Tolaga Research
Harness Mobile and IoT Intelligence

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Finding a 5G Future

Radio spectrum is a linchpin for 5G

Executive Summary

5G hype is thriving, driven by a vision for industry transformation and by nation states who are vying for 5G leadership. Even though the ink has barely dried on initial 5G standards and 4G is still relatively new, many operators across the globe are trialing 5G technology and establishing deployment strategies. 5G will only deliver marginal benefits when operating in 4G spectrum, but in new spectrum bands it enables wide-band radio channel aggregation for high peak data rates. 5G also supports mmWave operations, which rely on advanced radio technologies, such as massive MIMO and beam steering, to enable tremendous peak data rates and spectrum efficiencies.

Radio spectrum at sub-6GHz and mmWave frequencies are being earmarked for 5G. C-Band (3.4-4.2GHz) is most prevalent amongst the sub-6GHz bands intended for 5G operations. Other sub-6GHz spectrum bands include 450, 600, 700, and 900MHz, and 1.5, 2.3, 2.6 and 4.5GHz. Currently C-Band spectrum is used for satellite, and fixed and portable broadband services. Satellite services will continue to occupy parts of the band and other C-Band services will most likely be subsumed into 5G or refarmed to other spectrum bands. In the United States, where CBRS spectrum has already been allocated in the C-Band, spectrum sharing scenarios with satellite are being developed for the 3.7-4.2GHz bands.

Typically, mobile networks are designed for ubiquitous coverage at sub-1GHz or sub-2GHz frequencies and C-Band spectrum will only deliver partial network coverage. This partial coverage is generally sufficient for the 5G services that operators plan to offer, however we expect sub-1GHz deployment activity to accelerate once suitable spectrum becomes available. Operators will use sub-1GHz services to increase 5G availability, to future proof the technologies used in new spectrum bands, and to prepare for services that require full network coverage, such as autonomous vehicle control.

The value proposition and associated use-cases for mmWave are hotly debated. Advocates of mmWave point to field tests where non-Line-of-Sight (nLOS) coverage up to 200 meters has been achieved. Others question whether mmWave can achieve reliable nLOS operations at all. Extensive field trials have been conducted and illustrate the unique characteristics of mmWave radio channels, and the benefits of massive MIMO and dynamic beam steering technology. We believe that improved radio channel models, system level blueprints and economic models are needed before the industry can adequately assess the appropriate positioning of 5G-mmWave.

As 5G traverses its hype-cycle, industry sentiment will continue its roller-coaster ride. Radio spectrum is a linchpin for 5G. Since spectrum licensing is a protracted process, mobile operators must be proactive in their spectrum strategies, pay attention to mmWave deployments, and hedge themselves for future 5G opportunities as the market develops.

Finding a 5G Future

It is a familiar story. A new technology, in this case 5G, emerges with a vision for industry transformation, sporting numerous use-cases that have yet to prove their market worth. In the case of 5G, the story is more complicated. Countries including China and the United States are vying for 5G leadership and many others including Australia, Japan and South Korea are aggressively pursuing early market adopter status. These countries believe in the strategic importance of 5G, for national pride, Internet dominance, and to foster domestic technology companies and their intellectual property. We believe that this skews the market perception for 5G and to an extent undermines the market forces that will ultimately determine its fate.

This report is the first of a series that will be published by Tolaga Research to investigate critical technical, commercial and regulatory factors that impact 5G market adoption. In this report, we investigate the role of radio spectrum and technology in determining the adoption of 5G and the strategies that network operators, policy makers, and regulators should pursue based on the spectrum assets at their disposal.

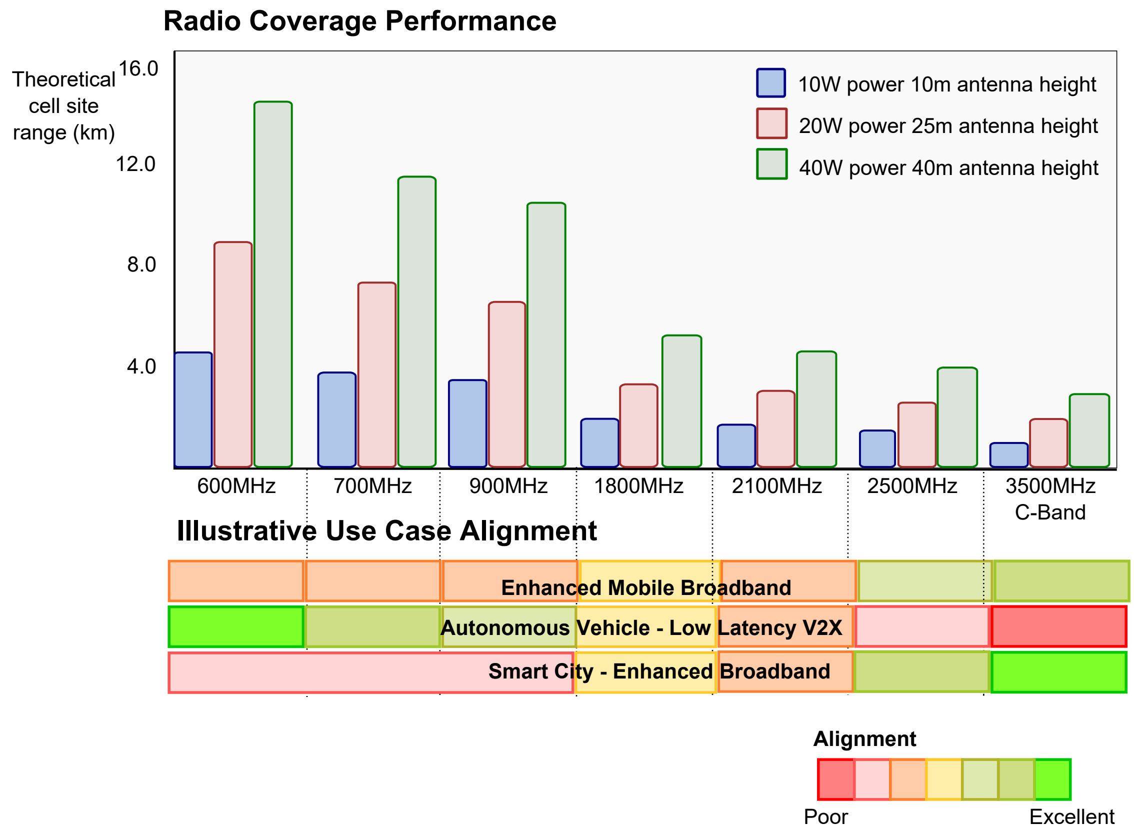
Radio spectrum is a proxy for 5G adoption

Tolaga estimates that at most, 5G will deliver 150 percent of the spectral efficiencies achievable with advanced 4G technology, when operating in the same spectrum band and with the same antenna technology. These efficiencies are not sufficient to justify refarming 4G spectrum for 5G services. Instead, 5G requires new spectrum. This spectrum can either be in sub-6GHz bands to parallel conventional mobile services, or at much higher centimeter and millimeter wave (mmWave) frequencies. In new sub-6GHz spectrum bands, 5G brings incremental performance gains, but more importantly wideband radio channels to enable high peak data rates. 5G systems operating at mmWave frequencies have the same benefits, but can also achieve higher spectral efficiencies using massive MIMO and dynamic beam forming/steering techniques. These techniques capitalize on the short signal wavelengths of mmWave to enable greater antenna densities and system resolution.

Getting under the hood of sub-6GHz

Sub-6GHz spectrum is used for mobile services because of its desirable radio propagation characteristics and available bandwidth. Mobile systems were initially deployed at sub-1GHz frequencies and subsequently also incorporated higher frequencies, such as 1.8GHz for 2G, 2.1GHz for 3G and 2.6GHz for 4G. Systems operating at lower frequencies achieve better coverage with less radio base stations. This is particularly valuable when networks are predominantly coverage limited and for services with demanding coverage requirements. Exhibit 1 uses an Okumura-Hata theoretical coverage model to demonstrate coverage variations between radio base stations operating at different frequencies and power levels. For example, the Okumura Hata model predicts that the coverage range of a 40W base station operating at 600MHz is 11.8 kilometers and decreases to 3.1 kilometers if the same base station were to use 3.5GHz (C-Band) spectrum instead.

Exhibit 1: Theoretical outdoor cell site coverage based on Okumura Hata model
Source: Tolaga Research 2018



In most markets, C-Band spectrum operating between 3.4 and 4.2GHz is being selected as the sub-6GHz spectrum band of choice for 5G. Other bands that are also being targeted for 5G include the 450, 600, 700, and 900MHz, and 1.5, 2.3, 2.6 and 4.5GHz bands. The rationale for using C-Band for 5G is that the band is sufficiently wide to enable high bandwidth services. However, this comes at the expense of reduced coverage relative to other bands that operate at lower frequencies. Regional C-Band allocations vary depending on needs of incumbent systems, particularly satellite. In the United States C-Band spectrum has already been allocated for 4G-LTE services under the guise of CBRS. The Federal Communications Commission (FCC) in the United States has been working with the satellite industry to avail C-Band spectrum in the 3.7-4.2GHz range, using spectrum sharing arrangements to ensure the satellite services are protected.

Getting the 5G coverage strategy right

In general C-Band systems cannot economically deliver ubiquitous coverage with standalone implementations and require the support of complementary systems operating at lower frequencies. For most cases, these complementary systems will be supported by 4G, until 4G passes through its technology lifecycle and is ultimately retired.

Some operators, such as T-Mobile in the United States, plan to deploy 5G in 600MHz spectrum to rapidly achieve a large 5G network footprint with comparable radio channel bandwidths to 4G. If the proposed T-Mobile/Sprint merger is successful, the combined entity would also have large tracts for 2.6GHz spectrum to provide a capacity overlay for the 600MHz footprint.

We expect that other network operators will follow suit as new sub-1GHz spectrum licenses (e.g. 600, 700 and 800MHz) and 5G-ecosystems become available. Although systems operating in these bands will generally use channel sizes similar to 4G, with only marginal performance gains, we believe that operators will seek opportunities to market the virtues of their wide area 5G coverage. Furthermore, some services, such as ultra-low latency V2X support for autonomous vehicles will require both 5G capabilities and ubiquitous 5G coverage.

Radio technology advancements and clever spectrum utilization schemes improve 5G performance. For example, improved C-Band coverage can be achieved with uplink/downlink decoupling to capitalize on the coverage being predominantly uplink limited. In November 2017, Huawei demonstrated this by combining a C-Band downlink with a 1.8GHz uplink channel to achieve balanced downlink/uplink coverage.

mmWave: game changer or an expensive distraction?

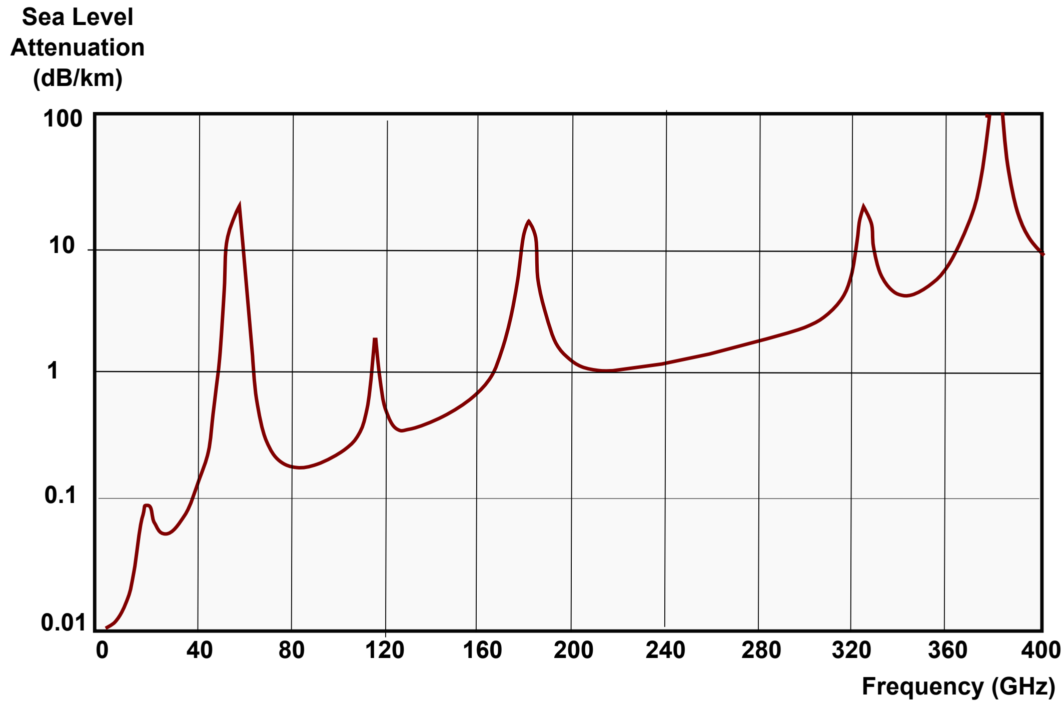
Ultra-broadband is a key pillar for 5G and requires exceptionally wide radio channels, which in general cannot be economically delivered at sub-6GHz frequencies. Instead, 5G relies on centimeter and millimeter-wave (mmWave) spectrum that operates at frequencies in the 10's of GHz range. In the case of 5G, the 28, 39 and 72GHz bands have been earmarked by the ITU. These bands are currently used for satellite, fixed point-to-point connections, military applications and LMDS (Local Multipoint Distribution Systems).

Conventional wisdom misrepresents mmWave radio performance

Conventional wisdom tells us that as the operating frequency of a radio system is increased, all other things being equal, the system will have reduced coverage, as is illustrated in Exhibit 1. On this basis the theoretical coverage of a mmWave system is pathetic. While this conventional wisdom holds true when legacy technologies and modeling assumptions are used, researchers have demonstrated that advancements in signal processing and antenna technologies greatly improve the mmWave performance, so that it can be applied to 5G applications. In particular, mmWave wavelengths are between one and ten millimeters as compared with typical cellular radio signals, which are tens of centimeters. The short wavelengths enable large antenna arrays with relatively small physical footprints. These arrays can greatly improve mmWave radio coverage with massive MIMO and beam steering to concentrate the radio energy in the direction of receiving devices. Wide beamwidth receiving antennas can be implemented to improve radio reception by capturing reflected, diffracted and scattered signals.

In addition to poor coverage expectations, a common misconception is that mmWave frequencies are unduly attenuated by water and oxygen in the atmosphere. This is generally exaggerated and in reality only applies to narrow frequency ranges, primarily in the vicinity of 60, 180 and 380GHz frequencies, see Exhibit 2.

Exhibit 2: Atmospheric absorption of electromagnetic waves at sea level
Source: IEEE Globecom, 2011



Field trials and channel models show promising results for 5G

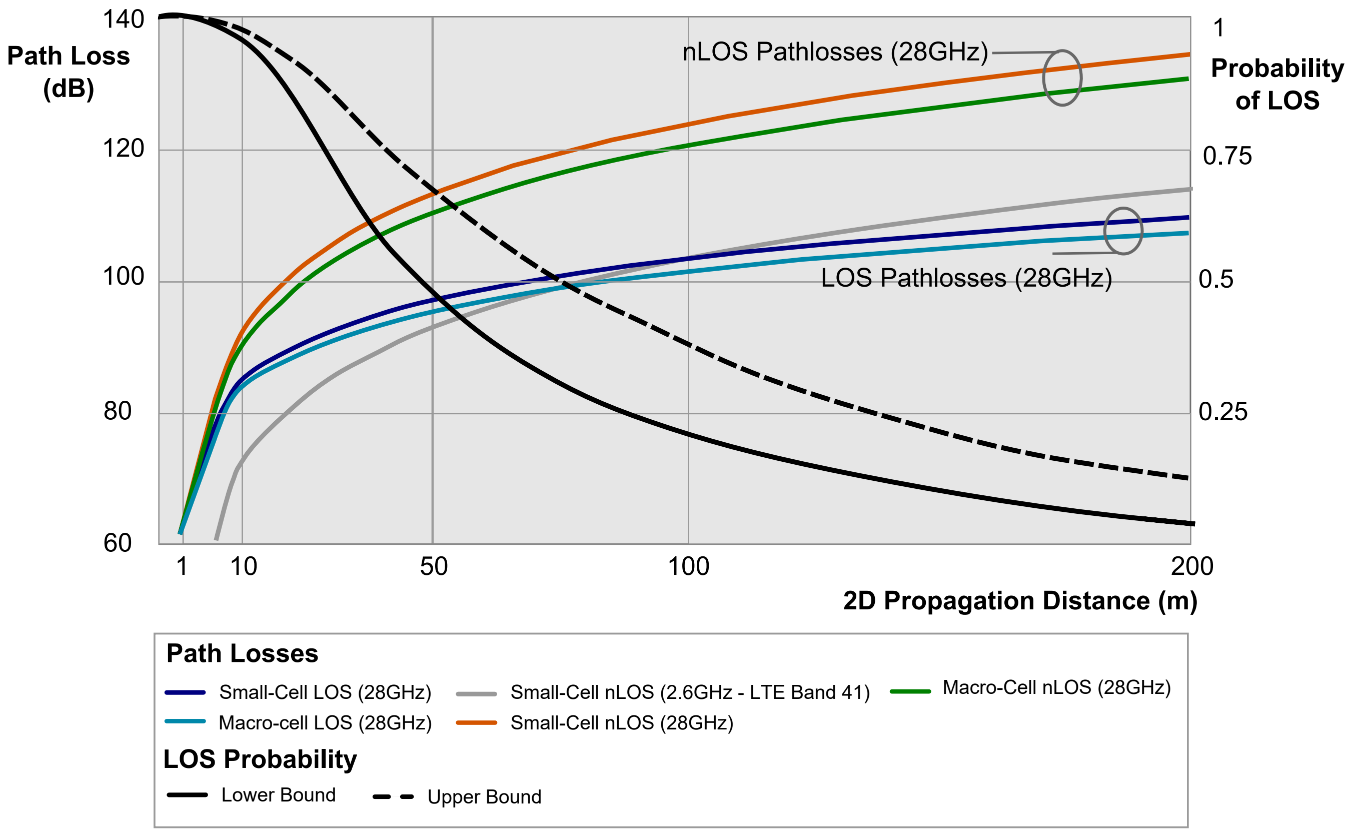
Field trials conducted by companies including Ericsson, Nokia, Qualcomm and Samsung, and Universities including New York University (NYU), Aalborg University, and Aalto University **have established LOS mmWave connections beyond 1km and over one hundred meters for non-LOS connections.** These and other field trials have enabled researchers to better understand the underlying mechanisms for mmWave propagation in both LOS and non-LOS environments. In addition, the trials provide a basis for radio channel models to support network design.

Exhibit 3 shows omni-directional outdoor path-loss predictions for small-cells operating in street canyons with both LOS and non-LOS operations. The predictions include both 2.6GHz (cellular) and 28GHz (mmWave) radio spectrum. In addition, lower and upper bounds for the probability of a LOS connection are predicted.

The results in Exhibit 3 predict that:

- mmWave operations are feasible for non-LOS conditions up to 200 meters using sufficiently directional transmitting and high gain receiving devices, with large antenna arrays and massive MIMO technology.
- Naturally the radio propagation range for LOS conditions exceeds that for nLOS operations. In addition, the LOS path-loss predictions for mmWave is comparable to non-LOS 2.6GHz cellular systems with path lengths at approximately 75 meters, and;
- The predicted probability of a LOS connection in the urban environments that were analyzed, exceeded fifty percent at path-length ranges between 50 and 75 meters. However, this probability is likely to vary greatly amongst different urban environments.

Exhibit 3: Omni-directional path-loss predictions and probabilities for LOS and nLOS connections at 2.6 and 28GHz
Source: New York University, and Nokia 2017



Qualcomm makes bold predictions using field trials and network simulations

In October 2017 Qualcomm published simulation results to estimate the outdoor coverage performance of mmWave if it were overlaid on existing network footprints. The simulations used measurement results and 3GPP propagation models to analyze networks in four US cities, two Korean cities, Hong Kong and one city in Japan. The simulation results are summarized in Exhibit 4 and predict that between 41 and 81 percent outdoor coverage could be achieved across these networks with 28GHz mmWave technology. Based on these results, Qualcomm determined that mmWave is a viable mobile technology. As a result, Qualcomm has developed prototype smartphones that incorporate mmWave connectivity.

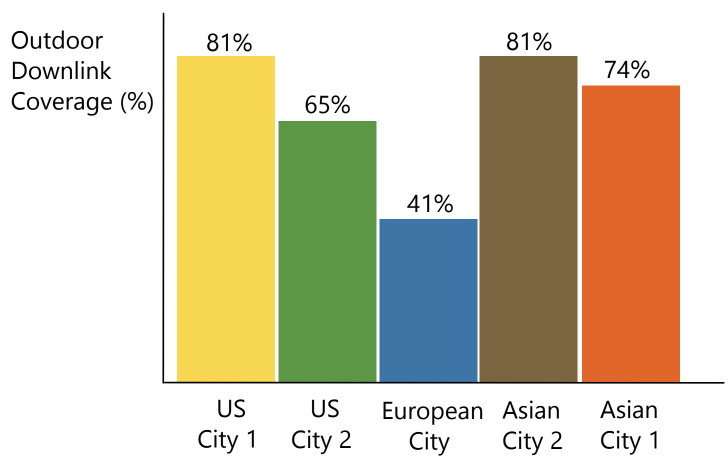
If Qualcomm is right and mmWave can achieve reasonable performance on existing mobile network footprints; and can be reliably implemented in smartphone devices without compromising user experience, we believe this would be a game changer. However, there are some unanswered questions. In particular:

- What about the 19-59 percent of the network footprint that is not covered by mmWave? How much infrastructure is needed to extend the reach of mmWave to align with cellular - particularly indoors?

In addition, are the coverage holes stationary, or do they change with moving traffic, pedestrians and other environmental dynamics? It might be that mmWave proves to be a local/campus based solution, with opportunistic capacity offload for wide area operations.

- How difficult is it to achieve reliable performance with mass market consumer devices? Will mmWave be overly taxing on device battery performance? How much will it cost to embed mmWave functionality?
- The RF design of devices is as much an art as it is a science. While mmWave is isolated from spurious emissions from the device screen, processor etc., large antenna arrays will be needed and are likely to prove difficult to implement. In addition, the device casing materials and other design features might also prove problematic for signal reception and transmission.
- What are the challenges in enabling scalable system level operations? The Qualcomm study focuses primarily on predicted signal coverage, which in essence identifies areas where the signal-to-noise-ratio (SNR) is sufficient. The SNR predictions depend on advanced radio technologies to provide sufficient link budget gain. However, when these technologies are used as part of a multi-user system, it would be necessary to optimize for the signal-to-interference-plus-noise ratio (SINR). We believe that this will be complicated to implement at scale.

Exhibit 4: Promising Coverage predictions for mmWave deployments using existing macro-cells and small-cells.
Source: Qualcomm 2017



Not everyone is so optimistic

While promising radio performance results for mmWave have been demonstrated, there are some players who have trialed the technology with lack-luster results, particularly for non-LOS connectivity, and when the receiving device is mobile. We believe that there are several contributing factors to these conflicting results. In particular, mmWave channels are normally more dynamic and volatile than cellular channels, particularly for non-LOS operations. Advanced radio technologies must be sufficiently nimble to respond to these conditions and incorporate design features that anticipate the salient characteristics of mmWave channels. For example:

- In contrast to cellular systems, non-LOS mmWave channels commonly depend on reflected as opposed to diffracted signals. The magnitude of reflected signals depend greatly on the characteristics of the reflected surfaces. In particular, glass surfaces are generally more reflective than rougher surfaces such as cinder-block, resulting in vastly different attenuation factors.
- In both cellular and mmWave systems, environmental shadowing can generally be well represented by lognormal distributions. However, in the case of mmWave, dynamic obstacles such as vehicles moving through an intersection can have a dramatic impact on radio coverage performance in localized areas, and;
- mmWave coverage predictions depend greatly on high performance radio and antenna technology that is optimized for mmWave signal reception. We anticipate that radio technology and network designs will evolve as the characteristics of mmWave channels become better understood.

Many mobile operators are dismissing mmWave in favor of sub-6GHz radio technology for 5G. Other operators like AT&T and Verizon that are more optimistic and are launching mmWave solutions for fixed wireless access (FWA) and portable wireless solutions. While we recognize that there are many complexities and uncertainties regarding mmWave, we do not believe that network operators can afford to ignore it, particularly with continued radio technology advancements. At a minimum, we believe that operators should trial mmWave technology to better understand how it performs, and participate in radio spectrum auctions, if and when they occur. This will enable the operators to hedge themselves in case mmWave becomes all that is promised by its advocates.

Conclusion

5G-hype is in full swing and operators across the globe are positioning themselves to deploy 5G in the the vicinity of 2020 or before. Radio spectrum plays a crucial role in enabling 5G deployments and is supported by new allocations in both sub-6GHz and mmWave frequency bands. In many markets the C-Band spectrum (3.7-4.2GHz) has been earmarked for sub-6GHz operations and 29, 38 and 72GHz for mmWave.

Both the C-Band and mmWave spectrum bands hold appeal for 5G because of the massive bandwidth resources they offer. However, when conventional radio technologies are used, the coverage performance of C-Band and mmWave pale in comparison to cellular technologies. C-Band has been used for satellite and fixed and portable broadband and can only provide partial mobile network coverage for 5G. mmWave is currently used for satellite, military, point-to-point and LMDS applications, and its role as a 5G access technology is hotly debated.

The rules are changing with 5G

For decades network operators have maintained relatively consistent radio spectrum strategies that covet the superior coverage of spectrum operating at lower frequencies, target bands that are widely used in other markets, and avoid the need for complicated radio antenna designs. In the past operators have paid the price when they have got it wrong. The affects of the wrong moves are amplified by the massive network and device ecosystem investments involved, operational overheads to cope with complex technologies, and the incremental investments needed to bolster coverage for higher band services.

While many of the same considerations still apply, 5G brings technology advancements that will impact the usefulness of spectrum bands that have been overlooked in the past. This is particularly the case for mmWave spectrum, where technologies like massive MIMO, and dynamic antenna beam steering are being developed to dramatically change its performance profile. While a lot of work is still needed to determine the role of mmWave in 5G, we believe that mobile operators must remain opportunistic and open minded as mmWave solutions mature.

Multi-faceted 5G coverage strategies are needed

Mobile network topologies are generally designed to achieve ubiquitous coverage at either sub-2GHz or sub-1GHz operating frequencies. Generally, 5G deployments in C-Band spectrum only provide partial network coverage and will be complemented by a legacy technology like 4G. Although we believe that C-Band will address most 5G service demands, and can be enhanced with downlink/uplink decoupling, we expect that many operators will also deploy 5G in sub-1GHz spectrum once it becomes available. This will support marketing initiatives to promote wide area 5G availability, futureproof technology investments, and support services that depend on wide-area 5G coverage, such as autonomous vehicle support.

5G hedging is the name of the game

Industry sentiment towards 5G will continue on its "rollercoaster ride" as 5G traverses its hype-cycle. Since radio spectrum is needed for 5G and spectrum licenses commonly have lifecycles that span multiple decades, mobile operators must be proactive in acquiring spectrum licenses to hedge their future 5G opportunities, depending on how the market develops.

About Tolaga Research

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