 5G NR trial system: functional testing and performance testing. Functional testing was conducted first to demonstrate the basic functionality and interworking of 5G NR RAN solution in NSA Option 3X mode. The high-level functional testing included the following tests for both 3.5 and 28 GHz:

- LTE-5G interworking
- NSA end-to-end first calls
- Handover testing
- Beamforming and beam selection

LTE-5G interworking validated the functionality of the X2 link between the LTE eNB and 5G gNB, including the X2-C and X2-U links. The S1-U link between the gNB and S/PGW was also tested. NSA end-to-end testing included DL and UL 5G data call attach procedures, DL & UL data, and data call release.

In addition, two tests were performed to validate beamforming and selection at both 3.5 GHz and 28 GHz. The first test verified that the carrier signal from each beam was visible within its expected coverage area. The second test confirmed that the beam selection and tracking functions were working properly by ensuring that UEs seamlessly switched from one beam to another as they moved within the cell site coverage area.

The performance testing included both stationary and drive testing. The stationary tests were conducted with the Qualcomm and WNC MTPs. Stationary throughput and latency tests were done at both 3.5 and 28 GHz for outdoor locations ranging from 50 m (164 feet) to up to 900 m (2,952 feet) from the cell sites. The drive testing involved driving a pre-defined route within the coverage area of the three cell sites and measuring key air interface and network quality parameters, including reference signal receive power (RSRP) and signal-to-interference-plus-noise ratio (SINR).

Keysight's Nemo Outdoor 5G NR drive test solution was used to collect drive test data and provide reports on the key metrics. In addition to collecting data from the mobile test platforms (MTPs), Nemo Outdoor was also used to collect data from two PCTEL scanning receivers: IBflex and HBflex.


(a) IBflex
(b) HBflex

Figure 18 – Scanning Receivers

IBflex was used to collect data for the 2.5 GHz and 3.5 GHz bands and HBflex was used to collect data for the 28 GHz band. Scanning receivers are best suited for coverage measurements because they can measure the signals from all cells in one pass, whereas a UE can only measure signals from a single cell. Scanners are also able to measure the synchronization signal block (SSB) beams, which is the basic coverage measure of the 5G NR. Both scanners were equipped with omni-directional antennas with 3 dBi gain, which were mounted on the roof of the drive test vehicle.

As shown in Figure 11, the Qualcomm MTP was mounted inside the vehicle on the passenger seat and the WNC MTP was mounted on the dash. Although the UEs support coarse beamforming, the antenna gain and MIMO performance is device dependent. In contrast, the scanners provide a common reference point for device agnostic coverage measurements.

The drive test route covered the area within roughly a 2 km (1.2 mile) radius from the three cell sites and is shown in Figure 19. The results of the drive tests were compared with the predicted coverage and are reported in Section 5.

Figure 19 - Drive Test Route

5. Test Results

5.1. Functional Tests

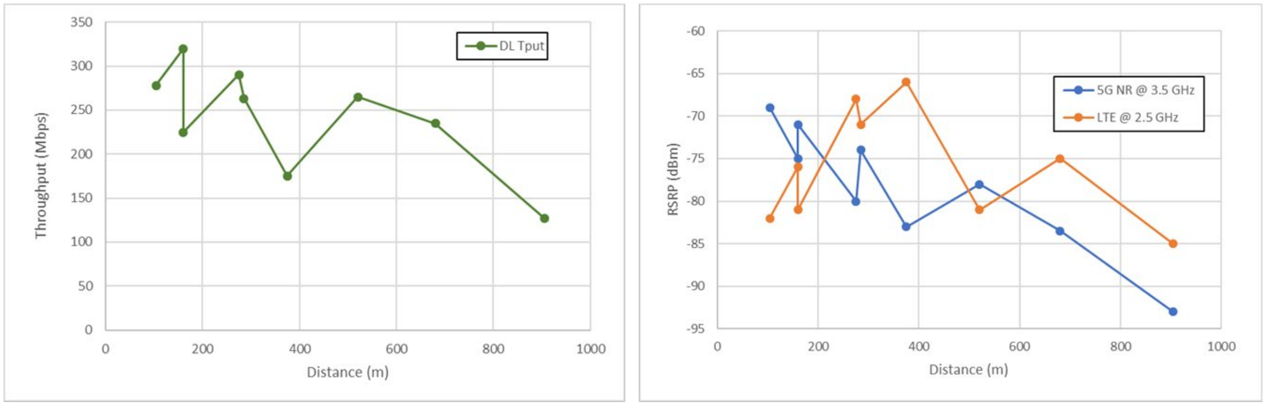
During functional testing, we were able to validate proper LTE-5G interworking on the X2 and S1 interfaces. We were also able to complete end-to-end 5G NR data calls at both 3.5 GHz and 28 GHz. Beamforming and selection tests validated that that the individual beams were being formed and selected as expected by the UE. We were also able to confirm that the UE could move from one beam to another without disrupting the session.

Although handover of 5G data calls was not supported by the gNB software release used in the trial, we were able to successfully test the reconnection of 3.5 GHz 5G NR data calls during LTE call handovers between adjacent sites. In this case, the 5G NR data call would drop when leaving the coverage area of one site and then seamlessly reconnect after entering the 3.5 GHz coverage area of the adjacent cell.

5.2. Performance Tests

5.2.1. Stationary Tests

The stationary tests at 3.5 GHz were taken at nine fixed locations ranging from about 100 m (328 feet) to 900 m (2,952 feet) from Site 1. All tests were taken with the WNC UE and the results are shown in Figure 20. The chart in Figure 20 (a) shows the DL throughput at 3.5 GHz at various distances. The maximum DL throughput measured was 320 Mbps at 160 m (525 feet), which is close to the maximum theoretical peak throughput of 342 Mbps. Even at 900 m, the DL throughput was over 125 Mbps. Unfortunately, reliable UL throughput results were not available due to limitations with the current test setup.



(b) Throughput

(a) RSRP

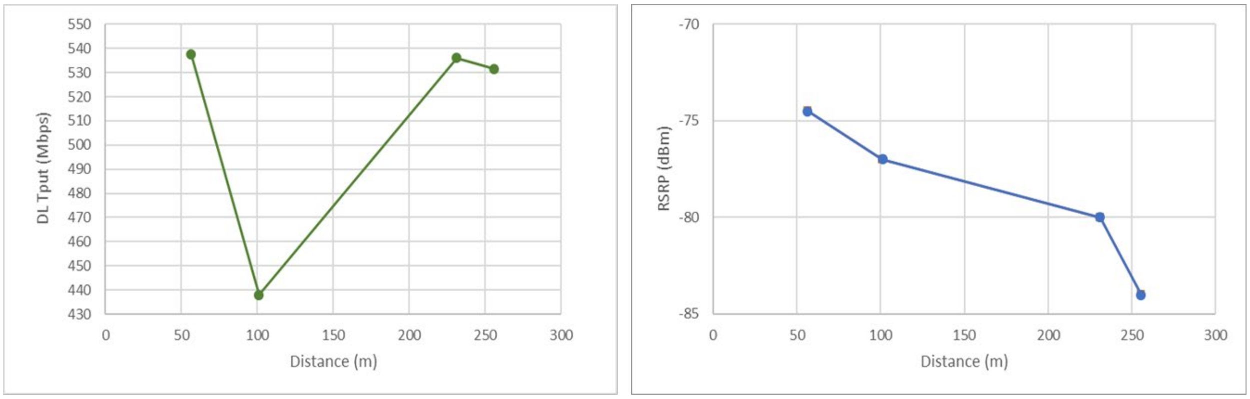
Figure 20 - 3.5 GHz Stationary Test Results

The chart in Figure 20 (b) compares the RSRP for 3.5 GHz and 2.5 GHz. These results show that while the RSRP at 3.5 GHz was higher than the RSRP at 2.5 GHz within the first 200 m from the cell site, the opposite was true beyond that distance with one exception. This is contrary to the coverage predictions in Section 3, which generally showed that the RSRP at 3.5 GHz was higher than that at 2.5 GHz at all distances.

To investigate this discrepancy, we also compared the actual and predicted RSRP at both 3.5 GHz and 2.5 GHz for all 9 test locations. On average, the actual RSRP at 3.5 GHz was 7.9 dB lower than the predicted

RSRP. In contrast, the actual RSRP at 2.5 GHz was 3.9 dB higher on average than the predicted RSRP, which is consistent with the typical accuracy for coverage predictions. Although these statistics were for a relatively small sample set, similar results were observed during drive testing, which is discussed further in Section 5.2.2. Although further investigation is required to determine the source of the above discrepancy, we suspect that further tuning of 3.5 GHz propagation model is likely required. Another possible source for the discrepancy is errors in the modeling assumptions, such as UE antenna gain, for which exact specifications were not available.

The stationary tests were also taken at 28 GHz at four fixed locations ranging from roughly 50 m (164 feet) to 250 m (820 feet) from Site 1. All test were taken with the Qualcomm UE and the results are shown in Figure 21.



(b) DL Throughput

(a) RSRP

Figure 21 - 28 GHz Stationary Test Results @ 100 MHz

The chart in Figure 21 (a) shows the DL throughput at 28 GHz for a single 100 MHz component carrier. The maximum DL throughput was 538 Mbps, which is close to the maximum theoretical throughput of 547 Mbps for a single 100 MHz component carrier. Results were fairly consistent up to a distance of 256 m (840 feet) for line of sight (LOS) locations (data points 1, 3 and 4). The minor differences in DL throughput are likely due to slight variations in the block error rate (BLER) experienced during testing. The second data point, collected at 100m, was shadowed by foliage per test design. This produced a higher BLER and lower modulation coding scheme (MCS) level, which in turn resulted in less than maximum throughput.

Separate testing with four (4) 100 MHz component carriers was also carried out and yielded DL throughput rates of up to 2.1 Mbps, slightly below the theoretical maximum. Unfortunately, limitations with the current test configuration prevented testing DL throughput at greater distances. Similarly, UL throughput testing was also unavailable. Both these aspects will be tested in a future phase.

The round-trip latency test results are shown in Figure 22 for both 5G (at 28 GHz) and LTE. These results were obtained by running ICMP (aka ping) tests between the UE and the core network. The results show that the median 5G latency at 8.5 msec is almost 4 times lower than median LTE latency at 32.5 msec. A couple of different factors were at play here. First, 5G allows a relatively shorter slot duration and more frequent scheduling. This minimizes the average wait time at the physical layer. Second, the use of connected mode discontinuous receive (DRx) was enabled in LTE to improve UE battery life. This resulted in a relatively larger spread in LTE latency. Further reductions in latency will be realized in 5G when mini-slots are supported in the future.

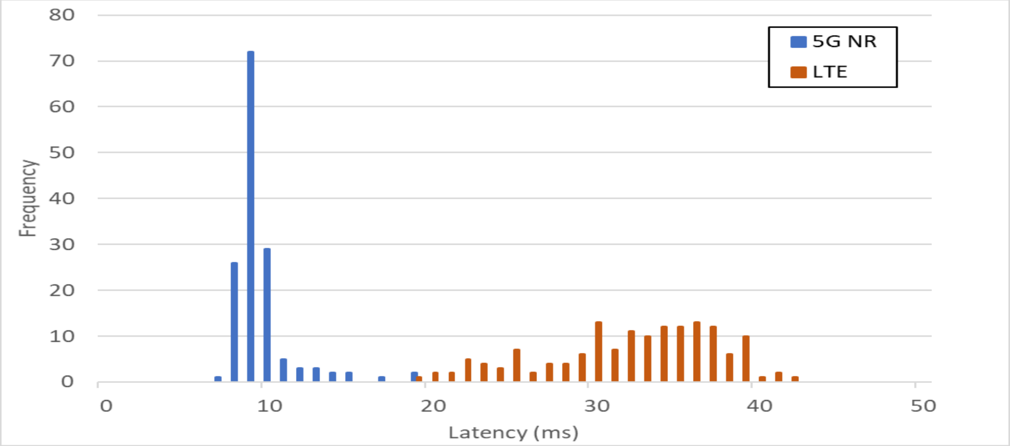


Figure 22 - Round-trip Latency Test Results

5.2.2. *Drive Tests*

The drive test results for 3.5 GHz and 2.5 GHz are shown in Figure 23 and Figure 24, respectively. These plots show the RSRP as measured by the PCTEL IBflex scanner during the drive testing. A visual inspection of these plots shows that the RSRP at 3.5 GHz is roughly 5 to 10 dB lower than the RSRP at 2.5 GHz over most of the drive route. These results are consistent with the stationary tests results reported in the previous section. As such, the 2.5 GHz band in the case could be used to extend the 5G DL coverage at 3.5 GHz, as described in Section 1.3.

A visual comparison between the drive test results in the figure below and the predicted coverage at 3.5 GHz in Section 3 also shows a noticeable difference between the predicted and actual RSRP, particularly at longer distances from the cell sites. This is shown more clearly in Figure 25, where the drive test data is overlaid on the coverage prediction. As mentioned in Section 5.2.1, we suspect these differences could be reduced by tuning the 3.5 GHz propagation model to better reflect the actual coverage.

Using the drive test data, we also took a closer look at the RSRP at 3.5 GHz and 2.5 GHz as a function of distance. These results are plotted in Figure 26 and Figure 27 for two specific cells: Site 1, Cell 1 and Site 3, Cell 3. These scatter plots show the drive test results from both the scanner and the WNC UE. As shown in Figure 26, there is good correlation between the scanner and WNC UE results, although the RSRP measured by the UE is roughly 4-6 dB lower. Figure 26 also shows, like the stationary tests in Section 5.2.1, that the 3.5 GHz RSRP is higher than the 2.5 GHz RSRP near the site, but lower at greater distances.

In contrast, Figure 27 shows that the 3.5 GHz and 2.5 GHz results are roughly the same over the entire range. In fact, there are several instances where the 3.5 GHz RSRP is higher than the 2.5 GHz RSRP at longer distances. These divergent results may be attributable in part to differences in the antenna/MAA height and down tilt. As indicated in Table 2, the 3.5 GHz MAA at Site 1 is mounted at 29 m above ground level, whereas the 2.5 GHz antenna is mounts at 40.2 m. At Site 3, both the 3.5 GHz MAA and 2.5 GHz antenna are mounted at the top of the tower at 30m. In addition, the antenna/MAA down tilt at Site 1 is 5 degrees for all sectors/cells versus 0 degrees at Site 3. This likely explains the relatively high RSRP at 3.5 GHz adjacent to the tower at Site 1. Based on the above, further optimization of the antenna/MAA heights and down tilts is required to fully maximize the 3.5 GHz coverage.

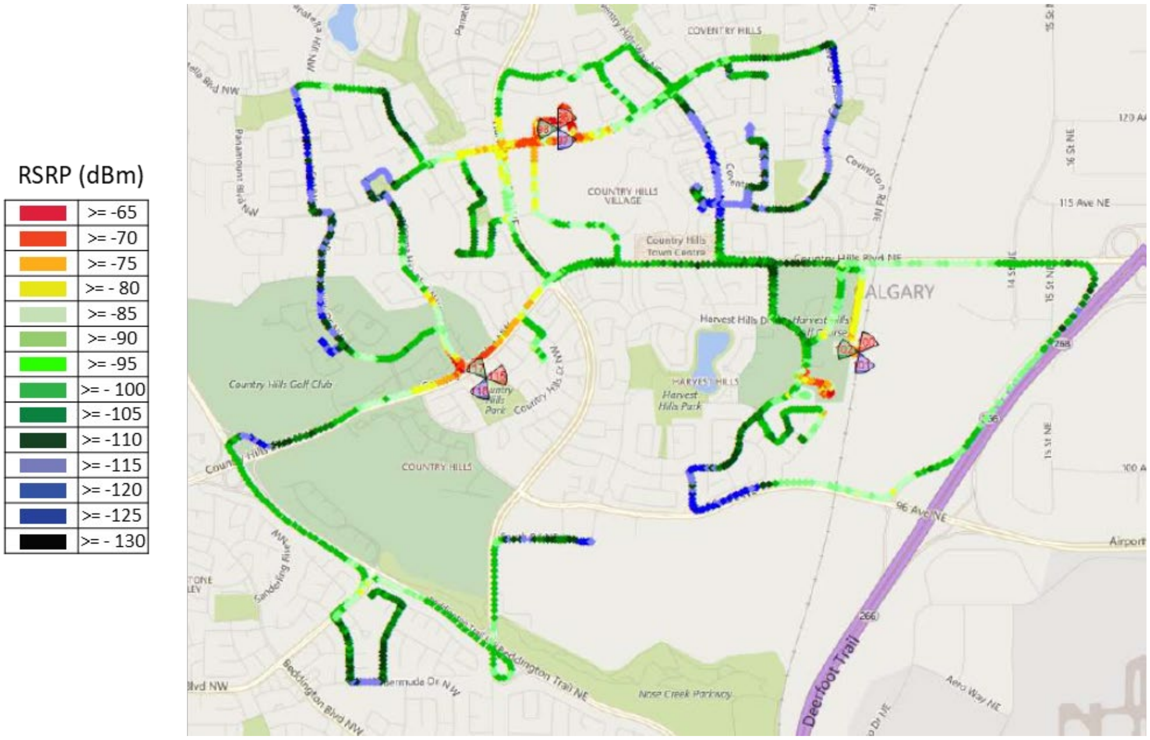


Figure 23 - RSRP on 5G NR @ 3.5 GHz

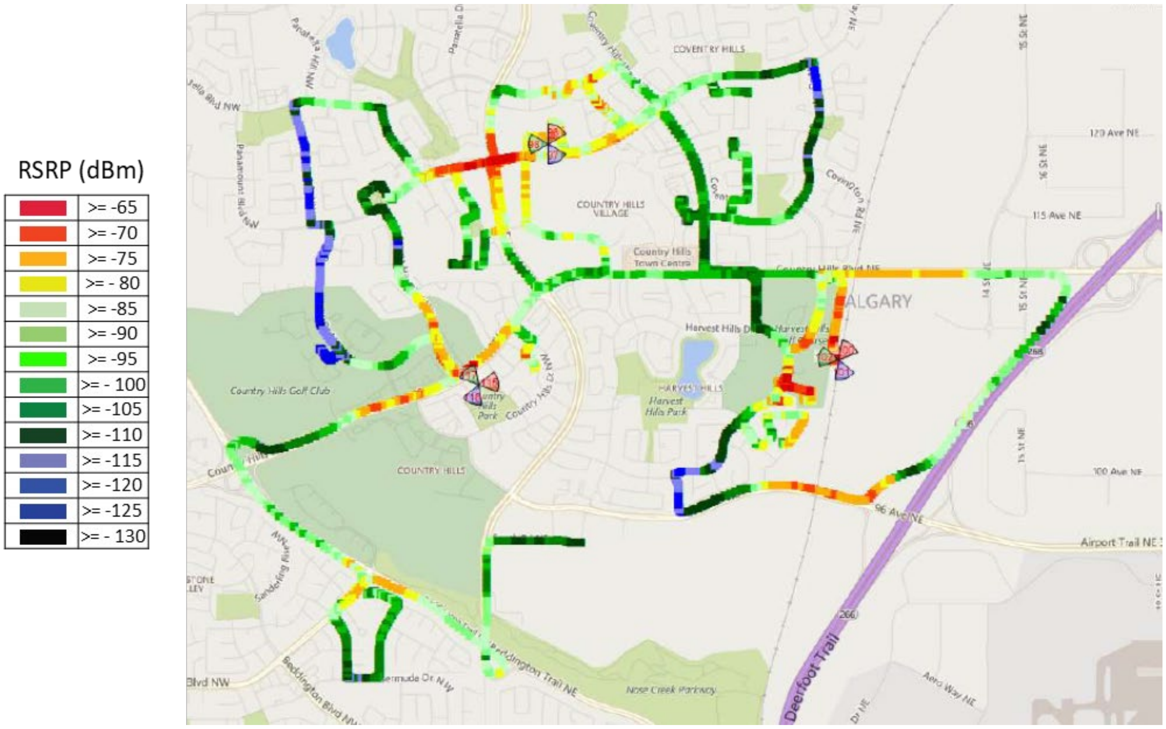


Figure 24 - RSRP on LTE @ 2.5 GHz

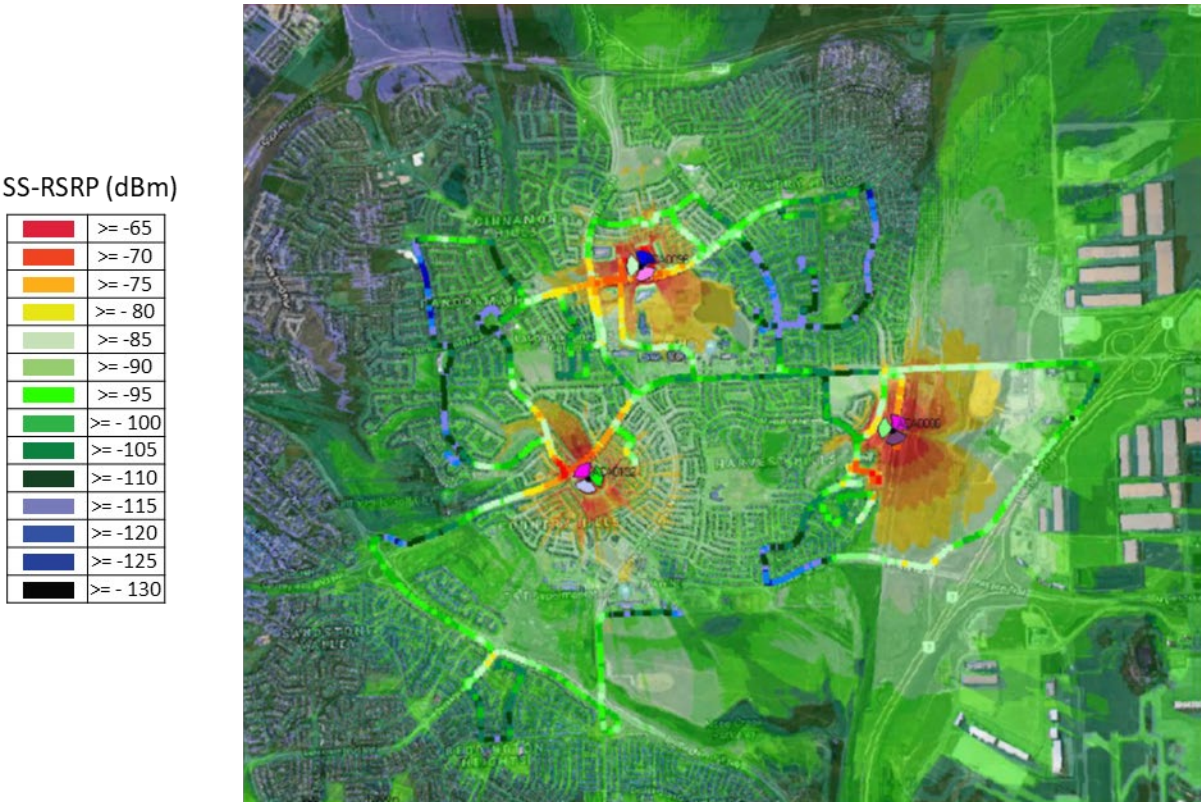
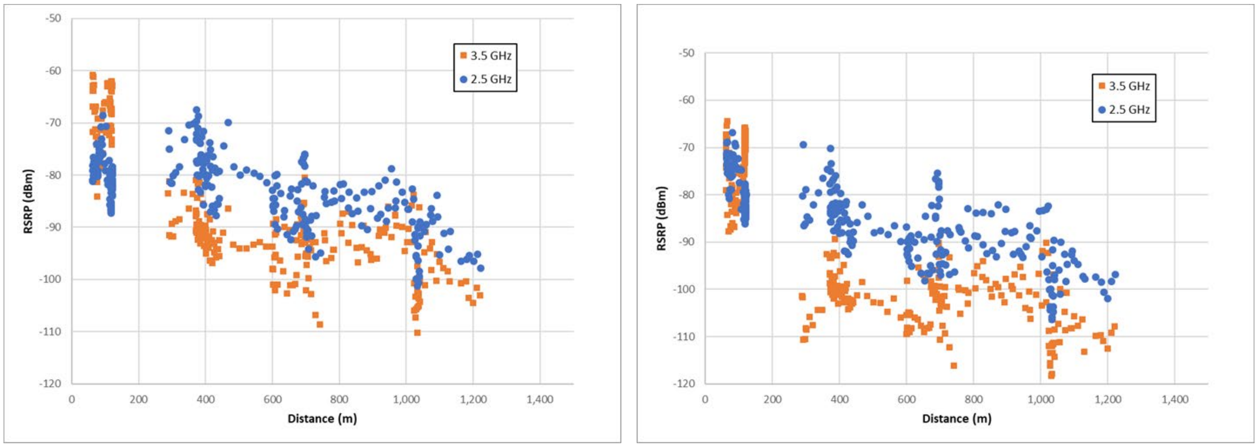


Figure 25 - 3.5 GHz Coverage Prediction and Drive Test Comparison

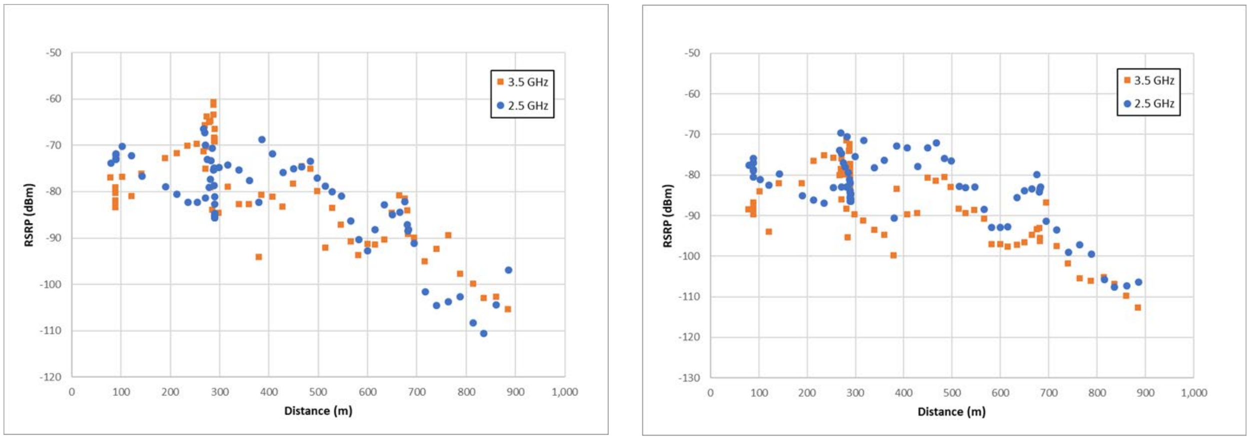


(a) Scanner RSRP

(b) UE RSRP

Figure 26 - 3.5 GHz and 2.4 GHz Drive Test Results for Site 1, Cell 1

Drive test results for the 28 GHz band are shown in Figure 28 for Site 1. This figure shows the RSRP as measured by the PCTEL HBflex scanner during the drive test. A visual comparison between the drive test results shown in the figure below and the predicted 28 GHz coverage in Section 3 shows relatively good correlation between the two within roughly 250m of the cell site. Beyond that distance, the predicted coverage diminishes rapidly, whereas the drive test data indicates that the actual coverage extends much farther, particularly where line of sight (LOS) locations. These results suggest that the 28 GHz propagation model also requires further tuning to better approximate the roll-off of RSRP with distance.



(a) Scanner RSRP

(b) UE RSRP

Figure 27 - 3.5 GHz and 2.4 GHz Drive Test Results for Site 3, Cell 3

While the coverage at 28 GHz is clearly not adequate to provide contiguous mobile coverage without significantly more cell sites, the results suggest that it can be used to provide exceptionally high speeds (up to 2.1 Gbps) in high traffic areas such as outdoor plazas and shopping areas.

SS-RSRP (dBm)

🟥	>= -65	0%
🟥	>= -70	0%
🟧	>= -75	0%
🟨	>= - 80	1%
🟩	>= -85	9%
🟩	>= -90	23%
🟩	>= -95	21%
🟩	>= - 100	17%
🟩	>= -105	7%
🟩	>= -110	5%
🟪	>= -115	3%
🟦	>= -120	3%
🟦	>= -125	7%
⬛	>= - 130	3%

Figure 28 - 28 GHz Drive Test Results

In addition, the 28 GHz band can potentially be used to provide fixed wireless access (FWA) services in suburban areas not already served by the MSO. Unfortunately, FWA terminals were not available for testing so this remains an area for further study.

Conclusion

While 5G deployments are progressing rapidly, relatively little has been published to date on real-world 5G performance. This paper attempts to fill that gap by presenting the results of extensive pre-commercial 5G field trials conducted by Freedom Mobile from June to August 2019. Both functional and performance tests were carried out in two 5G NR frequency ranges: the 3.5 GHz mid-band and the 28 GHz high band (or mmWave band). We also conducted extensive drive testing in both bands to validate RF coverage performance.

The test results showed that 5G can support extremely high DL throughputs under real-world conditions. For example, DL data rates of up to 2.1 Gbps were achieved at 28 GHz using a pre-commercial UE with 2x2 MIMO, 4 x 100 MHz channels, and a 4:1 DL/UL split ratio. At 3.5 GHz, DL data rates of up to 320 Mbps were observed using a pre-commercial UE with 2x2 MIMO, 60 MHz channel bandwidth, and an 8:2 DL/UL split ratio. These high data rates will enable a whole new range of applications such as augmented reality (AR) and virtual reality (VR).

Performance testing also showed significant reductions in latency are possible with 5G. A median round-trip latency of 8.5 msec was measured at 28 GHz. This was roughly 4 times lower than the LTE latency measured at 2.5 GHz. Further reductions in latency will be realized in 5G when mini-slots are supported in the future, which will make possible low latency applications such as autonomous driving and smart grid.

Coverage predictions and drive testing suggest that seamless (or near seamless) 5G coverage can be provided at 3.5 GHz using existing cell sites with careful site planning and optimization. This would significantly reduce the cost and time needed to deploy 5G networks. The same cannot be said for 28 GHz, where the coverage area was significantly smaller than at 3.5 GHz. As a result, deploying seamless handheld coverage at 28 GHz is not likely to be viable but it could be used to provide extremely high speeds and capacity in high traffic density areas such as outdoor plazas and shopping/commercial areas.

This paper also discussed a few practical considerations with deploying 5G networks. First, we showed that 5G NR coverage in non-standalone (NSA) mode is affected by the choice of LTE anchor carrier. Depending on the dual connectivity combination, coverage may be enhanced or reduced by the choice of LTE anchor carrier. For example, the trial results suggest that the combination a 2.5 GHz LTE anchor carrier with a 3.5 GHz 5G NR carrier can extend the 5G DL coverage area.

We also discussed the importance of RF safety when deploying 5G NR. Given the higher EIRP of the beamforming antennas, RF safety studies are required to ensure maximum permissible RF exposure levels are not exceeded in uncontrolled environments accessible to the public.

While the test results discussed in this paper should be of value to MSOs planning to deploy 5G wireless networks, several topics were identified for further study. These included UL throughput testing at 3.5 and 28 GHz; 5G performance and drive testing at 600 MHz; and 5G backhaul over DOCSIS trials.

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Abbreviations

3G	third generation
3GPP	3G partnership project
4G	fourth generation
5G	fifth generation
AR	augmented reality
BBU	base band unit
BLER	block error rate
bps	bits per second
CPRI	Common Public Radio Interface
DL	downlink
DRx	discontinuous receive
EIRP	effective isotropic radiated power
eNB	evolved node b
EN-DC	evolved universal terrestrial radio access – NR dual connectivity
EPC	evolved packet core
FDD	frequency division duplexing
FWA	fixed wireless access
GB	Giga byte
Gbps	Giga bits per second
gNB	g node b
HSS	home subscriber system
Hz	hertz
ISBE	International Society of Broadband Experts
LOS	line of sight
MCS	modulation coding scheme
MIMO	multi-input, multi-output
MAA	massive antenna array
mmWave	millimeter wavelength
MPE	maximum permissible exposure
MME	mobility management entity
MTP	mobile test platform
NR	new radio
NSA	non-standalone architecture
OFDMA	orthogonal frequency division multiple access
PGW	packet data network gateway
RAN	radio access network
RF	radio frequency
RRH	remote radio head
RSRP	reference signal receive power
SGW	serving gateway
SCTE	Society of Cable Telecommunications Engineers
SINR	signal-to-interference-plus-noise ratio
SS	synchronization signal
SSB	synchronization signal block

SS-RSRP	synchronization signal - reference signal receive power
TDD	time division duplexing
TX	transmit
UE	user equipment
UL	uplink
VR	virtual reality
VNF	virtualized network function

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