Qualcomm Technologies, Inc.

# Mobilizing 5G NR Millimeter Wave: Network Coverage Simulation Studies for Global Cities

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# Qualcomm Technologies, Inc.



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# 1 Executive summary

Enhancing mobile broadband services is one of the key initial driving forces behind 5G, fueled by the insatiable demand for faster and better mobile experiences. Mobile networks are facing soaring demands for mobile data as consumers increasingly utilize mobile devices to share and consume high-definition multi-media. In addition, as the capabilities of mobile devices continue to grow with advancements such as higher-resolution cameras, 4K video, always-connected cloud computing, and virtual/augmented reality, so does the ever-increasing demand for faster, better connectivity. A recent study[1] showed that mobile data traffic is expected to grow to approximately 50B Gigabytes per month by 2021, representing an impressive growth rate of 47% CAGR from the period of 2016 to 2021.

While it is still being extensively tested, the use of high-frequency spectrum bands above 24 GHz, loosely known as millimeter wave (mmWave), is emerging as a key 5G technology. The use of these bands is very compelling as the large bandwidths (100s of MHz) available at these high frequencies enable extremely high data rates and significant increases in capacity. Historically, mmWave bands were not robust enough for mobile broadband applications due to increased propagation loss and susceptibility to blockage (e.g. hand, head, body, foliage, building penetration). However, advanced antenna techniques that are being introduced with 5G New Radio (NR) – the global 5G standard – are changing this.

5G NR mmWave mobile deployments will require dense network topologies with inter-site distances (ISD) of ~150-200 meters. As a result, an additional potential deployment challenge with commercializing 5G NR mmWave is the perceived requirement for many additional small cell sites, which could delay the wide-scale commercial deployments and require large investments. One area of focus for 5G NR mmWave mobile deployments will be high-traffic urban areas in large global cities. To help assess this deployment challenge for 5G NR mmWave, Qualcomm Research conducted an extensive set of 5G NR mmWave network coverage simulation studies in numerous global cities.

The objective of this paper is to provide details on the methodology and results from these simulation studies. The results of the simulation studies conducted across ten global cities, show that significant outdoor downlink coverage (up to 81%) is possible when co-siting 5G NR mmWave with existing 4G LTE macro and small cell sites. The positive results show that mobile deployments in urban-areas based on existing LTE cell cities is feasible, especially when considering the tight-interworking of 5G NR with 4G LTE.

Although mmWave outdoor-to-indoor coverage for mobile is not feasible, the outdoor mmWave coverage will significantly free up resources in the spectrum bands below 6 GHz for outdoor-to-indoor capacity, utilizing either 4G LTE or 5G NR technology. In addition, outdoor mmWave coverage can be complemented with targeted indoor mmWave deployments. An example coverage simulation for a large indoor venue is also included in the paper.

The paper will also provide some background on the key properties for robust 5G NR mmWave operation in a non-line-of-sight (NLOS) mobile environment, as well as showcase how Qualcomm Technologies is leading the way to mobilize 5G NR mmWave and make it a commercial reality in 2019.

[1] Cisco Visual Networking Index: Global Mobile Data Traffic Forecast (Feb'17)

# 2 Mobilizing mmWave with 5G NR technologies

The ever-increasing global demand for enhanced mobile broadband service is driving the need to access more wireless spectrum. Spectrum is the lifeblood of mobile connectivity — access to more spectrum increases network capacity, which means faster data rates and better user experiences. One key opportunity 5G will bring is making use of new higher spectrum bands not previous suitable for mobile communications. 5G NR is being designed not only for bands below 3 GHz where most mobile communications happen today, but also to provide a unified design that will make use of mid-bands, such as 3.3 to 6 GHz, as well as high-bands above 24 GHz, loosely known as mmWave.

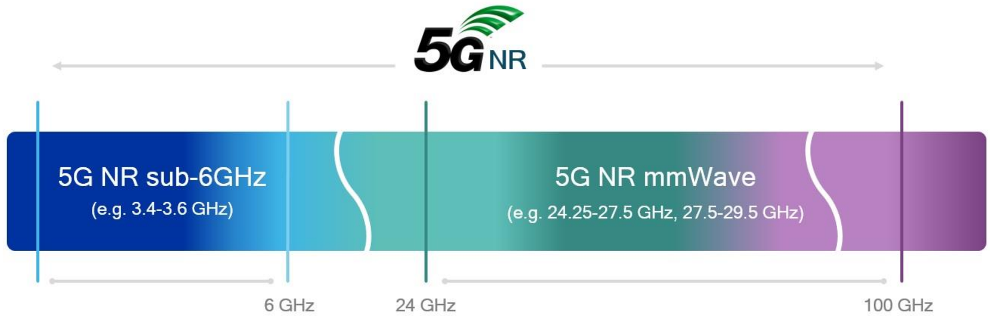



Figure 1: Unified 5G NR design across diverse spectrum bands and types

Although high-bands above 24 GHz have been utilized for quite some time in carefully engineered fixed, line-of-sight wireless communications for wireless backhaul and satellites, mmWave is a new frontier for mobile. To date, mobile networks were only deployed at scale below 3 GHz because higher frequencies, especially mmWave bands, were not robust enough mobile broadband applications due to increased propagation loss and susceptibility to blockage.

Mobilizing mmWave requires a new 5G NR system design, as shown in Figure 2, to overcome these robustness challenges. These advancements are being driven by radical improvements in silicon computation capability, as well as the ability to integrate large numbers of antenna elements and RF chains into cost-effective phased-array RFICs to make mobile device form factors, including smartphones, a possibility.

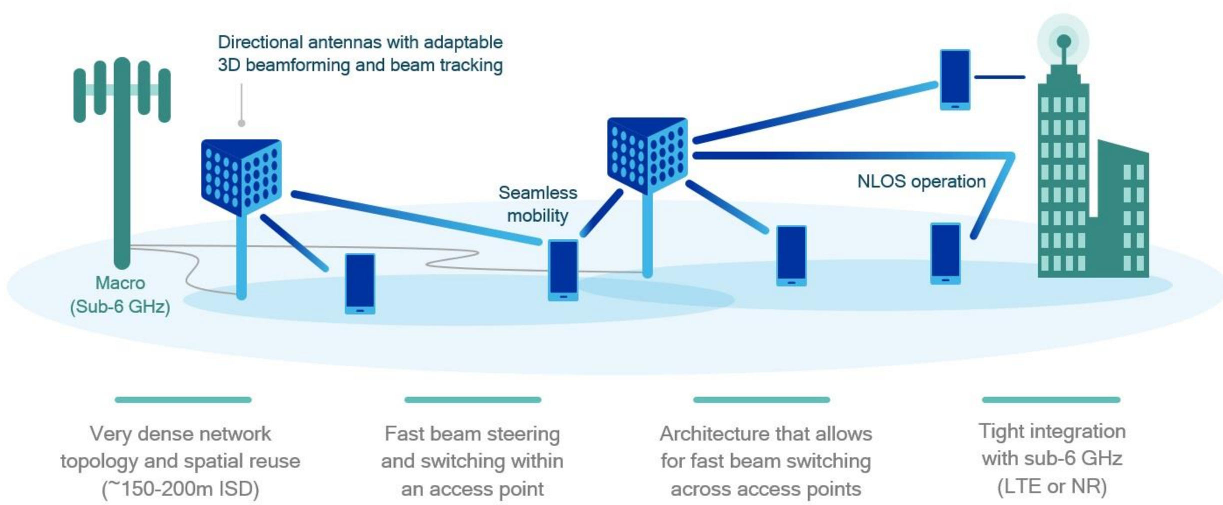



Figure 2: Mobilizing mmWave with advanced 5G NR technologies

As implied by the name (millimeter wave), the small wavelengths at these higher frequencies makes the use of many antenna elements in a relatively small form factor possible. This characteristic of mmWave will be utilized in the 5G NR mmWave system to make use of massive MIMO antenna arrays to create highly directional beams that focus transmitted RF energy to overcome the propagation and path loss challenges in both the uplink and downlink. These directional beams can also be utilized for spatial reuse.

A major lesson learned from the mmWave simulations, channel measurements, and field testing is that it is possible to capture reflected signals – in effect, non-line-of-sight (NLOS) signals – and use them to supplement the line-of-sight (LOS) signal to increase channel capacity. It is therefore possible to use reflected signals to maintain a link to a mobile device even when it moves entirely out of LOS of the transmitter and this is one reason we can radically expand the role of mmWave for 5G mobile broadband.

The 5G NR mmWave system must also adapt quickly to the rapidly changing channel conditions. At mmWave frequencies, even small variations in the environment, such as the turn of the head, movement of the hand, or a passing car, can change the channel and impact performance. The 5G NR mmWave system will employ fast beam steering and switching techniques to discover and switch quickly to the dominant beam path, both within and across access points.

As mmWave will deliver more localized indoor/outdoor coverage when compared to spectrum bands below 6 GHz, the 5G NR mmWave system will also require tight integration with sub-6 GHz bands to ensure wide area coverage and a seamless user experience. 5G NR will deliver this tight integration via dual-connectivity where multimode devices simultaneously connect to both sub-6 GHz bands for wide-area coverage and mmWave bands for additional bandwidth and capacity boost. Even in 5G NR mmWave coverage, devices will simultaneously connect to sub-6 GHz (with either 5G NR or 4G LTE technology) to provide faster system acquisition and robustness to fading and micro coverage holes. The anchor cell (typically a 4G LTE or 5G NR sub-6 GHz macro cell) provides coverage and handles control procedures for channel acquisition, paging and mobility, while a non-collocated mmWave booster cell provides more localized, high-capacity services with seamless mobility.

# 3 5G NR mmWave network coverage simulation studies

Based on a theoretical framework of mmWave mobile access, supported by extensive channel measurements and over-the-air testing conducted by Qualcomm Research, a set of simulation studies were performed in urban areas of large global cities to estimate the realistic span of outdoor coverage. This section describes the methodology used to perform these simulation studies in the most accurate manner.

## 3.1 Defining the geographic maps and site locations for the simulation studies

For the simulation studies, dense urban areas of global cities that experience high mobile traffic were selected. Barring some city-specific variations, a contiguous geographical area of approximately ten square kilometers was used for each of the cities. To ensure accurate signal propagation estimation, high-resolution geographical maps of the global cities with 2m x 2m resolution were utilized, including 3D building databases. In addition to the city buildings, since foliage can potentially create impediments to the propagation of mmWave signals, the 3D geographical maps utilized for the simulations also included accurate and up-to-date information about foliage type, depth, height, and other relevant details. This information was then used in the network planning tool to estimate foliage attenuation based on relevant details including attenuation-per-meter assumptions.

For the simulation studies for each city, a one-to-one 5G NR mmWave co-siting deployment on existing 4G LTE sites was assumed. This was based on existing site locations obtained from a leading mobile network operator in each city. The network operator identity and the exact details on the site locations is not disclosed to protect confidential data. Both macro and micro-cells that are in service today have been taken into consideration for such study, including exact antenna height and orientation of the existing LTE sites. No outdoor Wi-Fi assets or locations have been used for these simulations studies, which could have further improved the mmWave coverage footprint by including operator's Wi-Fi assets with one-to-one 5G NR mmWave co-siting.

## 3.2 Establishing a 5G NR mmWave link budget and RF propagation model

For the simulation studies, a 5G NR mmWave link budget was developed for a target downlink cell edge spectral efficiency of 0.4 bps/Hz using a 100 MHz component carrier (scalable up to 800 MHz).

To follow a consistent approach aligned with 3GPP for these studies, the 5G NR mmWave link budget utilized the NLOS street canyon propagation model defined in 3GPP TR 38.900 for dense urban and urban morphology. As the simulation studies include both macro and micro cells, 3GPP Urban Macro (Uma) and Urban Micro (Umi) propagation models have been used for macro and micro cells respectively. The 5G NR mmWave link budget also accounts for additional losses including hand loss, body loss, and lognormal shadowing, based on extensive channel measurements and testing conducted by Qualcomm Research.

An example high-level 5G NR mmWave UE link budget[2][3][4] for 28 GHz downlink outdoor coverage that was used to perform the network coverage simulation studies is shown in Figure 3.

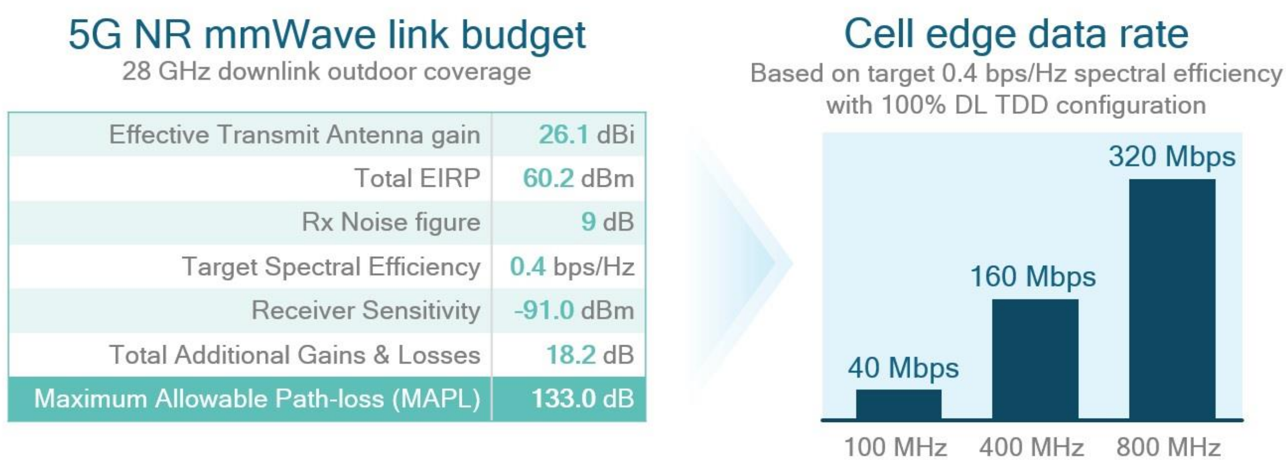



**Figure 3: Example high-level 5G NR mmWave link budget**

[2] Additional variations possible due to temporary blockage — field measurements to follow
[3] RX noise figure based on 3GPP TR 38.900 reference
[4] Additional gains and losses include receiver effective antenna gain, hand loss, body loss, lognormal shadowing, rain attenuation

## 3.3 Predicting 5G NR mmWave coverage

Once the 5G NR mmWave link budget was established and Maximum Allowable Path-Loss (MAPL) determined for the simulation studies, a commercial network planning tool used for LTE network planning was used for the simulation studies to predict 5G NR mmWave coverage. The studies were performed on a modified version of the LTE network planning module in line with 5G NR mmWave requirements based on the network planning tool vendor's guidelines. Considering the utilization of well-established network planning techniques, high-resolution geo maps with terrain and build data, actual LTE site databases, and 3GPP propagation models, there is high confidence that the results are very close to the actual 5G NR mmWave network coverage. Additional variations in coverage are possible due to temporary blockages and extensive over-the-air 5G NR mmWave field measurements are to follow.

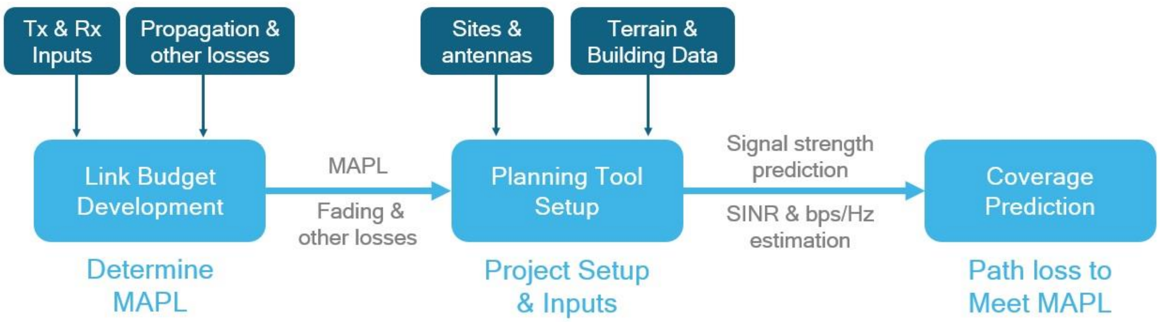



**Figure 4: 5G NR mmWave coverage prediction methodology**

# 4 5G NR mmWave network coverage simulation results

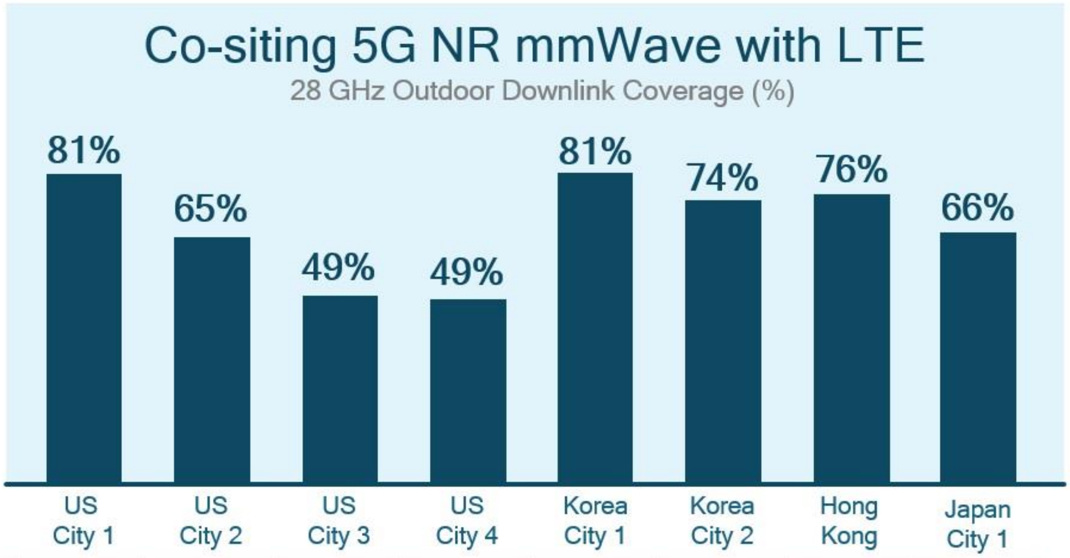
Based on the coverage prediction methodology summarized in Figure 4, an extensive set of 5G NR mmWave network coverage simulation studies were performed in large global cities. The key findings from these simulation studies are summarized below.

## 4.1 Significant 5G NR mmWave outdoor coverage with existing LTE sites

Based on the coverage prediction methodology summarized in the previous section, network coverage simulations studies were conducted across various global cities in dense urban areas approximately ten square kilometers in area (barring some city-specific variations). The results from these simulation studies for 28 GHz outdoor downlink coverage is summarized in Figure 5.

The results show that significant outdoor coverage is possible when co-siting 5G NR mmWave with existing 4G LTE macro and small cell sites. The positive results show that mobile deployments with seamless outdoor coverage in urban-areas is certainly feasible with high site density, especially when considering the tight interworking of 5G NR with 4G LTE. The results also show that macro cell density may not be sufficient for decent outdoor coverage, and that use of outdoor small cells is typically needed.

Although 5G NR mmWave outdoor-to-indoor coverage for mobile is not feasible, the outdoor mmWave coverage will significantly free up resources in the spectrum bands below 6 GHz for outdoor-to-indoor capacity utilizing either 4G LTE or 5G NR technology. It also frees up sub-6 GHz resources for outdoor capacity in areas not covered by 5G NR mmWave.




| Site density (per km2) | | US City 1 | US City 2 | US City 3 | US City 4 | Korea City 1 | Korea City 2 | Hong Kong | Japan City 1 |
|---|---|---|---|---|---|---|---|---|---|
| | Total | 48 | 36 | 32 | 31 | 41 | 31 | 39 | 37 |
| | Macro | 0 | 8 | 15 | 14 | 33 | 31 | 39 | 37 |
| | Small | 48 | 28 | 17 | 17 | 8 | 0 | 0 | 0 |

**Figure 5: Qualcomm Research 5G NR mmWave Network Coverage Simulation**

A signal strength heatmap for US City 2 (San Francisco, CA) based on these 5G NR mmWave coverage simulation results is shown in Figure 6. The cell edge data rate (based on target spectral efficiency of 0.4 bps/Hz) for the fair signal is 40 Mbps for 100 MHz bandwidth and 100% TDD DL configuration (320 Mbps for 800 MHz). Meanwhile, the cell edge data rate for an excellent signal based on the same assumptions is 500 Mbps for 100 MHz bandwidth (4 Gbps for 800 MHz).

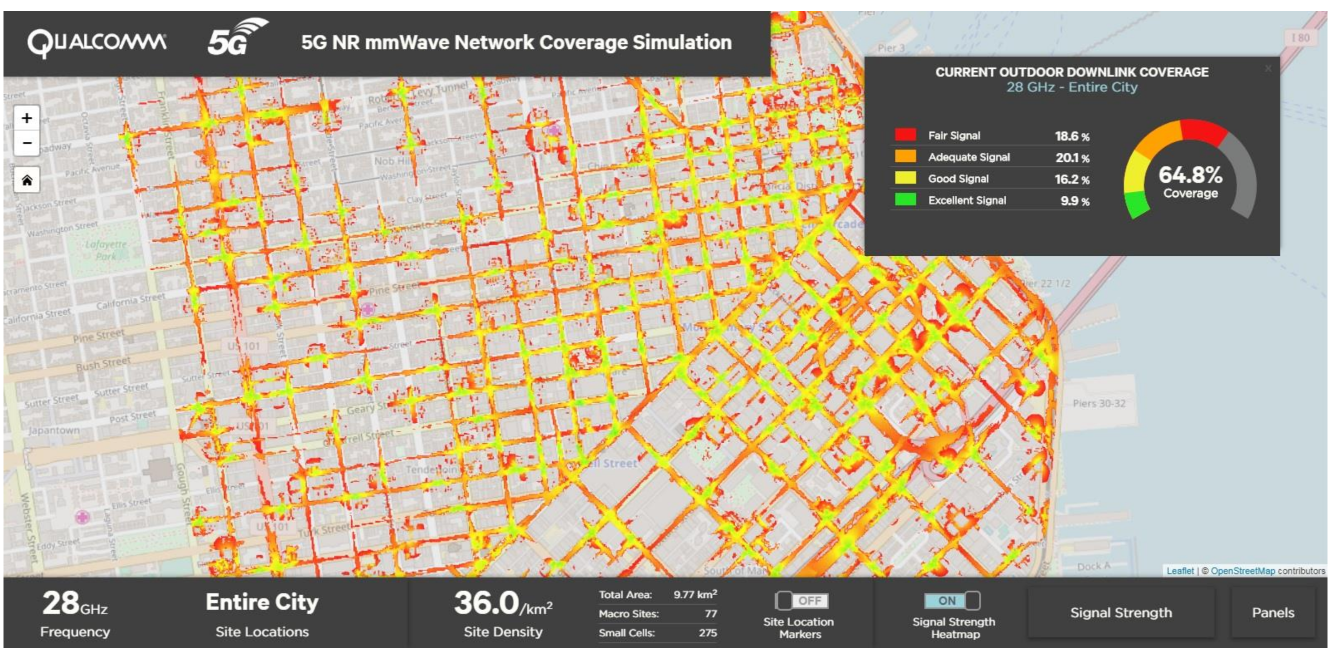



**Figure 6: San Francisco 5G NR mmWave coverage simulation**

Beyond the contributing impact of high site density on better outdoor coverage, the simulation studies revealed some key aspects of 5G NR mmWave helped contribute to the positive outdoor coverage results. One key contributing factor to the positive 5G NR mmWave outdoor coverage results is that legacy LTE sites were designed for out-to-in coverage. Other contributing factors include a higher Effective Isotropic Radiated Power (EIRP) for 5G NR mmWave versus 4G LTE small cells (while ensuring compliance with regulatory limits), as well as the use of massive MIMO antenna arrays (256x2 3D antenna array used for simulations) to create highly directional beams that focus transmitted RF energy to overcome the propagation and path loss challenges in both the uplink and downlink

Qualcomm Research is continuing to work on simulation studies for additional global cities and will also add uplink coverage studies to future simulation studies.

## 4.2 Achieving 95% 5G NR mmWave outdoor coverage with additional sites

In addition to the 5G NR mmWave network coverage simulation studies based on existing LTE sites in global cities, simulation studies were performed to assess the feasibility of achieving greater than 95% coverage, as well as compare 5G NR mmWave outdoor downlink coverage for 28 GHz versus 39 GHz (39 GHz outdoor MAPL ~1.5 dB weaker than 28 GHz[5]). The results of this are summarized in Figure 7. The study utilized a baseline configuration of 73 sites per square kilometer based on a 0.8 $km^2$ dense urban area in US City 2.

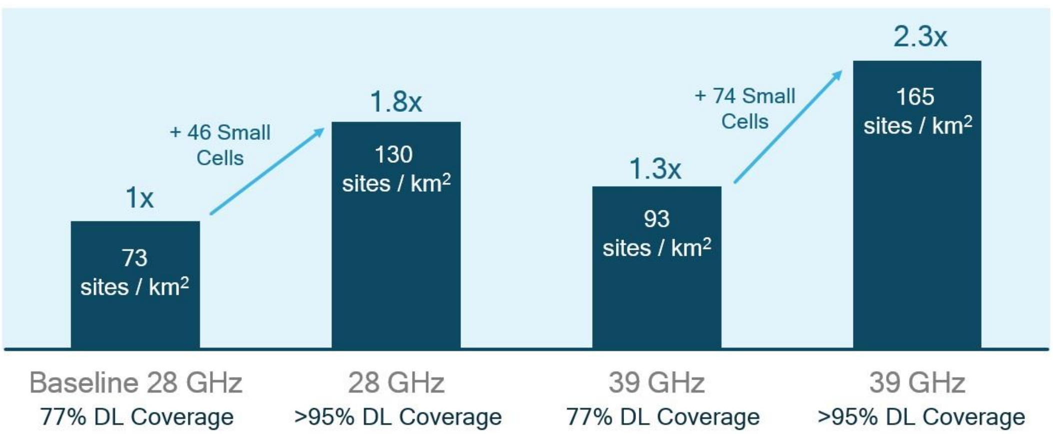



**Figure 7: Additional 5G NR mmWave coverage simulation studies**

The results show it is feasible to achieve 95% outdoor downlink coverage for 28 GHz by adding an addition 46 small cells (or increasing the site density by ~75%). Alternatively, the gap in coverage to reach 95% can be covered by utilizing sub-6 GHz bands (either LTE or 5G NR). The results also show that 39 GHz requires ~25% increase in site density to achieve the same outdoor coverage as 28 GHz.

## 4.3 5G NR mmWave can make use of LAA small cell deployments

4G LTE Licensed Assisted Access (LAA) was introduced in 3GPP release 13. It uses carrier aggregation in the downlink to combine LTE in unlicensed spectrum (5 GHz) with LTE in the licensed band. This aggregation of spectrum provides for a fatter pipe with faster data rates and more responsive user experience. LAA utilizes dual-connectivity, like 5G NR mmWave deployments, by maintaining a

[5] 1.5 dB MAPL delta does not include propagation difference; with ~3 dB propagation difference, the net delta would be ~4.5 dB

persistent anchor in the license spectrum that carries all the control and signaling information to deliver a user experience that is both seamless and reliable.

LAA is here today with commercial network launches in multiple cities, along with numerous commercial devices supporting LAA, powered by the Qualcomm Snapdragon X16 LTE modem. LAA is a key technology enabler to Gigabit LTE, which has become a global wireless phenomenon. LAA vastly expands the pool of operators that can deploy Gigabit LTE by reducing the requirement for licensed spectrum to reach Gigabit class speeds.

LAA is a small cell technology, and like 5G NR mmWave, will require dense network topologies. When mobile network operators deploy additional outdoor small cells to support Gigabit LTE launches, 5G NR mmWave can take advantage of these additional deployments as well in the future to deliver additional co-siting outdoor coverage. To assess this potential, a simulation study was conducted that compared LTE LAA coverage with 5G NR mmWave. The results for US City 1 and 2 can be seen in Figure 8.

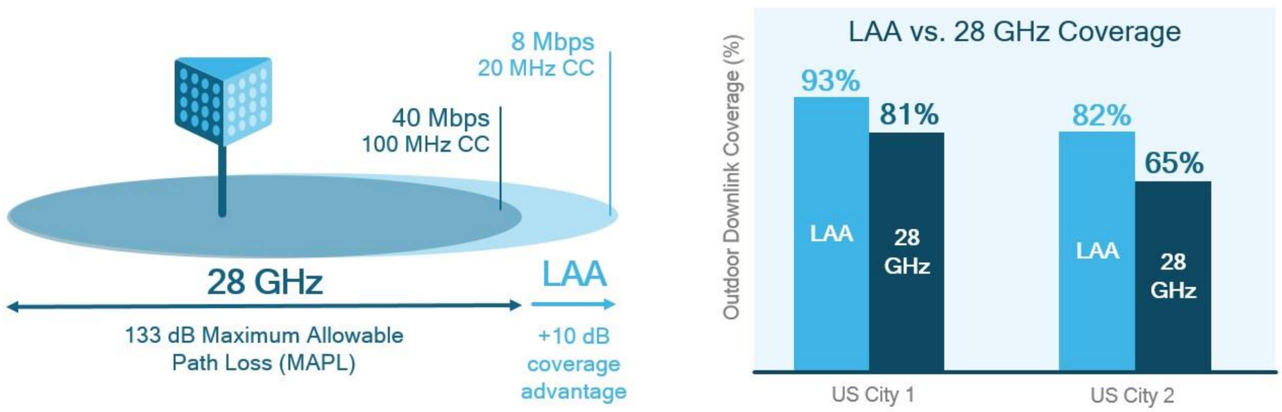



**Figure 8: Comparing 5G NR mmWave coverage with LTE LAA**

## 4.4 Outdoor coverage can be complemented with targeted indoor deployments

Although mmWave outdoor-to-indoor coverage for mobile is not feasible, outdoor mmWave coverage can be complemented with targeted indoor mmWave deployments in hyper-dense environments such as large venues. To assess the feasibility of targeted indoor 5G NR mmWave deployments, a network coverage simulation study was conducted on the Las Vegas Convention Center (LVCC), following a similar coverage prediction methodology as the outdoor coverage simulations and utilizing existing 4G LTE antenna locations in the venue (specifically North and Central Hall).

The link budget utilized for the outdoor coverage simulations was adjusted based on indoor-specific EIRP limits and deployment specific considerations (e.g., 64 vs. 256 antennas in gNodeB), resulting in a MAPL of 115 dB for indoor downlink coverage. In addition, path loss and indoor wall loss was adjusted inside the network planning tool (Indoor Ray Tracing model). The simulation study included an analysis of the North and Central Halls at the LVCC when empty, as well a mock-up of the Halls with exhibitor booths (including walls) to simulate indoor coverage at a live event like the International Consumer Electronics Show (CES®). As shown in Figure 9, a one-to-one overlay of 5G NR mmWave on the existing LTE antenna locations results in significant coverage and LTE offload in both scenarios.

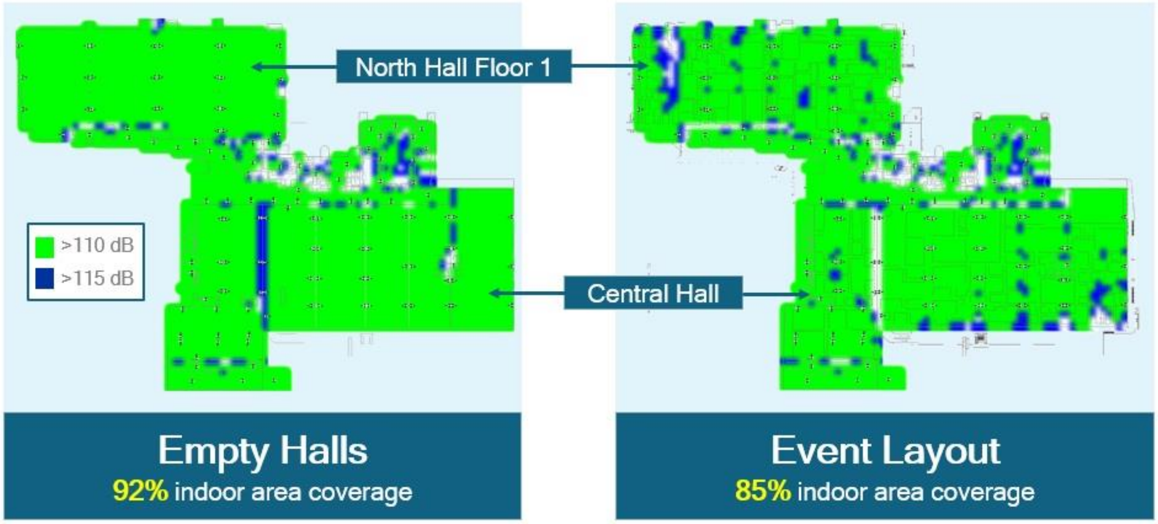



Figure 9: 5G NR mmWave indoor downlink coverage co-siting with LTE

# 5 Conclusion

The 5G NR mmWave network coverage simulation studies conducted by Qualcomm Research showcases that significant outdoor coverage is possible when co-siting 5G NR mmWave with existing LTE macro and small cell sites. It also shows how 5G NR mmWave outdoor coverage could potentially free up resources in the spectrum bands below 6 GHz for outdoor-to-indoor capacity, utilizing either 4G LTE or 5G NR technology. In addition, as shown in the 5G NR mmWave indoor coverage simulation for the Las Vegas Convention Center, outdoor mmWave coverage can be complemented with targeted indoor deployments.

Beyond these simulation studies, Qualcomm Technologies has been working on the key design elements necessary to harness mmWave bands for usage in mobile broadband communication systems for quite some time — leading the way to make mobile 5G NR mmWave a commercial reality in 2019.

Qualcomm is working closely with the industry to finalize the first release (Release 15) of the 3GPP 5G NR technical specifications with support for both sub-6 GHz and mmWave bands, including the Non-Standalone (aka NSA) 5G NR specifications that are expected to be completed at the end of this year. NSA 5G NR will make use of the existing LTE radio and core network (EPC) as an anchor for mobility management and coverage while adding a new 5G NR carrier. This will be the target of early 2019 deployments (in 3GPP terminology, this is NSA 5G NR deployment scenario Option 3).

At Mobile World Congress in Barcelona earlier this year, over-the-air testing of the Qualcomm Research 5G mmWave prototype system operating at 28 GHz was demonstrated. The over-the-air testing showcased how advanced 5G NR adaptive beamforming and beam tracking techniques can be utilized to deliver robust mobile broadband communications in real-world environments. These real-world environments included device mobility inside a moving vehicle and indoor mobility in an office environment with wall penetration and dynamic body/hand-blocking.

Qualcomm Technologies also recently announced a new 5G NR mmWave prototype and trial platform to accelerate mobile deployments for smartphones. The 2nd generation prototype system includes a 5G NR mmWave UE prototype that showcases an optimized mmWave RF Front-end design in a smartphone form factor. The UE prototype enables over-the-air testing of real-world mmWave mobile challenges, such as device and hand-blocking. Additionally, it provides mobile device OEMs an opportunity to gain an early start at optimizing their devices for the unique challenges associated with integrating 5G NR mmWave technologies in form factor-accurate devices.

The 5G NR mmWave prototype system will be utilized in upcoming 3GPP-based 5G NR mmWave interoperability testing and over-the-air 5G NR trials starting in the second half of 2017. The testing and trials intend to drive the mobile ecosystem toward rapid validation and commercialization of 5G NR technologies at scale. Learning from the testing and trials will be utilized to help continue to drive the ongoing development of the Qualcomm Snapdragon X50 5G modem family, with the first 3GPP standard-compliant 5G NR commercial products, including premium smartphones, featuring Snapdragon X50 5G NR modems expected to be available in 2019.

To learn more, please visit: www.qualcomm.com/5G-NR