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By ECFS

August 6, 2019

Ms. Marlene H. Dortch
Secretary
Federal Communications Commission
445 12th Street, S.W.
Washington, D.C. 20554

Re: Notice of *Ex Parte* Presentation, IB Docket No. 11-109; IBFS File Nos. SES-MOD-20151231-00981, SAT-MOD-20151231-00090, and SAT-MOD-20151231-00091

Dear Ms. Dortch:

On August 5, 2019, Doug Smith, Valerie Green, Maqbool Aliani, and Scott Wiener with Ligado Networks LLC ("Ligado"), Dennis Roberson with Roberson and Associates, LLC, and the undersigned met with Julius Knapp, Ronald Repasi, and Paul Murray (by phone) with the Office of Engineering and Technology; Dana Shaffer, Charles Mathias, Lloyd Coward, Jessica Greffenius, and Sean Spivey with the Wireless Telecommunications Bureau; Aaron Goldberger with Chairman Pai's office; and Jose Albuquerque and Robert Nelson with the International Bureau. The parties discussed Ligado's pending license modification applications ("Modification Applications"), and Ligado reiterated its request for prompt action on those Applications. In that context, Ligado's representatives explained how the record before the Commission regarding the Modification Applications fully supports approval and discussed in particular the points set forth below.

1. Power Level for the Lower Downlink

Ligado's representatives pointed out that its December 2015 Modification Applications requested with respect to the lower downlink spectrum at 1526-1536 MHz ("Lower Downlink"), that the power level be set at 32 dBW *or whatever level was determined by the FAA to protect certified aviation devices*. We explained that the proposed power level of 32 dBW was identified after extensive technical discussions with Deere and Garmin that were undertaken specifically to identify a power level that would not harm their devices. That power level was then reflected in

co-existence agreements with each of those companies, and a condition of the agreements was a requirement that Ligado file the Modification Applications and request 32 dBW as the power level for the Lower Downlink.

Moving from 32 dBW, which was determined during the discussions with the major GPS manufacturers, we then discussed the process that was used to identify the appropriate power level to protect certified aviation devices. After a year of discussion and analysis between Ligado and FAA engineers, which was based on the established receiver mask for certified aviation, the FAA concluded that the power level in the Lower Downlink should be set at a range of 9-13 dBW as determined on a tower-by-tower basis.[1] However, the DOT Report released in April 2018 concluded that there should be a single national power level for the Lower Downlink, and that number was identified as 9.8 dBW, a level that was arrived at specifically for the limiting case of helicopters. Accordingly, on May 31, 2018, Ligado submitted an amendment to its Applications and requested that the Lower Downlink power level be set at 9.8 dBW (10 W) in fulfillment of its December 2015 commitment to abide by the recommendation of the FAA.

In the filing accompanying that amendment, Ligado made clear that it agreed with the DOT Report recommendation with respect to *certified aviation devices* and the rigorous modeling process that FAA used to reach that conclusion.[2] Ligado made equally clear in that filing that it did *not* agree with the rest of the DOT Report with respect to GPS devices that were listening in outside of their allocated band since the analysis of *all other GPS devices* in that context was based not on "harmful interference," but rather on whether those devices reported a small decrease in C/N_0 of 1 dB.[3] The parties discussed that Ligado's proposed power and OOBE

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[1] *See* U.S. Department of Transportation, *Global Positioning System (GPS) Adjacent Band Compatibility Assessment*, Final Report, at 118-19, 149, 152-53 (April 2018), *available at* https://www.transportation.gov/sites/dot.gov/files/docs/subdoc/186/dot-gps-adjacent-band-final-reportapril2018.pdf ("DOT Report") (concluding EIRP limit of 9.8 dBW (10 W) will protect certified aviation receivers installed in helicopters operating in accordance with applicable existing MOPS).

[2] *See* Amendment to License Modification Applications, IBFS File Nos. SES-MOD-2015-1231-00981, SAT-MOD-20151231-00090, and SAT-MOD-20151231-00091, at 4 (May 31, 2018) ("Ligado accordingly submits this amendment to reflect the DOT Report's more conservative conclusion with respect to the needs of certified aviation receivers."); *see also id.* at 1 ("These stricter EIRP limits reflect not only the analysis Ligado committed to undertake in the Modification Applications with respect to the protection of *certified aviation operations* but also the conclusion of the Department of Transportation's Adjustment Band Compatibility Assessment (the "DOT Report"), which assessed the needs of certified aviation GPS receivers." (emphasis added)).

[3] *See* Letter from Gerard J. Waldron, Counsel to Ligado Networks LLC, to Marlene H. Dortch, FCC Secretary, IB Docket No. 11-109, IBFS File Nos. SES-MOD-20151231-00981, SAT-MOD-20151231-00090, and SAT-MOD-20151231-0009, at 3 n.9 (May 31, 2018)

levels in the Applications would protect GPS devices from a 1 dB change in the noise floor within their band. Ligado's representatives then cited the April 2016 Public Notice on the Modification Applications which asked "whether there remain any unresolved concerns of potential *harmful interference* to GPS receivers and devices should Ligado operate a terrestrial mobile network."[4] We reiterated the point we have made previously: Ligado responded to the Commission's request for analysis of harmful interference by submitting extensive testing results from the National Advanced Spectrum and Communications Test Network ("NASCTN")—a federal lab jointly run by the Department of Defense, NTIA, and NIST—and Roberson and Associates that showed the vast majority of GPS devices would not experience harmful interference as determined by studying "key performance indicators" and that those high-precision devices that did show impact on performance could be readily and affordably upgraded.[5] In the absence of a standard like the one established by the FAA for certified aviation receivers and in light of the comprehensive nature of the data presented in them, we think these test results along with the GPS manufacturer agreements give the Commission a basis for moving forward. These test results confirmed what the agreements with the GPS companies initially established, namely that the power levels submitted in the Modification Applications would protect the overwhelming number of GPS devices and that the small number of devices that experienced an impact could be readily upgraded.[6]

We then discussed how the 2015 co-existence agreements with the GPS companies, as well as important advancements in GPS resilience, have led to the development and deployment of filters and other techniques to increase the robustness of GPS devices, how this trend toward

("Amendment Cover Letter") ("The DOT Report's certified aviation analysis thus is free of a fundamental error that fatally undermines the DOT Report's assessment of all other GPS devices: its empirically unsupported treatment of a 1 dB decrease in a GPS device's idiosyncratic and self-reported carrier-to-noise-density ratio (C/N_0) as a proxy for defining when the device has experienced 'harmful interference.'"); *see also* DOT Report at IV (discussing assessment of GPS receivers utilizing a 1 dB signal-to-noise density (C/N_0) interference protection criteria).

[4] *Comment Sought on Ligado's Modification Applications*, IB Docket Nos. 11-109, 12340, DA 16-442, at 8 (April 22, 2016) ("Public Notice") (emphasis added).

[5] *See* Gerard J. Waldron, Counsel to Ligado Networks LLC, to Marlene H. Dortch, FCC Secretary, IB Docket No. 11-109, IBFS File Nos. SES-MOD-20151231-00981, SAT-MOD-20151231-00090, and SAT-MOD-20151231-0009, at 17-24 (June 5, 2017) (*citing* Roberson and Associates, LLC, *Summary of GPS Reacquisition Testing by Roberson and Associates*, IB Docket No. 11-109, at 2 (Dec. 22, 2016), *available at* https://ecfsapi.fcc.gov/file/122228424456/Ligado%20Ex%20Parte%20Letter%20re%20Reacquisition%20Testing%20(12.22.16).pdf ("Summation")); Dr. William Young et al., NASCTN, *LTE Impacts on GPS: Test and Metrology Plan* (July 22, 2016), *available at* https://www.nist.gov/sites/default/files/revised-test-plan-impact-of-lte-on-gps-22-july-2016.pdf.

[6] *See Summation* at 20-21.

more robustness was observable in the testing results, how the vast majority of consumer utilization of GPS in 2019 occurs on smartphones and tablets (which for many years have shown no GPS performance issues from simulated LTE signals in the bands that are the subject of this Modification Application), and how Ligado has committed to work closely with GPS companies when the Company begins to deploy. Specifically, Ligado agreed to notify those GPS companies that requested it six months in advance of deploying a network on a county-by-county basis.

We then explained how the record shows that a power level of 9.8 dBW for the Lower Downlink provides additional protection to all GPS devices beyond what the testing shows is needed. *First*, the level of 32 dBW submitted in the December 2015 Applications reflected lengthy discussions with the major GPS companies as to what was necessary to protect their devices. Further support for the conclusion that 32 dBW affords GPS devices the right level of protection can be found in letters in the record from NovAtel and TopCon.[7] *Second*, a power level of 9.8 dBW for the Lower Downlink, which is necessary to protect certified aviation devices installed in helicopters, provides all other GPS devices with approximately 99% more protection than the GPS companies agreed to in 2015. Thus, 9.8 dBW is not just better than the power level of 32 dBW contained in the co-existence agreements, it is 99% better for all other GPS devices. *Third*, the test results from NASCTN and Roberson that examined the key performance indicators of GPS devices experiencing a power level of 32 dBW show that, at those much higher power levels, the vast majority of all GPS devices did not experience harmful interference and the small number of devices that did could be readily upgraded. We explained that conclusion is now obviously and logically even stronger with a power level of 9.8 dBW, meaning that the small number of affected devices at 32 dBW is significantly smaller at the proposed power level for the Lower Downlink.

Lastly, we explained that in the context of Commission review of a license modification application, the Commission has a strong basis in the record to determine that the specific proposed power levels in that Application are in the public interest. On this point we bring to your attention the record evidence that demonstrates 32 dBW is the appropriate power level for devices other than certified aviation devices. As Roberson and Associates reported in July 2018, "an extensive open and repeatable measurement effort" found that "all of the devices [tested] were judged to be not susceptible to LTE interference from base-stations in the 1526 to 1536 MHz band operating at power levels of 32 dBW in at least 99 % of locations"—a finding that is

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[7] *See* Letter from Doug Smith, CEO, Ligado Networks LLC, and Ivan Di Federico, Chief Strategy Officer, Topcon Positioning Systems, Inc., to Marlene S. Dortch, Secretary, FCC, IB Docket No. 11-109 (Nov. 29, 2016), available at https://ecfsapi.fcc.gov/file/12062186417510/FCC%20Letter%20TopconLigado.pdf; Letter from Doug Smith, Ligado Networks LLC, and Michael Ritter, NovAtel Inc., to Marlene Dortch, Secretary, FCC, IB Docket No. 11-109 (June 27, 2016), available at https://ecfsapi.fcc.gov/file/10628411910166/NovAtel-Ligado%20Letter.pdf.

consistent with testing from NASCTN.[8] Thus, the 9.8 dBW power level, a "more than 100x reduction in transmit EIRP level," provides more than substantial protection for devices other than certified aviation devices. "The likelihood of Ligado's Lower Downlink Band operations causing harmful interference to any non-high precision GPS devices is extremely rare, with a probability of effectively zero."[9] And with respect to certified aviation devices, DOT itself determined 9.8 dBW to be the appropriate power level for the "most restrictive of the certified aviation scenarios [it] examined"—namely certified aviation devices in helicopters.[10] Moreover, Ligado repeatedly has committed to "protect[ing] certified aviation GPS receivers by limiting its power in the [Lower Downlink Band] 'as necessary to achieve compatibility with current and any future [Minimum Operational Performance Standards] insofar as they are incorporated into an active Technical Standard Order by the FAA.'"[11] As such, the Commission has sufficient record evidence to find that the proposed power levels are in the public interest.

2. With FCC Approval, Ligado's Spectrum Can Play an Important Role in 5G

Ligado's representatives explained the extensive work the company has undertaken, in conjunction with Nokia and Ericsson, its key technology partners, to evaluate 5G deployment strategies for the Ligado spectrum band and develop standards-based satellite IoT technology to support broad-based 5G coverage and private networks for the industrial sector. We described how the heterogeneity of 5G use cases requires a "network of networks" and the role of Ligado's satellite and terrestrial capabilities to address the need of the fast-developing market for 5G services where ubiquity, continuity, reliability, and scalability of service is critical.

Ligado outlined its plan to complement industry deployments as a network services provider and a spectrum partner. This plan entails using standards-based, state-of-the-art technology to provide connectivity to both satellite and terrestrial devices, building commercial partnerships that support deployment of custom private network solutions, and enabling lower mid-band spectrum deployment over wide-area networks to accelerate broad-based availability of 5G services.

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[8] Roberson and Associates, LLC, Comments on Recent Ligado Amendment to License Modifications, IB Docket No. 11-109, SAT-AMD-20180531-00044, SAT-AMD-20180531-00045, at 1-2 (July 9, 2018) (Attachment A).

[9] *Id.* at 2.

[10] *See* DOT Report at VI ("These analyses indicate that protection of certified avionics, operating under the assumption of the described 250 foot (76.2 m) radius assessment zone, requires that the ground station transmission not exceed 9.8 dBW (10 W) (cross-polarized) at 1531 MHz. This limit is obtained from the HTAWS scenario which was found to be the most restrictive of the certified aviation scenarios examined.").

[11] Amendment Cover Letter at 1 (quoting Modification Applications, Description of Proposed Modification at 7).

Mobile satellites have an important role to play in the 5G market, and Ligado is working with Ericsson to develop a satellite adaption of the 3GPP LTE-M and NB-IoT standards so that Ligado's MSS network can support the critical 5G IoT need for network redundancy and full North American coverage where it is not financially viable to build carrier networks (e.g., remote and rural areas). Thus, Ligado's plan to operate a standards-based satellite IoT network would address these challenges and, when combined with custom private networks, will drive adoption of 5G IoT solutions in the industrial sector, where service ubiquity and continuity are valued.

The rail industry provides one example of the potential benefits from Ligado's proposed new offering. Rail companies, with operations spanning over 138,000 track miles throughout the U.S., are arguably the country's most widely distributed complex, safety-critical industrial infrastructure. As such, rail operators require the ubiquitous network coverage, network control and customization, and highly-reliable performance that 5G private networks seek to provide to industrial facilities. Ligado is uniquely positioned to bring the benefits of 5G connectivity to the rail industry, with custom private networks deployable in areas of concentrated operation, and ubiquitous satellite coverage assuring service continuity—both provided using cost-efficient, standards-based technology. Support of advanced industrial IoT, particularly through the use of private networks, is a key goal of 5G, providing critical infrastructure industries, like rail, with guaranteed coverage, a high degree of control, and assured performance that is not offered by public wireless networks.

Ligado also described its partnership model to deploy lower mid-band spectrum. Because the Ligado spectrum is not encumbered by legacy network infrastructure, the company can flexibly offer coverage and capacity solutions using features that are part of the 5G standards. With that objective in mind, Ligado is working with Ericsson and Nokia to evaluate deployment approaches that can support broad-based 5G coverage, deliver additional 4G capacity, and enable private networks for the industrial sector.[12] Specific activities include:

- Developing a standardization plan in 3GPP for the Ligado spectrum band. Ligado already has standardized 30 MHz of the 40 MHz in 3GPP as part of 3GPP band 24, which allows 3GPP LTE technology to be used for this spectrum. Ligado plans to go back to 3GPP for any required modifications and will convert band 24 to 5G band n24, which will allow this spectrum to be also used with 5G-NR standard.

- Advancing technology progress for the Ligado band based on Nokia's development of prototype base stations and Nokia's network capacity simulation analysis of the 1526 MHz-1536 MHz downlink band. These Nokia-led technology efforts seek to define ways

[12] *See generally* Nokia Report (Attachment B).

to flexibly deploy and further advance the emerging 3GPP plan to standardize and commercialize Ligado spectrum.[13]

- Evaluating 5G deployment approaches to combine Ligado spectrum with higher mid-band spectrum to support broad-based 5G coverage. Several 3GPP and 5G techniques enable lower mid-band spectrum and higher mid-band spectrum to be used in combination with one another such as:
  - E-UTRAN New Radio – Dual Connectivity ("EN-DC"): A technique that allows for simultaneous LTE and 5G connections enabling user devices to optimally utilize downlinks and uplinks depending on their throughput requirements and location.
  - Carrier Aggregation: Combines channels of spectrum to create a broader path for the transmission of data, increasing capacity.
  - Supplemental Uplinks: A 3GPP 5G technique that makes use of adding a lower frequency carrier for uplink to the primary higher frequency 5G UL carrier. Using this technique, better uplink coverage can be achieved when selecting the low-band carrier for uplink transmission.
  - Downlink and Uplink Decoupling: A new feature for 5G deployment in multi-frequency bands and a key enabler for coverage extension of multi-band networks. This solution effectively makes the coverage of higher mid-band the same as lower mid-band and underscores the benefit from using lower mid-band and higher mid-band spectrum together for 5G.
- Developing a suite of technology and network services that leverage the 3GPP technology ecosystem and enables customization and control of private networks for the industrial sector.

These efforts with Nokia and Ericsson not only provide critical input into Ligado's plan to standardize and commercialize its spectrum, but they also validate the importance of lower mid-band spectrum to 5G deployments. The combination of lower mid-band spectrum (1-2 GHz) and higher mid-band spectrum (2-6 GHz) would:

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[13] The proposed power level of 9.8 dBW for the Lower Downlink band will not impede deployment of these technologies as this power level is entirely compatible with this network plan. Moreover, using the Lower Downlink band at this reduced power level for capacity augmentation will not result in a more highly-densified network deployment.

- Support broad-based 5G deployments by delivering a 4.8x increase in coverage. This improvement would allow 5G networks to use existing wireless towers for a fast and cost-efficient wide area network deployment thereby providing a consistent end user experience.

- Enable the "best of both worlds" in terms of coverage and capacity because uplink channels would use lower mid-band spectrum to deliver superior propagation characteristics—like in-building penetration and wide-area coverage—and downlink channels would use higher mid-band spectrum with wider channels to provide a capacity-rich network that can support gigabit speeds on the downlink.

Ligado's plan to serve as a network provider and spectrum partner to carriers and other providers advances several commercial and policy objectives, including building the largest possible ecosystem in the L-band, accelerating the deployment of mid-band spectrum for 5G services, and supporting low-cost platforms that Ligado and its partners will develop and operate to deliver standards-based MSS and custom private network solutions for 5G IoT.

3. Commitment to Repair or Replace USG Devices

The Company recognizes that some have raised general concerns about the potential impact to U.S. Government GPS devices. As part of its comprehensive commitment to protect GPS and to enable the FCC to both preserve a robust GPS system as well as deploy additional mid-band spectrum to meet our national 5G needs, the Company is committed to mitigating any such impact should it occur.[14] Thus to address those important concerns, Ligado has committed to repair or replace as needed U.S. Government GPS devices that experience or are likely to experience harmful interference from the company's operations.[15] To fulfill this commitment, Ligado will launch a program to facilitate the exchange of information between it and the

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[14] *See* Comments of Ligado Networks LLC, IB Docket No. 11-109, SAT-AMD-20180531-00044, SAT-AMD-20180531-00045, at 14 (July 9, 2018) ("Ligado Comments") ("Ligado has made a commitment to provide specific mitigation measures to address concerns about potential impact on U.S. Government devices, including the repair or replacement of such devices as necessary, both pre- and post-deployment of Ligado's proposed terrestrial network.").

[15] *See* 47 C.F.R. § 15.5 (providing that unlicensed devices may operate pursuant to Part 15 of the Commission's rules "subject to the conditions that no harmful interference is caused"); 47 C.F.R. § 15.15 (noting that the limits provided in Part 15 of the Commission's rules "will not prevent harmful interference under all circumstances"); 47 C.F.R. § 15.105 (stating that the FCC's Part 15 limits "are designed to provide reasonable protection against harmful interference" (emphasis added)); 47 C.F.R. § 27.64 ("If the FCC determines, however, that interference which significantly interrupts or degrades a radio service is being caused, it may, after notice and an opportunity for a hearing, require modifications to any WCS station as necessary to eliminate such interference.")

Government. Specifically, Ligado intends to cooperate directly with agencies that anticipate their GPS devices being affected by: (1) identifying GPS devices that could be impacted, (2) evaluating whether there is or will be interference from the Company's operations, and (3) developing a plan to implement a program to repair or replace any such devices that is consistent with that agency's programmatic needs, as well as applicable statutes and regulations relating to the ability of those agencies to accept this type of support. The Company has analyzed this issue extensively and has demonstrated that a program like the one being proposed is consistent with applicable statutes and regulations.[16] Ligado will make available technical experts needed to support the repair and replacement program described here. In addition, Ligado will identify and make known to the FCC and the NTIA, a point of contact who will be designated to support this program. In light of its knowledge and expertise, the NTIA may also be able to facilitate the exchange of information between the Company and agencies wishing to take advantage of this program. The Company is prepared to begin these cooperative efforts immediately and will be prepared to repair or replace GPS devices as they are identified and evaluated and in coordination with planned deployments.

4. Other issues

The parties also briefly discussed other issues. With respect to the 1627.5-1637.5 MHz band, we discussed the OOBE levels and outlined the analysis Ligado has submitted that addresses those concerns. The parties also discussed the work that the company has done with respect to 3GPP and how it helps push forward the standard-setting process for 5G in various bands. Lastly, Ligado's representatives urged the Commission to promptly approve the Applications that have been pending since December 2015.

Please direct any questions to the undersigned.

Sincerely,

/s/ *Gerard J. Waldron*
Gerard J. Waldron
Counsel to Ligado Networks LLC

cc: Meeting Attendees

Attachments

[16] *See* Ligado Comments at 15-17.

Roberson and Associates, LLC
Technology and Management Consultants ®

July 9, 2018

Ms. Marlene S. Dortch
Secretary
Federal Communications Commission
445 12th Street, SW
Washington, DC 20554

Re: Written *ex parte* presentation in IB Docket No. 11-109; IBFS File Nos. SAT-AMD-20180531-00044 and SAT-AMD-20180531-00045

Dear Ms. Dortch:

I write to provide technical support for Ligado Networks recent Amendment to its License Modification[1]. In the attached document we point out that based on the dramatic reduction in transmission power that they have propose in the Amendment, any remaining technical concerns about the deployment of Ligado's proposed terrestrial network should no longer be warranted. Based on significant testing effort conducted by the National Advanced Spectrum and Communications Test Network (NASCTN) and our own test results, no GPS devices should experience harmful interference based on Ligado's deployed system. Further, any lingering concerns, particularly for high precision GPS devices should be eliminated through use of readily available filtered antennas. With this amendment, Roberson and Associates sees no technical reason to delay a speedy approval of this amended license modification request.

Sincerely,

<u>/s/ Dennis A. Roberson</u>
Dennis A. Roberson
President, CEO and Member

[1] Amendment To License Modification Applications, IB Docket No. 11-109, IBFS File Nos. SES-MOD-20151231-00981, SAT-MOD-20151231-00090, and SAT-MOD-20151231-00091 (filed May 31, 2018) - https://ecfsapi.fcc.gov/file/1053120688074/Ligado%20License%20Modification%20Cover%20Letter%20and%20Amendment%20(5-31-2018).pdf.

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Roberson and Associates comments on recent Ligado Amendment to License Modifications

Ligado Networks recently filed an amendment[1] to its license modification applications with the FCC. The license modification applications, as originally filed on December 31, 2015,[2] had already reduced the maximum transmit power of the company's proposed base stations in the 1526 to 1536 MHz band (the "Lower Downlink Band") from 42 to 32 dBW EIRP, with Ligado agreeing to accept future reductions in base station transmit power based on an FAA analysis of potential impact to certified aviation equipment. In the recent amendment, Ligado proposes to further reduce the transmit power in the Lower Downlink Band from 32 dBW to 9.8 dBW (or 10 Watts, an extremely low transmit power equivalent to the output power of a very dim light bulb) based on a recommendation received from the FAA. This new reduction protects aviation equipment from any possible interference from base stations in the 1526 to 1536 MHz band.

The reduced power proposed in Ligado's amended modification applications also will further protect GPS equipment beyond the certified aviation category. In 2016 Roberson and Associates reported[3] the results of an extensive open and repeatable measurement effort where 27 GPS receivers and devices that include embedded GPS receivers (e.g., cellphones) were subjected to simulated LTE base station interference from the 1526 to 1536 MHz band. Except for certain high precision GPS receivers (retesting with filtered antennas removed them as exceptions – see below), all the devices in the report were judged to be not susceptible to LTE interference from

[1] Amendment To License Modification Applications, IB Docket No. 11-109, IBFS File Nos. SES-MOD-20151231-00981, SAT-MOD-20151231-00090, and SAT-MOD-20151231-00091 (filed May 31, 2018) - https://ecfsapi.fcc.gov/file/1053120688074/Ligado%20License%20Modification%20Cover%20Letter%20and%20Amendment%20(5-31-2018).pdf.
[2] License Modification Applications, IB Docket No. 12-340, IBFS File Nos. SES-MOD-20151231-00981, SAT-MOD-20151231-00090, and SAT-MOD-20151231-00091 (filed December 31, 2015) - https://ecfsapi.fcc.gov/file/60001396811.pdf.
[3] Roberson Report - https://ecfsapi.fcc.gov/file/60002112686.pdf

base-stations in the 1526 to 1536 MHz band operating at power levels of 32 dBW in at least 99 % of locations. In February 2017, the government's experts at the National Advanced Spectrum and Communications Test Network (NASCTN)[4] released a report containing detailed interference measurements on 14 GPS devices using a very disciplined and repeatable test approach. Although the NASCTN report did not make any statements regarding susceptibility to interference, the performance data results reported were similar to those observed in the Roberson testing.

The new 9.8 dBW EIRP power level agreed to by Ligado for its Lower Downlink Band terrestrial base stations is a greater than two orders of magnitude, from 1584 Watts to 10 Watts, or more than 100x reduction in transmit EIRP level. Applying the conclusions from the Roberson testing and analysis that assumed a 32 dBW base station power level to analyze Ligado's new power level results in a new conclusion that the likelihood of Ligado's Lower Downlink Band operations causing harmful interference to any non-high precision GPS devices is extremely rare, with a probability of effectively zero.

Both the Roberson and NASCTN testing showed that high precision GPS receivers can also be made immune to interference by using filtered antennas designed for the wide RF bandwidth requirements of high precision GPS receivers for received interference power levels equal to or greater than the levels expected from a 32 dBW EIRP base-station. The Roberson testing also shows that some of the high precision GPS receivers that would have been susceptible to interference from 32 dBW base-stations would no longer be susceptible at 9.8 dBW even without a replacement filtered antenna.

Roberson and Associates, in their measurement report,[5] calculated the expected power levels from a 32 dBW LTE base station in the 1526 to 1536 MHz band that a GPS receiver operating

[4] NASCTN Report - https://www.nist.gov/sites/default/files/documents/2017/05/04/nasctn_-_lte_impacts_on_gps_-_briefing_may_2017.pdf
[5] Roberson Report Appendix C - https://ecfsapi.fcc.gov/file/60002112686.pdf

at ground level would receive. Measurements from the 2011 Las Vegas testing, extensive Monte Carlo simulations, and extensive drive testing were used in the calculations. For a 32 dBW transmitter using Monte Carlo simulations the aggregate received power level would be less than -23.7 dBm in 99 % of locations. The Roberson analysis used a higher and therefore more conservative value of -20 dBm to indicate the 99th percentile (that is 99% of the locations have power less than -20dBm). Reducing the base-station station power to Ligado's proposed level of 9.8 dBW – a reduction of over 22 dB – would shift the 99th percentile received power level to less than -42 dBm or less than 1/10th of a microwatt. High precision GPS devices with filtered antennas have been shown to co-exist with 32dBW base transmitters, and reducing the base transmitter to 9.8 dBW further reduces the need for additional filtering.

In conclusion, the probability of interference to properly designed GPS devices from base stations in the 1526 to 1536 MHz band with power levels of 9.8 dBW EIRP is effectively zero. Any residual concerns, such as older high-performance GPS receivers can easily add additional protection by installing inexpensive nominal filters to cover any perceived filtering need. We note that the company has reached agreements with the major GPS providers including high precision device manufacturers. This underscores the fact that the modified Ligado plan should have no impact on GPS device performance.

Nokia's Study on Ligado Spectrum Deployment

February 2019

About Nokia

We create the technology to connect the world. We develop and deliver the industry's only end-to-end portfolio of network equipment, software, services and licensing that is available globally. Our customers include communications service providers whose combined networks support 5.7 billion subscriptions, as well as enterprises in the private and public sector that use our network portfolio to increase productivity and enrich lives.

Through our research teams, including the world-renowned Nokia Bell Labs, we are leading the world to adopt end-to-end 5G networks that are faster, more secure and capable of revolutionizing lives, economies and societies. Nokia adheres to the highest ethical business standards as we create technology with social purpose, quality and integrity.

Contents

Nokia's Network Planning and Optimization (NPO) team developed this analysis through its own engineering expertise using standard engineering simulation tools, with inputs provided by Ligado on spectrum details and power levels (See Appendix for Ligado Spectrum Overview). As part of this study, Nokia assessed the impact on the forward link capacity of an LTE network factoring in reduced downlink carrier EIRP. In addition, Nokia assessed whether using L-band spectrum for dedicated small cell service deployments would provide network capacity performance benefits relative to AWS band spectrum in a Heterogeneous network (HetNet) configuration. Though Nokia has tried to analyze the sensitivity of various technology assumptions including inter-site distances (ISDs), it is not possible to account for every field scenario.

1 Executive Summary

1.1 Minimal impact on capacity of downlink power restrictions of 9.8 dBW (10W) in Urban areas where inter-site distances are small (< 600m)

- 0-10% impact relative to full power L-Band channel
- No impact relative to full power AWS channel

1.2 Capacity per site is reduced at lower inter-site distances due to increased interference between co-channel sites

- Such capacity reductions become more pronounced at inter-site distances of 500m or less
- As a result, any impact from inter-site distances limitations that might be required as part of Ligado's license are expected to be limited

1.3 For HetNet scenarios, using Ligado's 9.8 dBW (10W) downlink on a dedicated basis for small cells will yield ~ 3x the capacity compared to using shared AWS spectrum between macro and small cell sites

- As such, use of Ligado's 9.8 dBW (10W) downlink for small cells reduces the required number of small cells as compared to enabling the equivalent capacity availability using AWS spectrum alone

The flexibility and versatility of lower mid-band spectrum provides significant economic and operational advantages to other higher-band alternatives. The Nokia analysis confirms that flexible use of lower mid-band spectrum across today's network infrastructure can achieve some combination of lower-cost and more rapid deployment of network capacity.

2 Technical Summary

2.1 The 9.8 dBW (10W) downlink power level has a minimal impact to capacity in urban areas where inter-site distances are small

Nokia estimates that capacity impact will be 0-10% for 9.8 dBW (10W) as compared to 32 dBW downlink power for inter-site distances of less than 600 meters, which are more typical in urban areas. This estimate is based on analyzing the capacity simulations of a network utilizing various MIMO configurations (2x2 and 4x2) serving a mix of indoor and outdoor users and no optimization between different scenarios.

2.2 The 9.8 dBW (10W) downlink power level has a moderate impact to capacity in suburban areas where inter-site distances are medium

Nokia estimates that capacity impact will be 20-40% for 9.8 dBW (10W) as compared to 32 dBW downlink power for inter-site distances of 1-1.7 km, which are more typical in suburban areas. This estimate is based on analyzing the capacity simulations of a network utilizing various MIMO configuration (2x2 and 4x2) serving a mix of indoor and outdoor users and no optimization between different scenarios.

2.3 The 9.8 dBW (10W) downlink power level has a significant impact to capacity in rural areas where inter-site distances are large

Nokia estimates that capacity impact will be 60% or more for 9.8 dBW (10W) as compared to 32 dBW downlink power for higher inter-site distances of 3.2 km or more, which are more typical in rural areas. This estimate is based on analyzing the capacity simulations of a network utilizing various MIMO configuration (2x2 and 4x2) serving a mix of indoor and outdoor users and no optimization between different scenarios.

2.4 Capacity per site is reduced at lower inter-site distances due to interference and at higher inter-site distances due to noise

Nokia estimates that throughput per cell site decreases with densification due to increased interference between co-channel cell sites. Deploying cell sites at distances less than 500m inter-site distance show such an increase in interference levels to a point that the network will need to be optimzied to maintain a similar weighted throughput. Throughput also decreases for very large inter-site distances due to increased propagation loss at higher inter-site distances and where throughput is driven by noise rather than by interference. This is an expected outcome as cells transition from being noise limited at large inter-site distances to being interference limited at smaller inter-site distances with no optimization between different scenarios.

2.5 Full power Ligado downlink channel will provide 5-10% more capacity than AWS downlink channels

Nokia analyzed the capacity difference between an equivalent full power AWS downlink channel and a full power Ligado downlink channel and estimates that the Ligado channel, due to inherent advantages of propagation associated with lower frequencies, provides an estimated capacity

benefit of about 5-10% over the equivalent AWS channel. This estimate was based on analyzing the capacity of a typical macro and small cell network located in a New York urban area.

2.6 For HetNet scenarios, utilizing Ligado's 9.8 dBW (10W) as dedicated downlink spectrum for small cells will yield ~3 times the capacity compared to utilizing shared AWS spectrum between macro and small cell sites

Nokia estimates that utilizing dedicated spectrum for small cells will provide a significant increase in overall network capacity of Heterogeneous networks. This estimate was based on analyzing the capacity addition from adding small cells using Ligado's 9.8 dBW (10W) power channel to a typical macro cell network in a segment of a New York urban area versus adding small cells using a co-channel AWS to the same network.

2.7 For HetNet scenarios, utilizing Ligado's 9.8 dBW (10W) as dedicated downlink spectrum for small cells allows for a reduced number of small cells relative to those required using AWS to achieve an equivalent capacity gain

Nokia estimates that utilizing Ligado's dedicated spectrum for small cells will require a reduced number of small cells relative to those required using AWS while achieving an equivalent capacity gain. This estimate was based on analyzing the capacity addition from adding small cells using shared AWS spectrum power to a typical macro cell network and then eliminating half of small cell sites and replacing shared AWS spectrum with dedicated 9.8 dBW (10W) Ligado spectrum on small cells in a segment of New York urban area.

2.8 For HetNet scenarios, utilizing Ligado's 9.8 dBW (10W) downlink spectrum for macro as well as small cells will yield a significant capacity improvement

Nokia estimates that utilizing Ligado's 9.8 dBW (10W) spectrum for both macro and small cells will provide a significant increase in overall network capacity of heterogeneous networks. This estimate was based on analyzing the capacity addition from adding Ligado's 9.8 dBW (10W) downlink channel to a typical macro and small cell network in a segment of a New York urban area.

3 Simulation Analysis Overview

Nokia analyzed the impact of reduced power of a BTS LTE carrier on the downlink throughput. This document provides a summary of the results.

The following three cases were analyzed:

- Analysis 1: Impact of a reduced BTS LTE carrier EIRP for a single 10x10 MHz carrier network
- Analysis 2: Impact of a reduced BTS LTE carrier EIRP for one of two 10x10 MHz carrier network
- Analysis 3: Impact of a reduced BTS LTE carrier EIRP in a heterogenous network

4 Methodology Overview

4.1 Capacity Analysis for a Single 10x10 MHz Carrier

The objective of this analysis was to determine the impact on the downlink capacity of an LTE network due to the reduction of the forward link carrier EIRP.

To analyze this scenario, Nokia utilized a hexagonal grid of 19 sites (57 sectors) as shown in Figure 1 below::

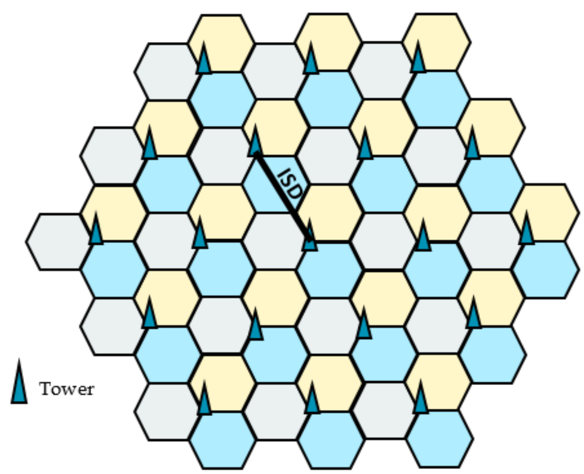

Figure 1: Hexagonal Site Layout Used for Analysis

Inter-site distances (ISDs) were varied from 430 meters to a maximum of 3,200 meters. Specific ISDs analyzed within this range were 430m, 500m, 600m, 800m, 1km, 1.7km, 2.5km and 3.2km.

600 users were distributed using Monte Carlo simulations within the analysis area with an average DL requirement of 2.5Mbps. Two scenarios were simulated: one with outdoor and one with indoor users. A flat earth model without any terrain was used for the analysis. The simulations were repeated with 2° and 7° antenna down tilts.

Other key assumptions were:

- BTS Radiation Centre: 26m
- BTS antenna Beam width: 65 deg (Horizontal) / 7.5 deg (Vertical)
- MIMO: 2x2 and 4x2
- Indoor Loss considered: 15dB
- Propagation Tool and Propagation Model: Atoll with NOK modified Standard Propagation Model
- Standard UE, Max power: 1T2R, 22 dBm maximum power, 0dBi antenna gain, height of 5ft

4.2 Capacity Analysis for a two 10x10 MHz carrier network

The objective of this study is to assess the impact on the downlink capacity of a dual channel LTE network due to the reduction of the forward link carrier EIRP on one of the channels.

Propagation tools used for these simulations do not take advantage of base station smart scheduling and traffic management features, therefore simulations via propagation tools for scenario 2 were not effective. Nokia decided to interpolate data from Analysis 1 to achieve Analysis 2 results.

Nokia believes that actual HetNet capacity performance could be higher than the results shown in this report via site by site optimization, traffic management and smart scheduling.

Given the interpolation process, all scenario 1 assumptions are also applicable to scenario 2.

4.3 Capacity Analysis for a HetNet network

Purpose of this analysis was to assess whether Ligado’s L-band spectrum would provide network benefits in terms of performance for dedicated small cell service deployments relative to AWS spectrum in a HetNet network configuration.

To mimic a real-world scenario, an urban area (~45 km^2) in New York was selected as a HetNet analysis area.

Site data from various publicly available sources (such as Cellmapper, etc.) was used to design an equivalent network representative of a typical 4G AWS Band LTE network for the above selected area. Macro design for the above area resulted in 46 macro cells. This base layer of macro cells was additionally supplemented by a small cell layer which consisted of 50 small cells.

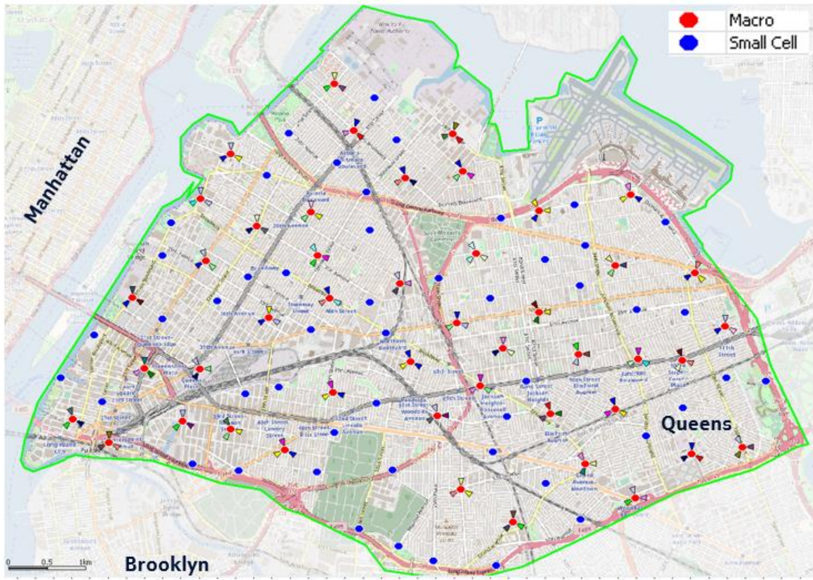

Figure 2: New York Area Design for Macro and Small Cell

The following deployment cases were analyzed:

- AWS HetNet: Macro as well as small cells reusing the same 10 MHz AWS channel
- L-band HetNet: Macro as well as small cells reusing same 10 MHz L-band channel
- AWS Macro/L-Band small cells: AWS Macro using 10 MHz AWS channel and L-band small cells using 10 MHz L-band dedicated channel
- AWS Macro/ L-band HetNet: Macro using both 10 MHz AWS channel and 10 MHz L-band and small cell reusing only 10 MHz L-band channel.
- AWS HetNet + L-band HetNet: Macro as well as small cells using 10 MHz AWS channel and 10 MHz L-band channel

All scenarios above were performed with 500 and 1000 distributed users as well as MIMO 2x2 and 4x2 configurations.

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5 Ligado Spectrum Simulation Details

5.1 Analysis 1 Results: Capacity for a Single 10x10 MHz Carrier

5.1.1 Impact of Power Reduction to 9.8 dBW (10W)

The below graph shows the capacity difference between that of a network at 32 dBW to that of a network at 9.8 dBW (10W), with all users distributed outdoors within the coverage area. As can be seen from the chart, the capacity impact of reducing power to 9.8 dBW (10W) is minimal for inter-site distances of less than 600 meters.

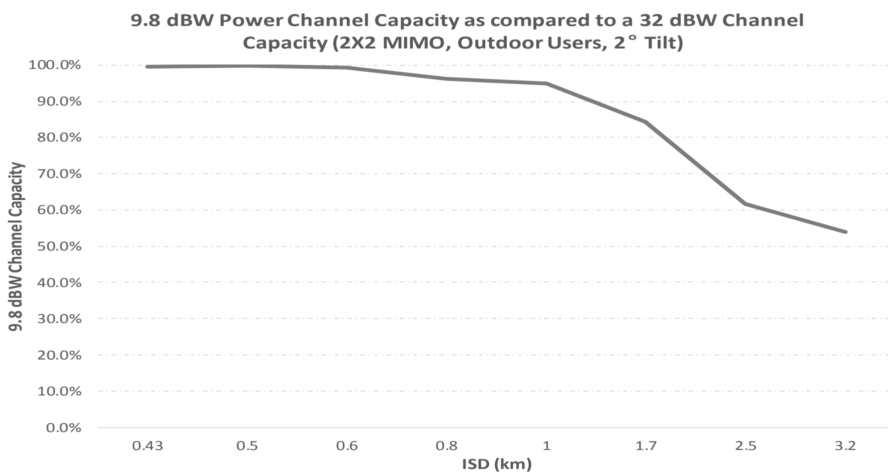

Figure 3: Simulation Results: 9.8 dBW Channel Capacity Compared to 32 dBW Channel (2X2 MIMO, Outdoor Users, 2 Deg Antenna Tilt)

A second set of simulations were run with a 15dB penetration loss to simulate indoor users and simulate a more coverage limited scenario. The output chart below shows the weighted capacity of a network comprised of users equally distributed across both indoor and outdoor morphologies. As can be seen from this chart, the capacity impact of reducing power to 9.8 dBW (10W) is minimal (<10%) for inter-site distances of less than 600 meters. Impact is significantly higher for inter-site distances of 3,200 meters.

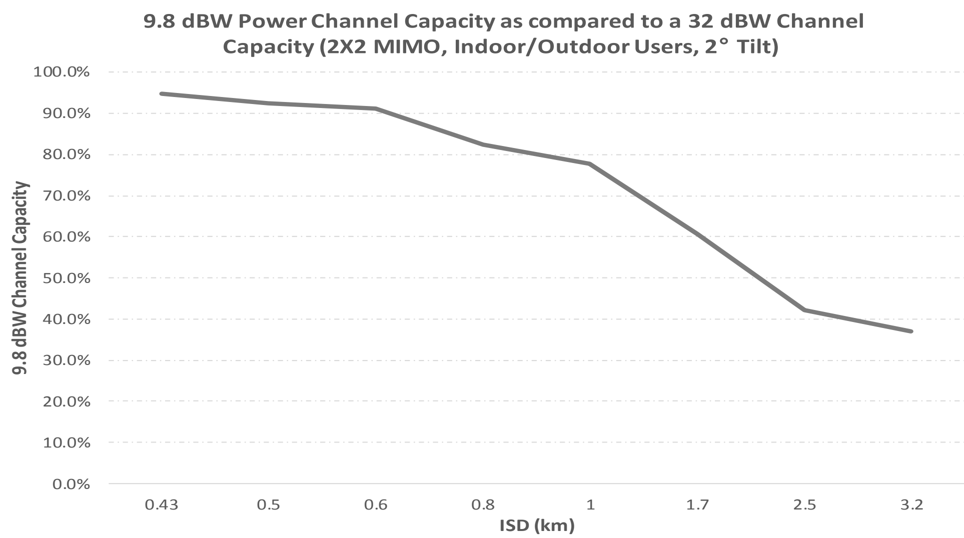

Figure 4: Simulation Results: 9.8 dBW Channel Capacity vs. 32 dBW Channel (2X2 MIMO, Indoor/Outdoor Users, 2 Deg Antenna Tilt)

Simulations were repeated with antenna down tilt increased to 7° to optimize capacity based on down tilt. Below results show the optimum throughputs selected out of the 4 possible network configurations of EIRP of 9.8 dBW (10W) and 32 dBW at 2 and 7 deg tilt. In a typical network the tilts for each inter-site distance would be optimized to get the most capacity from the network.

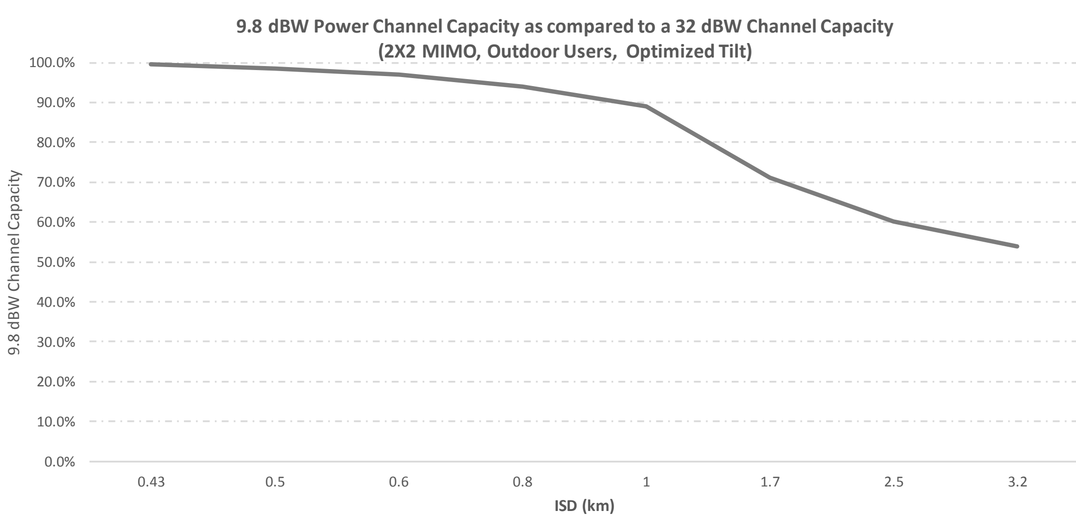

Figure 5: Simulation Results: 9.8 dBW Channel Capacity Compared to 32 dBW Channel (2X2 MIMO, Outdoor Users, Optimized Antenna Tilt)

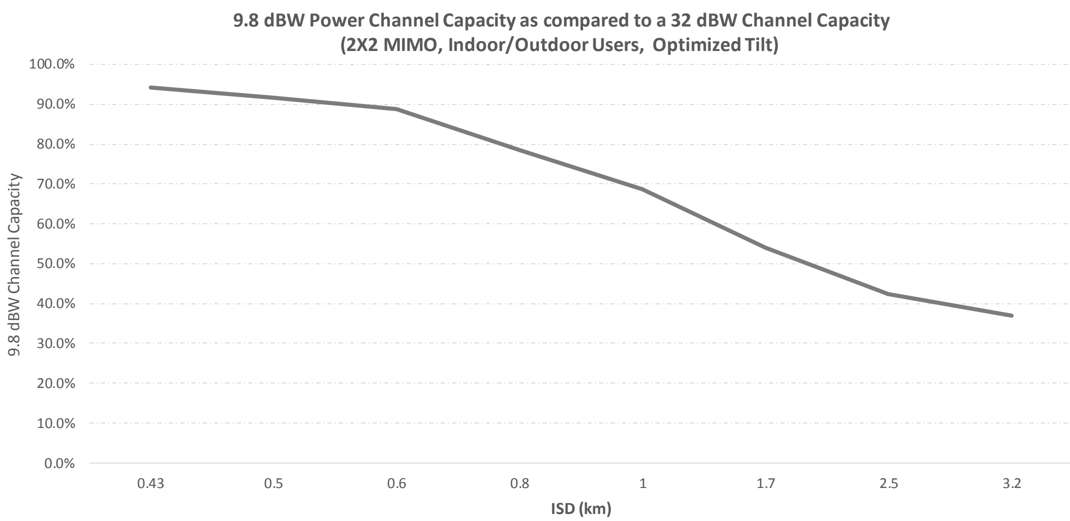

Figure 6: Simulation Results: 9.8 dBW Channel Capacity Compared to 32 dBW Channel (2X2 MIMO, Indoor/Outdoor Users, Optimized Antenna Tilt)

5.1.2 Throughput versus Densification

Nokia also ran simulations to quantify the impact of inter-site distances on throughput. Results show that throughput per cell decreases with densification due to increased interference between cell sites. Throughput also decreases for very large inter-site distances due to increased propagation loss at higher inter-site distance where throughput is driven by noise rather than by interference at large distances.

The results below are shown for a 9° antenna down tilt and same EIRP for all sectors. Typically, to improve the performance of the network at lower inter-site distance, the coverage over shoot of the sites will be limited by controlling the heights, tilts and power control. On the other hand, to improve the performance of the network at higher inter-site distance, a combination of antenna tilts, heights, power optimization and further network densification would be performed.

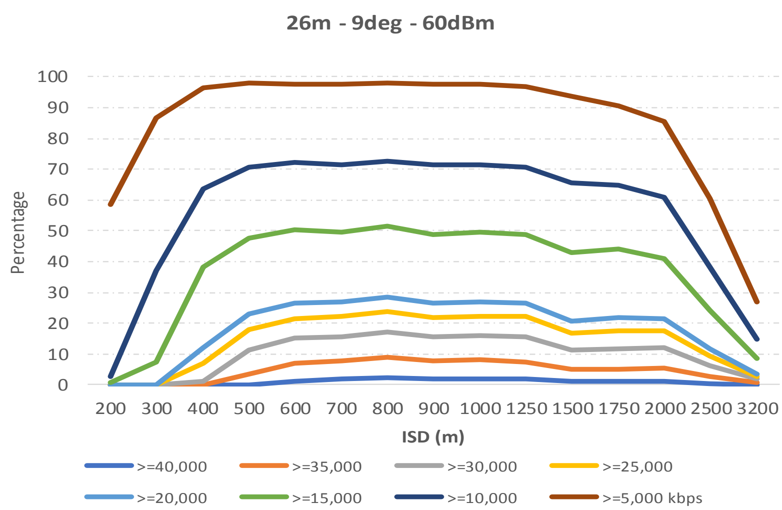

Figure 7: Throughput Distribution over area under consideration versus Inter Site Distances for 9° Antenna Tilt

The above simulations were also repeated with a lower down tilt of 3°to capture the scenarios representative of larger inter-site distances. Throughput results were weighted over the cell coverage area. Below graph shows the maximum weighted throughput over cell coverage area with optimized down tilt (3°or 9°) between these two analyzed down tilt scenarios.

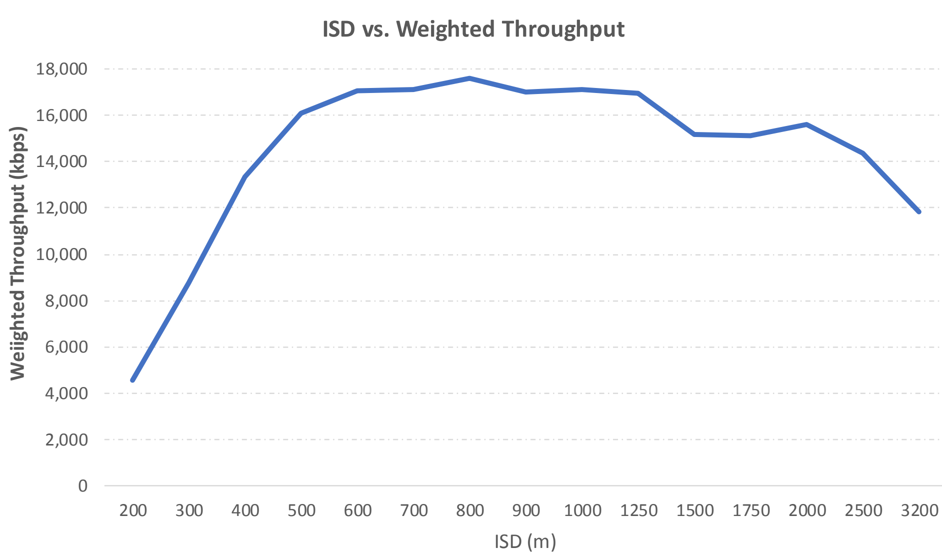

Figure 8: ISD versus Weighted Throughput

This is an expected outcome as cells transition from being noise limited at larger inter-site distances to being interference limited at smaller inter-site distances. When inter-site distances are large, cells are spread over a large area and throughput is generally driven by system noise

whereas with densification, inter-site distances become smaller and per cell throughput will decrease with increased interference.

5.2 Analysis 2 Results: Capacity for two 10x10 MHz carriers

Propagation tools used for these simulations do not take advantage of base station smart scheduling and traffic management features, therefore simulations via propagation tools for scenario 2 were not effective. Nokia decided to interpolate data from scenario 1 to achieve scenario 2 results. Nokia believes additional HetNet capacity gains are practically feasible than interpolated results shown in this report via site by site optimization, traffic management and smart scheduling.

The below graph shows the relative capacity of a site utilizing two channels with one transmitting at 32 dBW and the other at 9.8 dBW (10W) compared to a site with both channels transmitting at 32 dBW.

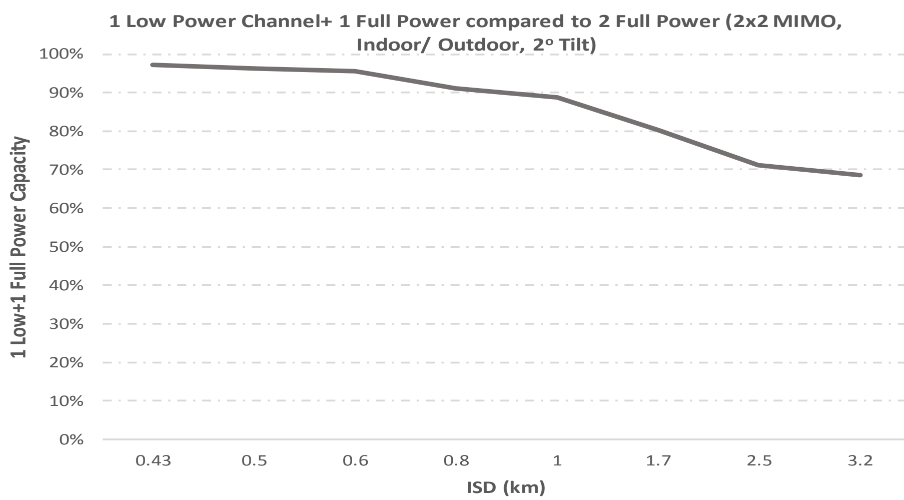

Figure 9: Simulation Results for 1 Low Power + 1 Full Power vs. 2 Full Power Channels (2X2 MIMO, Outdoor Users, 2 Deg Antenna Tilt)

5.3 Analysis 3 Results: HetNet Capacity

5.3.1 AWS versus Ligado Full Power Channel Capacity

To evaluate the relative capacity of a Ligado full power channel compared to an equivalent AWS channel, the following three use cases were analyzed:

5.3.1.1 Macro Cell Only Use Case:

In this macro cell only scenario, capacity was calculated for a baseline layer of macro cells utilizing AWS 10 MHz spectrum. Then the same macro cell layer spectrum was replaced with Ligado spectrum at the same power, optimized and the network capacity was calculated with the same set of users.

- Macro Cell Capacity using AWS spectrum: 1.80 Gbps
- Macro Cell Capacity using Ligado spectrum: 1.90 Gbps.

In this scenario, the Ligado spectrum provided ~ 5% capacity benefit compared to AWS spectrum owing to better propagation and in-building penetration associated with lower frequency spectrum than higher frequency spectrum.

5.3.1.2 Small Cell Only Use Case:

In this small cell scenario, capacity was calculated for a baseline layer of small cells utilizing AWS 10 MHz spectrum. Then the same small cell layer spectrum was replaced with Ligado spectrum at the same power, optimized and the network capacity was calculated with the same set of users.

- Small Cell Capacity with AWS spectrum: 0.83 Gbps
- Small Cell Capacity with Ligado spectrum: 0.93 Gbps.

In this scenario, Ligado full power spectrum provided ~ 12% capacity benefit compared to AWS spectrum owing to better propagation and in-building penetration associated with lower frequency spectrum than higher frequency spectrum.

Based on the above two use cases analyzed, Nokia estimates that Ligado spectrum at full power can provide 5-10% improvement over AWS spectrum depending on the deployment scenario.

5.3.2 Dedicated Ligado Spectrum for Small Cell Versus Using AWS Shared Spectrum Between Macro and Small Cells

To evaluate the relative additional capacity utilizing dedicated Ligado spectrum for small cells versus using shared AWS spectrum between macro and small cells, the following three use cases were analyzed.

5.3.2.1 AWS HetNet Capacity:

This macro cell layer was then supplemented with a small cell layer. In the first instance, both small cells as well as macro cells utilized same 10 MHz downlink AWS channel. As expected, the performance of the AWS macro cells is impacted due to the interference created from the AWS

small cells and similarly the users on the small cells are also impacted by the interference from macro cells. Overall capacity does go up due to addition of small cells.

- AWS Macro Layer Capacity: 1.83 Gbps
- AWS Small Cell Layer Capacity: 0.83 Gbps
- AWS HetNet Capacity: 2.51 Gbps (1.8 Gbps on Macro and 0.71 Gbps on Small Cell)

5.3.2.2 AWS/Ligado HetNet Capacity:

In the second instance, the small cells utilized a dedicated 10 MHz downlink Ligado channel (9.8 dBW). As expected, even macro cell capacity increased since the small cell layer helped in offloading some of traffic at the cell edges. Overall capacity also increased significantly due to addition of small cells.

- AWS Macro Layer Capacity: 1.83 Gbps
- Ligado Small Cell Layer Capacity: 0.93 Gbps
- AWS Macro + Ligado Small Cell Layer Capacity: 4.02 Gbps (1.99 Gbps on Macro and 2.03 Gbps on Small Cell)

5.3.2.3 Comparison AWS HetNet vs. AWS/Ligado HetNet:

Below table summarizes the capacity benefits of using dedicated spectrum for small cells versus using shared spectrum between macro and small cells.

Baseline Scenario with 500 Simultaneous Users	Capacity (Gbps)	Capacity Increase
AWS Macro Cells Only Scenario	1.83	-
AWS HetNet: AWS Macro Cells & AWS Small Cells	2.51	37%
AWS/Ligado HetNet: AWS Macro Cells & Ligado Small Cells	4.02	120%

Figure 10: AWS HetNet versus AWS-Ligado HetNet Capacity Results

As can be seen from the above table, using dedicated Ligado spectrum at 9.8 dBW (10W) provides ~ 3 times the capacity benefits (120% versus 37% increase) compared to using shared AWS spectrum between AWS macro cells and small cells.

The benefit is achieved by eliminating the interference between macro and small cells. For the current simulation, the user is assigned to a serving cell based on the best RSRP (signal power) at the user location. The performance of the AWS small cell is impacted by the interference from the AWS macro cell and similarly the users on the macro are also impacted by the addition of the small cells. However, when the Ligado frequency is used for the small cells, users served by the Ligado small cells have much lower interference and show better throughputs. Also, small cells using Ligado band do not negatively impact the performance of the AWS macro cells but help offload cell edge users to improve the overall capacity of the AWS macro network.

5.3.3 Ligado Spectrum overlaid over AWS HetNet

In this scenario, capacity of a HetNet utilizing AWS spectrum along with Ligado spectrum at 9.8 dBW (10W) was estimated. In this case the Ligado Network adds additional capacity to the existing AWS HetNet capacity and the two are added to give us the total capacity of the Network.

5.3.3.1 Ligado channel at 9.8 dBW (10W) overlaid with Macro Cells:

- AWS only HetNet Capacity: 2.51 Gbps
- Ligado Only Macro Capacity (limited to 9.8 dBW): 1.66 Gbps
- AWS HetNet + Ligado Macro Capacity: 4.17 Gbps

5.3.3.1 Ligado channel at 9.8 dBW (10W) overlaid with both Macro and Small Cells:

- AWS only HetNet Capacity: 2.51 Gbps
- Ligado only HetNet Capacity: 2.12 Gbps
- AWS HetNet + Ligado HetNet Capacity: 4.63 Gbps

Based on the above two use cases analyzed, Nokia estimates that Ligado spectrum at 9.8 dBW (10W) can provide significant capacity improvement when overlaid with a deployed AWS spectrum

6 Sensitivity Analysis

6.1 Higher Order MIMO Sensitivity

Simulations were repeated with higher order 4x2 MIMO for Scenario 1. As expected, overall throughput increased by 10%-15%.

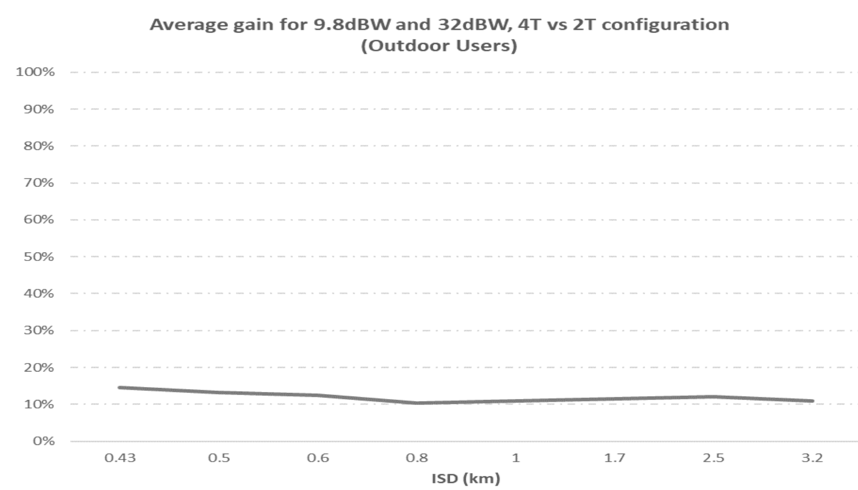

Figure 11: Average gain for 9.8 dBW and 32 dBW for 4x2 vs 2x2 MIMO

Capacity due to power reduction for Ligado channel to 9.8 dBW (10W) were in line with results for 2x2 MIMO showing smaller impact for lower inter-site distances and larger impact for larger inter-site distances.

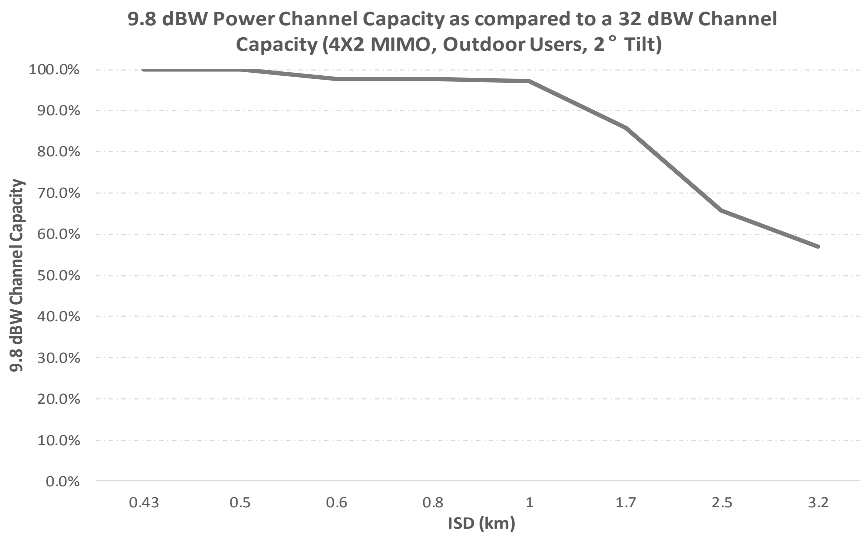

Figure 12: Simulation Results for 9.8 dBW Channel Capacity Compared to 32 dBW Channel (4x2 MIMO, Outdoor Users, 2 Deg Antenna Tilt)

6.2 AWS HetNet vs. AWS/Ligado HetNet Sensitivity Analysis

HetNet simulations were repeated by doubling the number of users to validate the sensitivity of the AWS/Ligado HetNet results.

Sensitivity Scenario with 1,000 Simultaneous Users	Capacity (Gbps)	Capacity Increase
AWS Macro Cells Only	1.96	-
AWS Macro Cell & AWS Small Cell	2.85	45%
AWS Macro Cell & Ligado Small Cell	4.69	139%

Figure 13: HetNet Sensitivity Scenario Results

Sensitivity results were consistent with baseline results meaning the use of dedicated Ligado spectrum at 9.8 dBW (10W) provided ~3 times the capacity benefits (139% vs. 45% increase) compared to using shared AWS spectrum between AWS and small cells.

7 Appendix – Supporting Information and Assumptions

Contained in this appendix are:

- Ligado Spectrum Overview
- Propagation Tool/Propagation Model Details
- Additional Charts and Data

7.1 Ligado Spectrum Overview and Power Restrictions

Ligado holds 35 MHz of nationwide low frequency mid-band spectrum in the 1.5-1.6 GHz range and is seeking to supplement those holdings with an additional 5 MHz. Post Ligado's License Modification approval, Ligado will hold licenses for 35 MHz of spectrum in the L-band, which is mid-band spectrum situated in the 1.5-1.6 GHz range; Ligado is seeking to supplement these holdings with 5 additional MHz to create a 40 MHz portfolio.

Ligado's current and potential portfolio includes two main types of spectrum:

- "9.8 dBW" Power L-band
  - 10 MHz of downlink spectrum (1526-1536 MHz) that will have lower operating power limits than typical spectrum bands. We have analyzed this spectrum using the assumed power (EIRP) range provided by Ligado of 9.8 dBW (10W).
- "32 dBW" Power L-band
  - 5 MHz of downlink spectrum (1670-1675 MHz) that has no power restrictions.
  - Potential for an additional 5 MHz of downlink spectrum (1675-1680 MHz), immediately adjacent to the 5 MHz discussed above.
  - We have analyzed this spectrum using the assumed power (EIRP) range provided by Ligado of 32 dBW.
- 20 MHz of uplink L-Band spectrum

The aforementioned spectrum bands are shown in the chart below in relation to other bands:

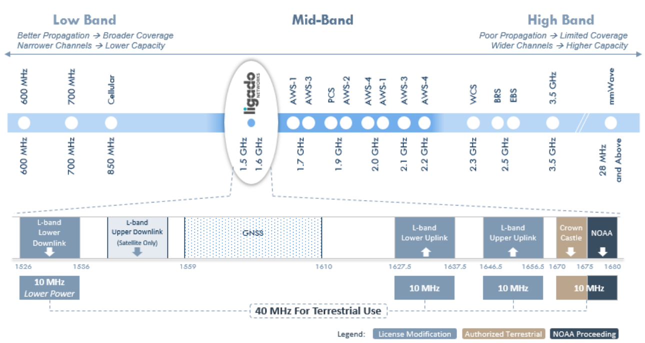

Figure 14: Ligado Spectrum Bands

Source: Ligado

7.2 Propagation Tool and Propagation Model Details

Atoll is a multi-technology wireless network design and optimization platform that supports wireless operators throughout the network lifecycle.

For analysis 3.1 and 3.2, Standard Propagation Model (SPM) is optimized based on NOKIA's work in various markets is used. A flat earth model with no clutter is used to make the study generic and independent of any market specific data.

The Standard Propagation Model (SPM) is based on the Hata formulas and is suited for predictions in the 150 to 3500 MHz band over long distances (from one to 20 km). The Standard Propagation Model is based on the following formula:

$$P_R = P_{Tx} - \begin{pmatrix} K_1 + K_2 \times Log(d) + K_3 \times Log(H_{Tx_{eff}}) + K_4 \times DiffractionLoss + K_5 \times Log(d) \times Log(H_{Tx_{eff}}) + \\ K_6 \times H_{Rx_{eff}} + K_7 \times Log(H_{Rx_{eff}}) + K_{clutter} \times f(clutter) + K_{hill,\,LOS} \end{pmatrix}$$

P_R	received power (dBm)
P_{Tx}	transmitted power (EIRP) (dBm)
K_1	constant offset (dB)
K_2	multiplying factor for *Log(d)*
d	distance between the receiver and the transmitter (m)
K_3	multiplying factor for *Log(HTxeff)*
$H_{Tx_{eff}}$	effective height of the transmitter antenna (m)
K_4	multiplying factor for diffraction calculation. *K4* must be a positive number
DiffractionLoss	losses due to diffraction over an obstructed path (dB)
K_5	multiplying factor for *Log(HTxeff) x Log(d)*
K_6	multiplying factor for *HRxeff*
K_7	multiplying factor for *Log(HRxeff)*
$H_{Rx_{eff}}$	mobile antenna height (m)
$K_{clutter}$	multiplying factor for *f(clutter)*
f(clutter)	average of weighted losses due to clutter
$K_{hill,\,LoS}$	corrective factor for hilly regions (=0 in case of NLoS)

For analysis 3.3, simulations are run for an area in NY using CrossWave Propagation model tuned and adjusted based on NOKIA's work in various markets. CrossWave is a high-performance universal propagation model developed by Orange Labs. It supports all wireless technologies and all types of environments, from rural to dense urban areas. The CrossWave model relies on geographical data to provide realistic modelling by combining Vertical diffraction using elaborate clutter information (Morphology), Horizontal guided propagation (Graph calculation) and Reflection on mountains (Facet calculation). For the analysis, 5m resolution Digital Terrain Model, clutter classes, and clutter heights are used along with 3D building vectors.

7.3 Additional Charts and Data

7.3.1 AT&T and TMO site layout for New York area from CellMapper.com

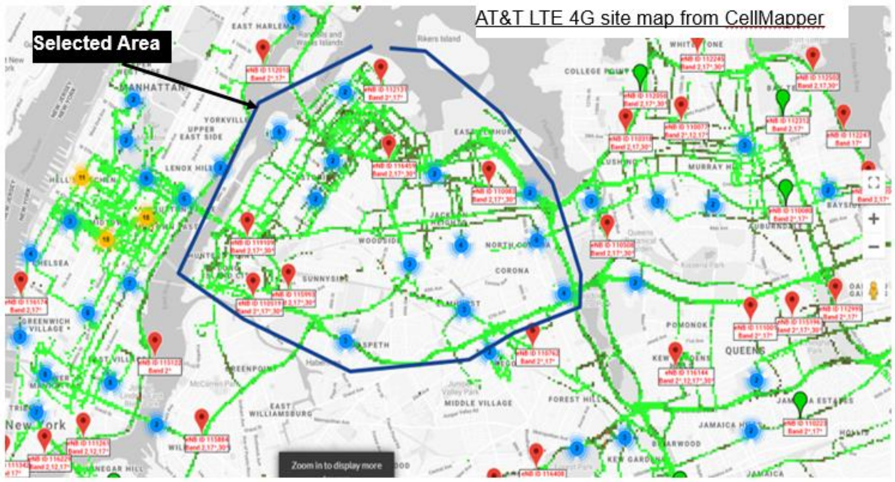

Figure 15: New York Urban Area AT&T LTE 4G Site Layout

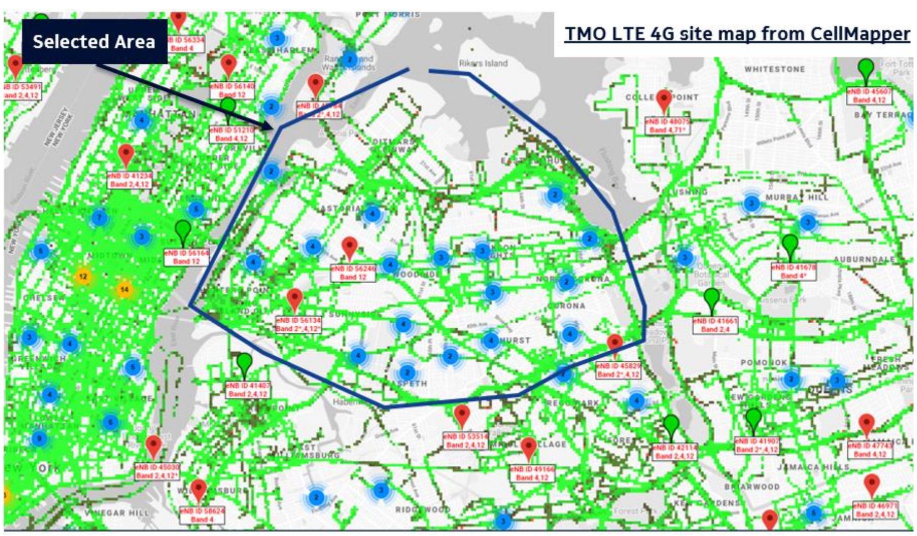

Figure 16: New York Urban Area TMO LTE 4G Site Layout

7.3.2 RSRP Comparison plot between AWS Small Cells and Ligado Small Cells

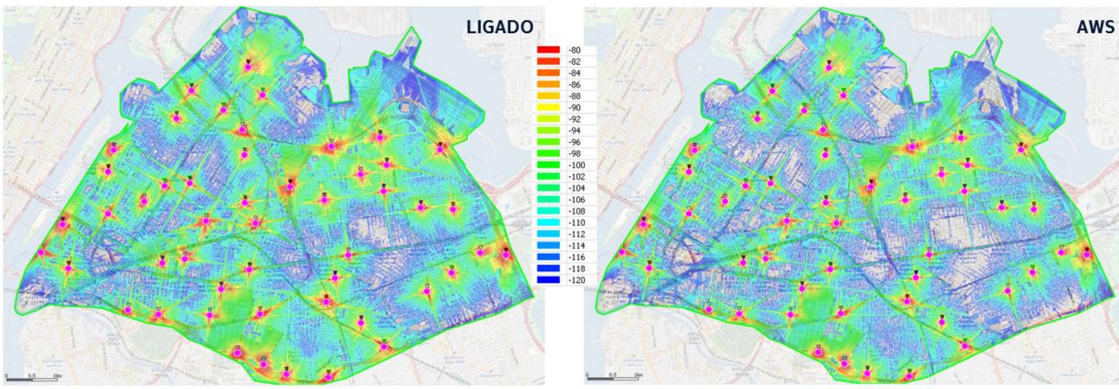

Figure 17: RSRP Comparison plot between AWS Small Cells and Ligado Small Cells