Assessment of Feasibility of Coexistence between NGSO FSS Earth Stations and 5G Operations in the 12.2 – 12.7 GHz Band

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Executive Summary

RKF Engineering Solutions, LLC (RKF) prepared this study to analyze the feasibility of coexistence between uncoordinated operations of terrestrial 5G and Space Exploration Holdings, LLC's (SpaceX's) non-geostationary orbit (NGSO) fixed-satellite service (FSS) deployments in the 12.2-12.7 GHz band (12 GHz band). This study finds that coexistence between robust deployments of 12 GHz spectrum, both for 5G and for NGSO FSS broadband, is achievable in nearly all deployment scenarios – even without coordination.

RKF relies on a probabilistic technique known as Monte Carlo analysis to identify and quantify the interference risk between (1) a nationwide 5G deployment of 12 GHz spectrum and (2) a much larger-than-currently-authorized number of SpaceX user terminals downlinking in the 12 GHz band. The analysis provides a transparent, reproducible means of evaluating the potential for sharing between these two uses.

RKF models terrestrial and NGSO FSS networks operating in the 12 GHz band. The model does not look at a high-level, simplistic urban-rural divide but instead uses a textured population model that recognizes pockets of high population densities throughout the United States. The model ensures that at least 10% of the population in each Partial Economic Area within the contiguous United States (CONUS) receives 12 GHz 5G service, simulating delivery of mobile 5G capacity service to the most populous parts of many rural markets, as well as to large portions of the largest cities. RKF's terrestrial model assumes a 5G network of 49,997 terrestrial macro-cell base stations, 89,970 fixed small-cell base stations, 1,949,760 simultaneously active mobile devices, and 6,999 point-to-point backhaul links across CONUS.[1] These network features are placed using an algorithm in a manner that approximates the real-world siting of a terrestrial 12 GHz network operator's macro-cell base stations. Satellite user terminal locations were sited by an algorithm consistent with most likely satellite broadband use cases. In particular, the areas and number of locations identified by the FCC as being unserved in the Rural Digital Opportunity Fund (RDOF) auction, Auction 904, were used as a proxy for areas most likely to benefit from satellite broadband and exhibit a greater propensity for satellite terminal deployment in the model. Today, SpaceX has a small number of beta subscribers in the United States. The NGSO model assumes that SpaceX is able to achieve 2,500,000 subscribers at a hypothetical time in the future, which is 1,500,000 more terminals than SpaceX is currently authorized to operate in the United States.

For all infrastructure and equipment, the analysis uses actual performance specifications where available. Where actual performance specifications are unavailable, RKF relies upon standard

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[1] This model is consistent with a multi-band 5G deployment model.

International Telecommunication Union (ITU) and 3GPP specifications, methods, assumptions, and interference thresholds. RKF's simulation also takes into account the relevant parameters associated with SpaceX's third modification, which the FCC recently granted.

Once the terrestrial and satellite networks are modeled, RKF simulates 2,500,000 Starlink terminals in groups of 2,500 terminals over 1,000 iterations. Each iteration drops 1,499,910 macro-cell simultaneously active user equipment (UEs) and 449,850 small-cell simultaneously active UEs within the coverage area of macro-cell and outdoor small cell 12 GHz base stations. The model also simulates beamforming of 5G macro-cells to the UEs and accounts for the assumed omnidirectional nature of 5G small-cell base stations. The 12 GHz band is unpaired, and 5G systems in the band would operate on a time-division duplex (TDD) basis. Consistent with other TDD networks, RKF assumes synchronized TDD operations with a four-to-one downlink-to-uplink ratio, such that 80% of the time base stations are transmitting and 20% of the time UEs are transmitting. Thus, the model assumes that, in 80% of the iterations, Starlink terminals receive interference from the base stations (macro-cells and small-cells) and, in 20% of the iterations, they receive interference from the UEs, with the 12 GHz point-to-point links being active in all iterations. RKF then calculates the interference-to-noise ratio (I/N) at each Starlink terminal from active 12 GHz transmitters within 50 kilometers of the Starlink terminal, including macro-cell base stations, small-cell base stations, point-to-point links, and UEs. The model calculates aggregate interference to Starlink terminals sufficient to arrive at a statistically significant output.

The modeling results in a cumulative distribution function to assess the probability of interference *to* the simulated deployment of 2,500,000 Starlink earth terminals *from* the simulated national deployment of terrestrial 12 GHz operations, including macro-cell base stations, small-cell base stations, point-to-point backhaul links, and mobile devices. Results showed that, with no coordination used or mitigation steps taken, a small percentage (about 0.888%) of Starlink user terminals over CONUS could experience an event that exceeded a nominal ITU threshold of -8.5 dB. The small percentage of interference cases also does not account for coordination measures that could easily be taken. And the results suggest that coordinated siting – as opposed to the stochastic approach taken by the simulation – alone would significantly reduce the already very low risk of harmful interference events occurring.

Few, if any, of the 0.888% of nominally affected Starlink terminals will experience service interruption, or even service degradation, in actual practice for several reasons. *First*, the study uses a variety of conservative assumptions that tend to overstate the likelihood of exceeding nominal interference thresholds for the satellite terminals. *Second*, the model does not implement any of the case-by-case site coordination or mitigation measures that operators routinely employ to mitigate the potential for interference in the ordinary course of business (and that – if needed – are particularly easy to implement before systems are widely deployed).

Third, the Starlink terminals have access to 1,500 megahertz of spectrum that is not co-frequency with the 5G infrastructure and UE envisioned for deployment in the 12 GHz band; these additional frequencies provide an operational safe harbor for Starlink users in the unlikely event that a nominal interference event were to occur.

Moreover, several qualitative factors account for the highly favorable coexistence environment in the 12 GHz band.

- NGSO satellite constellations that are designed to provide mass-market broadband internet access typically include thousands of satellites; therefore, user terminal operation is typically limited to comparatively high elevation angles.
- Both the base stations and UEs that comprise terrestrial 12 GHz systems are all relatively close to the ground and therefore operate at low elevation angles.
- 12 GHz base stations often utilize antenna downtilt to avoid self-interference, which also further limits the risk of interference to NGSO user terminals.
- 5G macro-cell base stations in 12 GHz will be beamforming, which further focuses their radiated energy on the UEs being served and not on NGSO user terminals.
- The primary markets for NGSO user terminals are in less densely populated areas, whereas terrestrial 12 GHz systems will be primarily deployed in areas of greater population density.
- Both NGSO systems and terrestrial 12 GHz systems are designed to operate in – and mitigate – an interference-prone environment.

In sum, RKF finds that coexistence in the 12 GHz band between 5G and NGSO FSS is readily achievable.

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1. Introduction

The 12.2-12.7 GHz band (12 GHz band) is allocated for Broadcasting Satellite Service (better known in the United States as DBS), non-geostationary satellite orbit (NGSO) fixed-satellite service (FSS), and fixed service. The Federal Communications Commission allocated the 12 GHz band for DBS in the early 1980s.[1] In 2000, the Commission added allocations for Fixed Service through the Multi-Channel Video and Data Distribution Service (MVDDS) and NGSO FSS operations.[2] NGSO FSS and MVDDS services are co-primary with one another but must operate on a non-interfering basis with DBS. There also is an international allocation for mobile except aeronautical mobile.

In January 2021, the Commission adopted a notice of proposed rulemaking seeking comment on, among other things, "whether it is technically feasible to add additional or expanded spectrum rights in the 12 GHz band without causing harmful interference to incumbent licensees."[3] This report is being submitted by RKF Engineering Solutions, LLC (RKF) to aid the Commission's assessment of expanded flexible-use rights in the 12 GHz band by studying the risk of interference to NGSO FSS terminals from a new allocation for 5G mobile networks in the band.

To analyze the impacts of sharing between 5G terrestrial systems and NGSO FSS operations, this study focuses on Starlink satellite terminals,[4] the largest planned deployment of such terminals. The study examines the risk of interference into Starlink terminals from 5G macro-cell and small-cell base stations (BS) and user equipment (UEs) as well as point-to-point wireless backhaul in the 12 GHz band. In designing the simulations, RKF first models a terrestrial 12 GHz 5G network comprised of 49,997 macro-cell base stations, 89,970 outdoor small-cell base stations, and 6,999 point-to-point backhaul connections, all of which are assumed to transmit in the 12 GHz band. RKF then models a generous deployment of 2,500,000 fixed-satellite service user terminals throughout the contiguous United States (CONUS) receiving on 10.7-12.7 GHz from an NGSO FSS system modeled on the most recently authorized constellation of space stations licensed to Space Exploration Holdings, LLC (SpaceX). As of this writing, Starlink is offering a "Public Beta Service," with a "[f]ocus on remote, rural communities with un/underserved households."[5] The model

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[1] *See Inquiry into the Development of Regulatory Policy in Regard to Direct Broadcast Satellites for the Period Following the 1983 Regional Administrative Radio Conference*, Report and Order, 90 FCC2d 676 (1982).

[2] *See Amendment of Parts 2 and 25 of the Commission's Rules to Permit Operation of NGSO FSS Systems Co-Frequency with GSO and Terrestrial Systems in the Ku-Band Frequency Range et al.*, First Report and Order and Further Notice of Proposed Rule Making, 16 FCC Rcd 4096 ¶ 2 (2000).

[3] *Expanding Flexible Use of the 12.2-12.7 GHz Band et al.*, Notice of Proposed Rulemaking, 36 FCC Rcd 606 ¶ 19 (2021).

[4] The feasibility of coexistence with the third co-primary service in the band, the DBS, is not addressed in this study.

[5] Letter from David Goldman, Director of Satellite Policy, SpaceX, to Marlene H. Dortch, Secretary, FCC, WT Docket No. 20-133, Attachment at 7 (filed May 3, 2021). The number of ordinary-course (i.e., non-beta) commercial U.S. subscribers

incorporates more terminals than most analysts predict SpaceX will prove able to sell in the United States[6] and, therefore, allows for the possibility that other NGSO FSS licensees may one day succeed in the marketplace.

Once the terrestrial and satellite networks are modeled, RKF simulates 2,500,000 Starlink terminals in groups of 2,500 terminals over 1,000 iterations. Each iteration drops 1,499,910 macro-cell simultaneously active UEs and 449,850 small-cell simultaneously active UEs within the coverage area of macro-cell and outdoor small cell 12 GHz base stations. The model also simulates beamforming of 5G macro-cells to the UEs and accounts for the assumed omnidirectional nature of 5G small-cell base stations. To account for the four-to-one downlink ratio of a prototypical time-division duplex (TDD) system, the model further assumes that in 80% of the iterations, Starlink terminals receive interference from the base stations (macro-cells and small-cells) and in 20% of the iterations, they receive interference from the UEs, with the 12 GHz point-to-point links being active in all iterations. RKF then calculates the interference-to-noise ratio (I/N) at each Starlink terminal from active 12 GHz transmitters within 50 kilometers of the Starlink terminal, including macro-cell base stations, small-cell base stations, point-to-point links, and UEs.

After analyzing the results, RKF concludes that the potential for emissions in excess of a nominal interference value of -8.5 dB will occur in only about 0.888% of Starlink terminals deployed. This 0.888% result is statistically valid for any large number of satellite user terminals. Stated differently, although the absolute number of terminals that may be affected by interference will change if the actual number of terminals were higher or lower than the 2,500,000 RKF examines, the percentage will not. Few, if any, of the 0.888% of nominally affected Starlink terminals will experience service interruption, or even service degradation, in actual practice for several reasons. *First*, the study uses a variety of conservative assumptions that tend to overstate the likelihood of exceeding nominal interference thresholds for the satellite terminals. *Second*, the model does not implement any of the case-by-case site coordination or mitigation measures that operators routinely employ to mitigate the potential for interference in the ordinary course of business (and that – if needed – are particularly easy to implement before systems are widely deployed). *Third*, the Starlink terminals have access to 1,500 megahertz of spectrum that is not co-frequency with the 5G infrastructure and UE envisioned for deployment in the 12 GHz band; these additional frequencies provide an operational safe harbor for Starlink users in the unlikely

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to Starlink's service is zero. SpaceX may never achieve a subscriber base of 2,500,000, but this conservative figure provides a generous upper limit for NGSO FSS service uptake.

[6] *See* note 28 and accompanying discussion.

event that a nominal interference event were to occur.[7] RKF's findings are clear: licensed 5G services can successfully coexist with authorized NGSO FSS operations in the 12 GHz band.

1.1. Approach

This study employs a probabilistic (Monte Carlo) analysis to identify and quantify the interference risk among co-primary services in the 12 GHz band.[8] The analysis is intended to offer a transparent, reproducible means of evaluating the potential for sharing between currently authorized hypothetical NGSO FSS operations and future terrestrial 5G operations.[9]

In identifying where to position the terrestrial and satellite infrastructure, broadly accepted market and service definitions, revenue models, and cost models were analyzed to develop algorithms that would replicate or anticipate real-world site locations for each service. In the model, macro-cell base stations are placed in commercially relevant locations, and the cell footprint of the 12 GHz base stations is not contiguous. Base station transmitters using high capacity 12 GHz spectrum would most likely be deployed as part of a multi-band spectrum strategy and, combined with other bands, would ensure a reliable, seamless user experience. Similarly, satellite user terminals are weighted toward areas where SpaceX has committed to offering service under the Rural Digital Opportunity Fund (RDOF) program as well as those areas where the fixed-satellite service value and service proposition relative to existing fixed and mobile broadband infrastructure is likely to result in the highest degree of market penetration.[10]

For both the terrestrial and satellite services, no areas are excluded from service. That is, 5G macro-cell base stations, small-cells, and point-to-point backhaul links appear in "rural" areas, and satellite user terminals appear in "urban" areas (as defined in Section 1.2 below). The model employs weightings rather than rigidly deterministic criteria to offer realistic scenarios for real-world conditions of each system's infrastructure. The exact infrastructure-placement algorithms for Starlink terminals and 5G infrastructure are described in Sections 2.1 and 2.2, respectively.

The analysis generates a network of terrestrial base stations across CONUS by placing them randomly in the most densely populated areas comprising at least 10% of the population of each Partial Economic Area (PEA), *approximating* the siting of a terrestrial 12 GHz network operator's

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[7] In addition, SpaceX also possesses a total of 13,550 MHz in other spectrum, of which two GHz (40-42 GHz) is available for user terminal downlinks.

[8] A Monte Carlo simulation uses random sampling and statistical modeling to estimate mathematical functions and mimic the operations of complex systems. *See*, *e.g.*, Harrison RL., *Introduction To Monte Carlo Simulation*, AIP Conf Proc. 2010;1204:17–21. doi:10.1063/1.3295638.

[9] *See* note 4.

[10] SpaceX was the largest winning bidder in the RDOF auction that uses the 12 GHz band.

macro-cell base stations. This model results in a 12 GHz deployment area that includes smaller cities and towns as well as the largest and most populous cities in CONUS.[11]

The model then adds 12 GHz small-cell infrastructure in areas of high traffic density. The study adds mobile UEs in the service area of the macro-cell base stations and small-cells. Finally, the study adds wireless point-to-point links for backhaul to macro- or small-cells based on known requirements for wireless backhaul in the United States. Each of these types of infrastructure equipment transmits in the 12 GHz band and are therefore potential sources of interference to satellite terminals.

The analysis next models SpaceX's NGSO FSS system to assess coexistence potential with terrestrial 5G operations. SpaceX's current license in support of its "Starlink" satellite system authorizes 4,408 satellites in orbit with a primary operational altitude in the 540-570 kilometer range.[12] The Starlink constellation will operate globally in the Ku- and Ka-band, including the 12 GHz band segment assigned to terrestrial wireless operators in the United States.

The model assumes a generous deployment of fixed NGSO end-user terminals throughout CONUS that uses satellite downlink spectrum between 10.7-12.7 GHz to receive signals from the thousands of NGSO space stations in SpaceX's satellite system. Consistent with SpaceX's self-installation model, the analysis assumes earth station terminals are installed primarily near ground-level using the vendor-provided mounting tripod and occasionally on rooftop locations using additional mounting hardware and, more likely than not, professional installation.[13]

For both the terrestrial and satellite systems considered in this coexistence analysis, the model assumes performance characteristics consistent with standard reference design parameters and publicly available data. The simulation modeled a full national deployment of the 5G network as well as an extensive, nationwide deployment of Starlink terminals throughout CONUS to characterize all possible interference paths. By simulating a large number of random interference paths that produce statistically significant results, the study identifies the likelihood of worst-case interference that could arise under real-world conditions. The analysis confirms that the aggregate risk of harmful interference to NGSO satellite terminals is low.

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[11] Joint *Ex Parte* Presentation of Competitive Carriers Association *et al.*, GN Docket Nos. 12-268 and 13-185, at 2 (filed Mar. 11, 2014) (Joint CCA *Ex Parte*) ("PEAs will ensure that some licenses consist of large population centers while others consist of less populous areas.").

[12] *Space Exploration Holdings, LLC Request for Modification of the Authorization for the SpaceX NGSO Satellite System*, Order and Authorization, IBFS File No. SAT-MOD-20200417-00037, FCC 21-48 (rel. Apr. 27, 2021) ("*SpaceX Mod 3 Grant*").

[13] Rooftop installations require special mounting hardware and typically require professional installation to ensure the antenna's data and power cable are run from the roof through the exterior envelope of the building into customers' homes or businesses without introducing opportunities for water penetration or structural damage, and without violating local building codes.

1.2. Population Density and Morphology

For reasons of capacity, physics, and economics, terrestrial deployments are more likely to occur in "urban" areas, and satellite deployments are more likely to occur in "rural" areas. This is not to say that NGSO FSS satellite deployments will not occur in urban areas or that terrestrial deployments will not occur in rural areas. They will. And, to be clear, the model takes note of multiple possible paths to economic sustainability – as well as the variability of population density within nominally "rural" and "urban" areas – by allowing for satellite and terrestrial infrastructure to deploy at nearly any location suitable for deployment. At the same time, the model assumes a propensity for satellite terminals to support comparatively lower population densities, where fiber, hybrid-fiber, and terrestrial wireless service is less widely deployed, or at least less well established, and terrestrial terminals to support comparatively higher population densities, given the sizeable market penetration and substantial existing investments in terrestrial cellular infrastructure capable of supporting multiple bands of frequency operation. This is not a simple urban-rural dichotomy. The model uses a statistical sampling of many possible deployment scenarios to arrive at a composite view of the statistical likelihood of proximate deployments and, ultimately, the potential for interference under deployment conditions likely to be found in actual deployments.

1.2.1. Terrestrial Network Model Approach

RKF uses the 406 PEAs in CONUS[14] to define where the 5G network will be deployed. PEAs are well suited to mapping 5G deployment areas.[15] PEAs are the most commonly used market

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[14] There are 416 PEAs nationwide, but the model did not consider ten PEAs outside of CONUS, including PEAs in Alaska (PEAs 212, 264, 298 and 360), Hawaii (PEA 042), U.S. territories (PEAs 412, 413, 414 and 415) or the Gulf of Mexico (PEA 416).

[15] MVDDS authorizations were assigned in market areas (MVDs), which are based on Designated Market Areas (DMAs) demarcated by Nielsen Media Research in September 2002. *See, e.g.*, *Requests of Ten Licensees of 191 Licenses in the Multichannel Video and Data Distribution Service for Waiver of the Five-Year Deadline for Providing Substantial Service*, Order, 25 FCC Rcd 10097, n.4 (2010) ("Although Nielsen revises DMAs periodically, the MVDDS license areas remain fixed to the boundaries of the 2002 DMAs. To avoid confusion with Nielsen's current DMAs, MVDDS license areas are designated as "MVDs" in the Universal Licensing System."). PEA market areas were chosen, however, to more closely track the FCC's prevailing approach to wireless broadband licensing. PEAs were first proposed for use in terrestrial licensing by a coalition of rural operators as a compromise geography between the 176 nationwide Economic Areas ("EAs") the commission had proposed and the 734 Cellular Market Areas (CMAs) the rural operators had initially sought. *See* Joint CCA *Ex Parte*. The Commission had expressed concern that using CMAs would create too many "products" in the already-complex incentive auction, but the rural operators expressed concern that EAs would be too large and include too many costly urban areas for them to compete. PEAs were reached by dividing the EAs into urban and rural areas. This approach offered predominantly rural operators markets on which to bid with the added benefit of fitting within or "nesting" inside EAs. The Commission subsequently adopted PEAs as the market area for the incentive auction on June 2, 2014 and has used them in several auctions since then. *Expanding the Economic and Innovation Opportunities of Spectrum Through Incentive Auctions*, Report and Order, 29 FCC Rcd 6567 ¶ 18 (2014); *Expanding Flexible Use of the 3.7 to 4.2 GHz Band*, Report and Order and Order of Proposed Modification, 35 FCC Rcd 2343 ¶ 79 (2020); *Facilitating Shared Use*

geography and the market geography that is most readily translated into geographic market areas of smaller and larger sizes that are used in mobile wireless licensing; therefore, RKF used PEAs as its base unit of analysis in determining areas of 12 GHz coverage.

As terrestrial mobile networks have matured, operators have pursued higher frequency spectrum to satisfy increasing capacity requirements. Higher frequency bands can carry more traffic than lower frequencies because more bandwidth is typically available than at lower frequencies; however, higher frequencies cover comparatively shorter distances than lower frequencies, other things being equal, due to path loss, rain fade, and related propagation limitations. The 12 GHz band has a large available bandwidth of 500 megahertz and is especially well-suited to providing high capacity service in areas of high population density. Therefore, the 5G deployment is weighted to the high population density areas within PEAs.

For purposes of the 5G network model, RKF identifies different intensities of terrestrial infrastructure and user equipment deployment based on whether an area's classification is urban, suburban, or rural. RKF defines urban, suburban, and rural based on the population density thresholds of more than 7,500, between 7,500 and 600, and fewer than 600 people per square mile, respectively. These classifications determine a number of characteristics of the 5G network model, including where base stations are placed; how close together the base stations are located; how close to the base stations' user equipment (UE) is located; the propagation modeling; the heights of buildings in which the UEs are located; and so forth. These classifications are summarized in Table 1-1, and a nationwide map is shown in Figure 1-1 below.

Table 1-1: Population Density Thresholds Used in the 5G Network Model

	Population Density Thresholds (population/mile^2)
Urban	> 7500
Suburban	Between 600 and 7500
Rural	< 600

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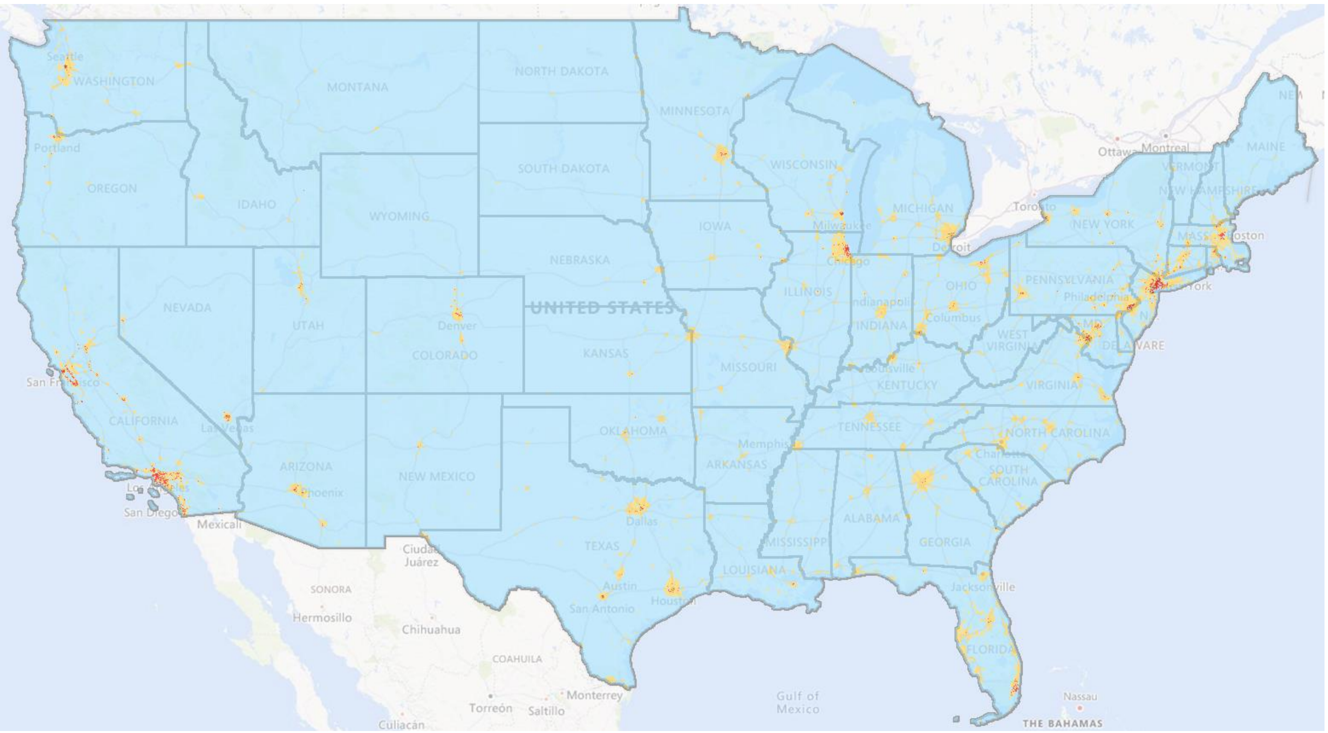
in the 3100-3550 MHz Band, Second Report and Order, Order on Reconsideration, and Order of Proposed Modification, WT Docket No. 19-348, FCC 21-32 ¶ 111 (rel. Mar. 18, 2021).

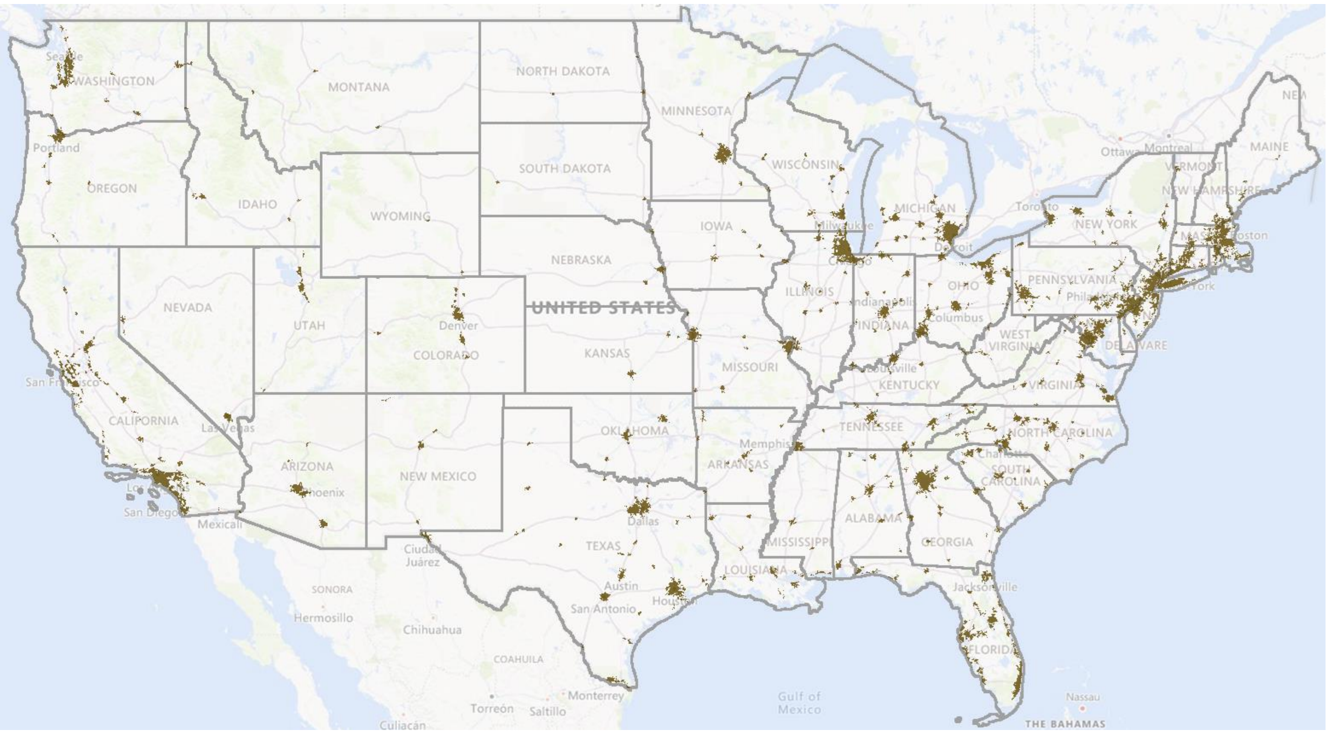
Figure 1-1: Nationwide Map of Urban (red), Suburban (yellow), and Rural (blue) Areas per Table 1-1



1.2.2. Satellite User Terminal Model Approach

For purposes of the satellite network model, RKF identifies different intensities of satellite terminal deployment based on the area's geographic classification.[16] RKF defines metropolitan areas using the Census Bureau's definition of "urban area" in which any area that is not classified as "urban" is considered to be "non-urban." The Census Bureau's definition of "urban area" is not a measure of population density or morphology or land use, which are often relevant considerations in situating a 5G terrestrial network deployment. Instead, the Census Bureau's definition of "urban area," or "metropolitan area" in our parlance, is a useful tool to identify the nation's major cities and their surrounding suburbs, which, generally speaking, are already well served by terrestrial broadband solutions and are likely to exhibit the lowest levels of market penetration by the Starlink system and other NGSO FSS broadband deployments. A map showing the Census Bureau's "urban" or metropolitan areas is shown in Figure 1-2:

Figure 1-2: Nationwide Map of Census Bureau's "Urban" (or "Metropolitan") Areas



RKF uses the Census Bureau's definition of "urban" areas to weight satellite terminals to "rural" areas. Modeling a rural-deployment weighting for Ku-band satellite user terminal sites is well supported by the operational characteristics of satellite systems. Even a low-earth orbit satellite system will produce cells on the ground that are many times as large as those produced by terrestrial base stations. The large satellite cells reduce frequency reuse and constrain capacity

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[16] *See* Table 1-1.

and performance in densely populated areas.[17] While an NGSO FSS licensee can deploy terminals in metropolitan areas, such as New York City or Los Angeles, satellite capacity constraints limit the total number of terminals NGSO FSS licensees can support in any one of these densely populated zones. In this case, an even more urbanized configuration of Starlink terminals would likely reach capacity limits before a change in the statistically significant 0.888% result would occur. Indeed, RKF's methodology currently assumes such a dense deployment of satellite terminals in metropolitan centers where RDOF funds were assigned, such as Chicago, San Francisco, and Baltimore, that deployments there may already exceed the capacity of SpaceX's satellite system to support them while still offering a competitive level of service. An examination of the capacity of SpaceX's satellite system is beyond the scope of this study. But as SpaceX's chief executive officer, Elon Musk, has explained, "The challenge for anything that is space-based is that the size of the cell is gigantic … it's not good for high-density situations. We'll have some small number of customers in LA. But we can't do a lot of customers in LA because the bandwidth per cell is simply not high enough."[18]

RKF also relies on the results of the RDOF auction to identify areas especially well-suited to satellite deployment.[19] As part of the RDOF initiative, the FCC identified areas unserved by broadband with a minimum download rate of at least 25 megabits per second (Mbps) and an upload rate of 3 Mbps. Eligibility was based on census block-level data, and certain areas were excluded to avoid duplicative support.[20] For example, areas that received funding from the U.S. Department of Agriculture's ReConnect program or similar federal or state broadband subsidy programs to provide 25/3 Mbps or better service were not eligible under RDOF.[21] The FCC held a reverse auction to determine which operators would receive support. SpaceX, one of the

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[17] Other factors constrain satellite capacity as well.

[18] Jon Brodkin, *Elon Musk: Starlink latency will be good enough for competitive gaming*, ARS TECHNICA (Mar. 10, 2020 2:28 PM), https://bit.ly/3dUrbbu; *see also* Sascha Segan, *Who Needs Starlink Internet? These Rural US Counties Top the List*, PC MAGAZINE (Mar. 31, 2021), https://bit.ly/3a5z9gW; *see also* Anshu Goel, *Intelligence Brief: Is direct-to-consumer satellite broadband now viable?*, Mobile World Live (Mar. 10, 2021), https://bit.ly/3dVmTke ("Given the current prices for satellite broadband, it looks likely consumer uptake will probably be highest amongst rural households in developed countries.")

[19] While some RDOF support went to metropolitan areas, most went to non-metropolitan areas; weighting the Starlink deployment toward non-metropolitan areas reflects SpaceX's commitment to satisfying its outstanding RDOF obligations as well as the practical limits of frequency reuse in congested metropolitan areas.

[20] Census blocks are "statistical areas bounded by visible features, such as streets, roads, streams, and railroad tracks, and by nonvisible boundaries, such as selected property lines and city, township, school district, and county limits and short line-of-sight extensions of streets and roads." For more information, *see* United States Census Bureau, 2010 Census Summary File 1 2010 Census of Population and Housing, Technical Documentation, September 2012, p. 614, https://bit.ly/3b3QbMS.

[21] The FCC also established a challenge process in which parties could identify areas that receive service that met the FCC's 25/3 Mbps or better standard despite an initial finding of no such service being available.

largest auction winners,[22] won funding to offer service to 643,000 locations across 35 states with a commitment to low-latency service at 100/20 Mbps. For these reasons, the satellite terminal deployment is weighted to RDOF areas, with the highest weighting to rural RDOF areas in which SpaceX secured funding in the auction. However, the model does not restrict satellite deployment to RDOF areas and also assumes deployment in areas outside of RDOF in lower population density areas of the United States.

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[22] *Rural Digital Opportunity Fund Phase I Auction (Auction 904) Closes, Winning Bidders Announced, FCC Form 683 Due January 29, 2021*, Public Notice, 35 FCC Rcd 13888 (2020).

1.2.3. Certain Limitations of the Model's Approach

Using heuristics for positioning terrestrial and satellite terminals tends to exaggerate the number of satellite terminals in proximity to terrestrial base stations, which raises the likelihood of interference events compared to what would occur if the study had used the same sorting process for both types of infrastructure. For example, many tracts with a density greater than 7,500 persons per square mile exist in areas that do not fit the Census Bureau's definition of "urban."[23] In the case of a smaller town with a pocket of dense population surrounded by rural areas, for example, the model would place 12 GHz terrestrial base stations in and around the small town at a comparatively high rate because that area would be deemed "urban" or "suburban." But the model would place satellite earth terminals in and around the small town at a comparatively high rate too because, for satellite purposes, the area would typically be deemed "non-urban" or non-metropolitan. Because it is difficult to see this effect at the national level, Figure 1-3 shows a zoomed view of Pennsylvania as an example of the difference between the two methods. The map reveals several tracts that have a density greater than 7,500 persons per square mile that are not classified by the Census Bureau as "urban," identified for clarity with arrows.

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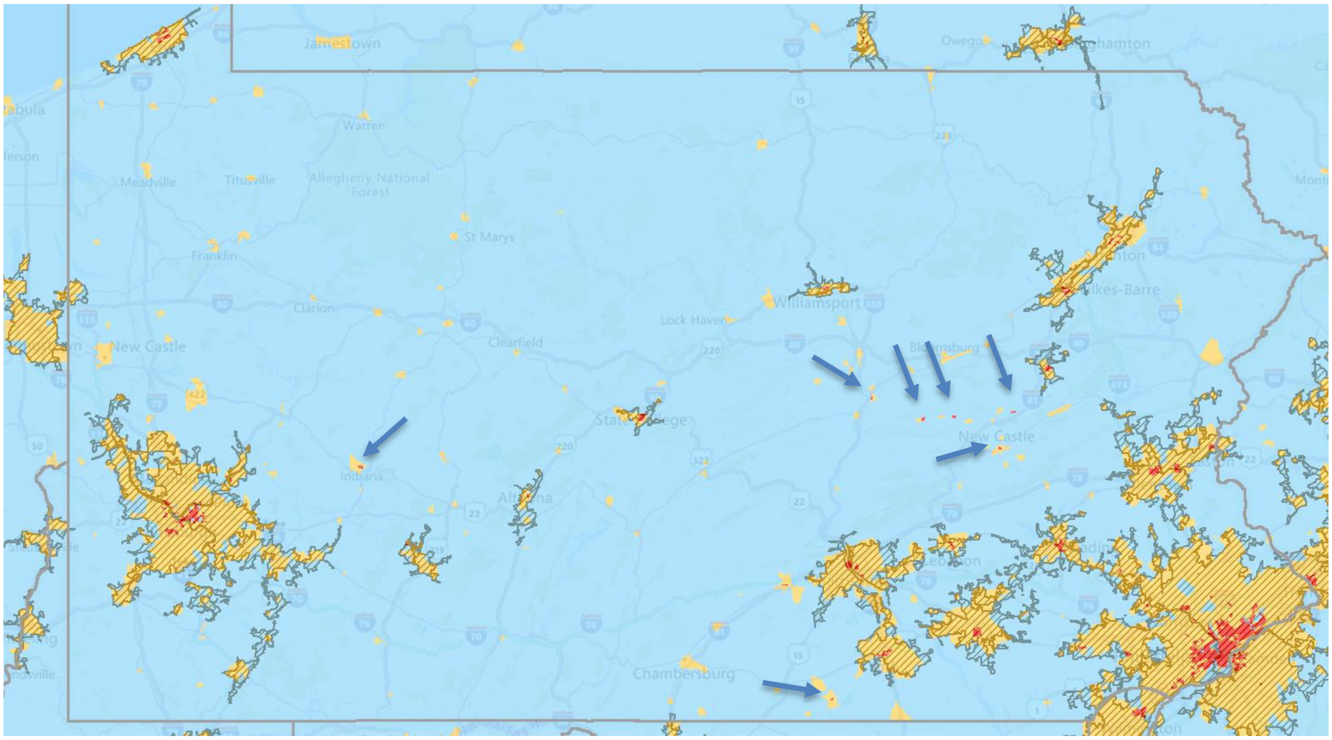
[23] In analyzing tracts, RKF used the latest decennial census, which is currently 2010. Tracts are defined by the Census Bureau and are part of their hierarchy of geographies which includes more well-known geographies such as counties and states. Unlike counties and states, tract boundaries and IDs are subject to change with each decennial census. *See* https://bit.ly/33gw6i5.

Figure 1-3: Example of the Difference Between the Census Bureau's "Urban" Areas (brown hash and outline) and Areas of Population Density in Table 1-1



While the model strives for realistic deployment scenarios in all cases, the exaggerated presence of satellite terminals in suburban and urban areas in the RKF model amounts to a conservative assumption and yet still results in a very low rate of potential interference events.

Section 2 discusses, in detail, the deployment strategy used in the simulation for Starlink terminals (Section 2.1) and for the 12 GHz 5G network (Section 2.2).

2. Deployment and Operational Assumptions

This section describes the simulation assumptions. Starlink deployment and terminal assumptions are described in Section 2.1, and the 5G base stations, backhaul, and UE assumptions are described in Section 2.2.

This study assumes 49,997 5G macro base stations are deployed throughout CONUS. These are distributed in the most populated areas, including at least 10% of population density areas in each PEA. An outdoor small-cell deployment is also modeled. The number of small-cells is assumed to be double the number of urban macro-cells. Cellular backhaul is provided by fiber or point-to-point microwave links. As shown in Section 2.2.4, less than 5% of the cell sites would use microwave backhaul. Therefore, in the simulations, 5% of rural macro-cells, 5% of the remaining macro-cells, and 5% of small-cells are assumed to require microwave backhaul. In the simulation, 5G cells that require microwave backhaul are connected to the nearest base station that has fiber. Once the 5G network deployment is selected for the base stations and backhaul, it is fixed for the rest of the simulation.

The proposed 5G base station/UE operation is TDD. Therefore, Starlink terminals receive interference from both base station and mobile terminal UE. Base station transmissions are assumed to be synchronized so that the interference into Starlink terminals is either from base stations or from UEs, but not both at the same time. The proposed 5G backhaul operation is frequency-division duplex (FDD) and, as such, transmits continuously.

In the simulation, 2,500,000 Starlink terminals are distributed throughout the model or "dropped" into it. More than 1.6 million terminals are dropped in RDOF blocks won by SpaceX and other bidders, and the remaining are dropped in rural areas (as defined in Table 1-1) outside of RDOF blocks. The SpaceX network was simulated to produce distributions of Starlink pointing directions that are a function of terminal latitude.

The UEs are dropped randomly within each terrestrial base station coverage area. The macro-cell base station beamforms a narrow beam toward each UE. The Starlink terminal selects a random pointing direction from the distribution of simulated pointing directions. Then the aggregate interference from all simultaneously active macro base station beams and small-cells on the downlink or all active UEs on the uplink, as well as the point-to-point backhaul uplink and downlink transmissions to each of the Starlink terminal receivers within 50 kilometers is computed. The objective of the simulation is to model a large number of statistically significant interference paths to evaluate the risk of interference to the Starlink terminals.

The interference power, I, from each 5G transmitter is computed per Equation 2-1 below:

Equation 2-1

$$I = Tx\ Power + G_{5G\text{-}to\text{-}Rx} - L_{PathLoss} - L_{BodyLoss} + L_{BuildingLoss} + L_{SpectralOverlap} + G_{Rx\text{-}to\text{-}5G}$$

where,

- I (dBW) = Interference power from the 5G transmitter (Tx) at the Starlink terminal
- $Tx\ Power$ (dBW) = 5G Tx Power at the antenna input within the 5G Tx channel bandwidth
- $G_{5G\text{-}to\text{-}Rx}$ (dBi) = Gain of the 5G Tx antenna towards the Starlink receiver (Rx) based on the azimuth and elevation angles relative to the boresight direction
- $L_{PathLoss}$ (dB) = Propagation path loss including clutter loss at the 5G transmitter and/or Starlink terminal per Section 3
- $L_{BodyLoss}$ (dB) = User equipment body loss (=4 dB)
- $L_{BuildingLoss}$ (dB) = Building Penetration Loss applied to indoor UEs (ITU-R Rec. P.2109 as described in Section 3)
- $L_{SpectralOverlap}$ (dB) = 10*log10(spectrum overlap between the 5G Tx channel and the Starlink receiver occupied channel / 5G Tx channel bandwidth)
- $G_{Rx\text{-}to\text{-}5G}$ (dBi) = Gain of the Starlink Rx antenna towards the 5G Tx based on the angle off boresight

The I/N is the ratio of the interference power and the receiver noise power. The receiver noise power for each Starlink terminal is calculated using Equation 2-2 below:

Equation 2-2

$$N = 10*\log10(k\ T\ B)$$

where,

- N (dBW) = Starlink terminal noise power at receiver input
- k ($m^2\ kg\ s^{-2}\ K^{-1}$) = Boltzmann's constant (= $1.38064852 \times 10^{-23}\ m^2\ kg\ s^{-2}\ K^{-1}$)
- T (K) = Starlink Terminal System Noise Temperature (= 200 K per Table 2-2)
- B (Hz) = Starlink Terminal Noise Bandwidth (= 240 MHz)

The aggregate interference is compared against an I/N of -8.5 dB, which is the interference criteria from ITU-R Rec. SF.1006-0 (04/1993).[24]

Figure 2-1 below shows the channel plan for the Starlink terminals and the 5G network. The Starlink terminals have eight 240 MHz channels to choose from, but only the two channels

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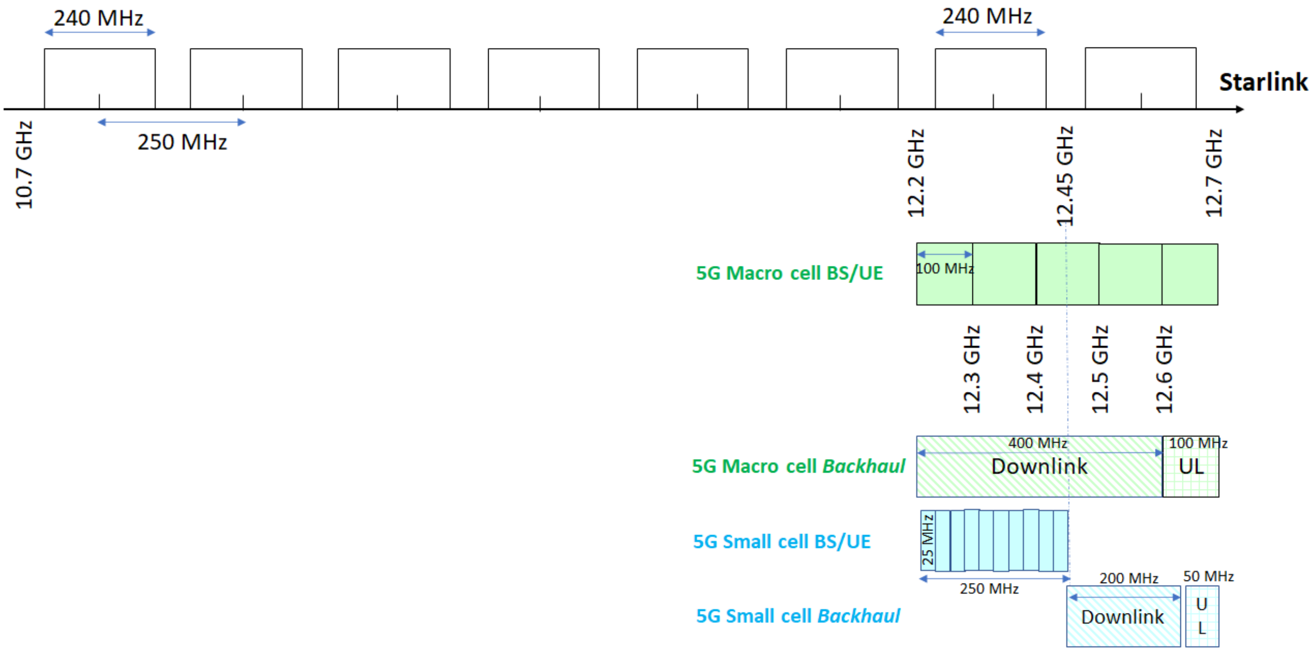
[24] ITU-R Rec. *SF.1006*, *Determination of the Interference Potential Between Earth Stations of the Fixed-Satellite Service and Stations in the Fixed Service*, International Telecommunication Union, Table 1 (Jan. 13, 2017), https://bit.ly/3eYqhew.

between 12.2 to 12.7 GHz can receive interference from the 5G network.[25] The simulation assigns channels randomly to Starlink terminals. The macro-cell base stations are assumed to operate with 100-MHz channels. Since the base stations generate narrow beams to each user, the simulation assumes four simultaneous active users per 100-MHz channel and that each user has access to 100 MHz of spectrum. There is an assumed four-to-one downlink-to-uplink ratio for the TDD transmission times. Beamforming is not used on small-cells, so for small-cells the four UEs are assumed to split the channel, each being allocated 25 MHz. The backhaul links are designed to achieve higher throughput efficiency than the mobile links so they can backhaul the full-cell capacity with less spectrum. The backhaul links operate in FDD mode so they have separate uplink and downlink spectrum. For small cells, the backhaul links are assumed to use a separate 250 MHz channel from the small cell mobile links. Since the small cell base stations do not have the ability to beamform, channel separation was used to avoid interference between backhaul and small cells. The backhaul links are assumed to be able to use the spectrum simultaneously with the macro-cell base stations and UEs, which is a conservative assumption, as some reduction in base station spectrum or beam allocation might be needed to accommodate the backhaul in practice.

Figure 2-1: Starlink Terminal and 12 GHz Base Station, UE, and Backhaul Channel Plan



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[25] Space Exploration Holdings, LLC, Request for Modification of the Authorization for the SpaceX NGSO Satellite System, IBFS File No. SAT-MOD-20200417-00037, Schedule S (filed Apr. 17, 2020) ("SpaceX Mod 3 Application")

2.1. Starlink Terminal Deployment

2.1.1. Number of Active Starlink Terminals and Deployment Distribution

The model assumes 2,500,000 Starlink terminals are deployed throughout CONUS. This figure exceeds SpaceX's currently authorized terminal number as well as industry analyst estimates. The number of terminals used in the study is, therefore, another in a series of conservative assumptions biased against a finding of limited harmful interference.

On March 13, 2020, the FCC authorized SpaceX to deploy up to 1,000,000 Starlink UTA-201 terminals.[26] SpaceX subsequently filed an application for 5,000,000 terminals, which has not yet been granted.[27] The research firm MoffettNathanson recently estimated SpaceX's total U.S. market penetration to be unlikely to exceed 300,000 to 800,000 end users, assuming SpaceX fully deploys its presently authorized constellation of more than 12,000 space stations across several spectrum bands.[28]

For purposes of this engineering study, RKF generously assumes that 2,500,000 Starlink user terminals might be in operation in the United States. As noted earlier, SpaceX's U.S. commercial service is currently limited to beta testing by a small number of users.[29] SpaceX may never achieve a subscriber base of 2,500,000. This number of terminals would represent 3 to 8 times the number of U.S. subscribers SpaceX is projected to acquire over the long term by independent industry analysts.[30] RKF's assumption of 2,500,000 eventual U.S. Starlink terminals is also 2.5 times the 1,000,000 terminals the FCC has currently authorized.[31] As a result, the study assumes SpaceX will receive authority to deploy many more terminals than its current authorization allows and the company will prove highly successful in attracting and retaining customers.

As described below, these 2,500,000 Starlink terminals for hypothetical future SpaceX satellite broadband customers are dropped over CONUS using rules to represent a realistic deployment of terminals. More important than the exact number of Starlink terminals deployed is the statistical significance achieved by the simulation over the entirety of morphologies and interference paths represented. With 2,500,000 Starlink terminals along with the large numbers of 5G macro-cells,

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[26] *See* Application of SpaceX Services, Inc., Call Sign E190066, SES-LIC-20190211-00151 (granted Mar. 13, 2020).

[27] *See* Application of SpaceX Services, Inc., SES-MOD-20200731-00807 (filed July 31, 2020).

[28] Craig Moffett *et al.*, *Is Starlink a Substitute for, or a Supplement to, Wired Broadband?*, MoffettNathanson, at 25 (Apr. 5, 2021); *see also* Jeff Baumgartner, *Starlink's threat to wired broadband 'minimal' – analyst*, LIGHT READING (Apr. 5, 2021) https://bit.ly/3wM6abE.

[29] *See* note 5.

[30] *See id.* and accompanying discussion.

[31] *See* IBFS File No. SES-LIC-20190211-00151 (granted Mar. 13, 2020) (call sign E190066).

small-cells, and UEs, the simulation provides confidence in the estimates for interference exceeded with a probability of at least 10^{-5}.[32]

The deployment distribution of the 2,500,000 is informed by SpaceX's obligations following the Rural Digital Opportunity Fund (RDOF) Phase I Auction (Auction 904).[33] The RDOF areas in which SpaceX won support include approximately 643,000 locations (defined as residences and small businesses) in census blocks that were identified as being unserved by the FCC's current definition of broadband of 25/3 Mbps.[34] Since these areas do not currently offer high quality broadband, the study assumes that these areas will account for roughly two-thirds of SpaceX's terminal deployments.[35] SpaceX will face little competitive pressure in these unserved areas; therefore, it is reasonable to assume that SpaceX's market penetration will be especially high in these areas because consumers may have few, if any, other choices for broadband service.[36] As shown in Table 2-1, for purposes of this analysis, the study assumes that SpaceX would have a penetration rate of 60% in non-metropolitan RDOF areas (or 327,511 terminals) in which they won funding.[37] Likewise, the study assumes a 30% penetration rate in non-metropolitan RDOF areas (or 1.3 million Starlink terminals) where another auction participant won funding. Some RDOF areas are in metropolitan areas in the U.S. where competition for services is likely to be more intense and where terrestrial broadband solutions are more likely.[38] For those metropolitan RDOF areas that SpaceX won, the study assumes a penetration rate of 15%, which amounts to an assumed 14,600 total Starlink terminals. These assumptions, along with metropolitan RDOF areas that SpaceX did not win, resulted in an assumed 1.65 million Starlink terminal deployments. These terminals were placed in random locations within the respective areas. The remainder of the Starlink terminals, approximately 850,000, were deployed over the rural areas[39] outside of the RDOF regions in CONUS using the GPW population density database described in Section 2.2, in proportion to the population density. In other words, the model's siting methodology for Starlink terminals in non-RDOF regions is more likely to place terminals

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[32] With interference to 2,500,000 Starlink terminals, a probability of 10^{-5} represents 25 I/N exceedance events which is statistically significant.

[33] *Rural Digital Opportunity Fund Phase I Auction (Auction 904) Closes Winning Bidders Announced*, Public Notice, 35 FCC Rcd 13888 (2020).

[34] For purposes of Auction 904, the FCC defined 25/3 Mbps as the minimum throughput for broadband connectivity. *Id.* ¶ 9.

[35] The assumption is that SpaceX will be twice as likely to sell Starlink terminals in RDOF areas than outside of RDOF areas. This results in two thirds of terminals in RDOF areas and one third outside RDOF areas.

[36] *See* note 40 and accompanying text

[37] RDOF blocks in Hawaii were not considered in this analysis.

[38] To determine metropolitan versus non-metropolitan RDOF areas, we used the Census Bureau 2010 definition of urban areas. *See 2010 Census Urban and Rural Classification and Urban Area Criteria*, United States Census Bureau (Dec. 2, 2019), https://bit.ly/3xIS4sd.

[39] As defined in Table 1-1 (i.e., the population density in the 30-arc-sec grid is less than 600 PoPs per square mile).

in *more populous rural areas*, which is similar to how the model sites 12 GHz terrestrial base stations. As a result, the model very likely overestimates the risk of harmful interference in non-RDOF regions because Starlink's "Better than Nothing"[40] service is most competitive in regions where broadband service is less robust and/or very expensive, which are very often *less populous rural areas*.[41]

For all drops, Starlink terminals were allowed to be within 5 meters of a 5G base station.

Figure 2-2 shows RDOF blocks won by SpaceX. Since the metropolitan RDOF blocks are not visible in the nationwide view, Figure 2-2 (bottom figure) shows a zoomed view of Chicago indicating these regions.[42]

As seen in Figure 2-2 and detailed in Table 2-1, the RDOF blocks won by SpaceX include areas in population centers and areas around population centers. 342,132 Starlink terminals were dropped throughout CONUS in these RDOF blocks. Nearly four times as many Starlink terminals were dropped throughout CONUS in the RDOF blocks that SpaceX did not win as those it did. Another 845,174 Starlink terminals were dropped over CONUS in rural areas outside RDOF blocks.

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[40] Rachel Jewett, *SpaceX Launches Public 'Better Than Nothing Beta' for Starlink With $99/Month Service*, VIA SATELLITE (Oct. 28, 2020), https://bit.ly/2PPNiIf.

[41] *See generally* discussion at Section 1.2.3.

[42] The dark red and dark green are small and not clearly visible in the nationwide map. The zoomed-in map (bottom figure) shows this granularity more clearly.

Figure 2-2: RDOF Blocks Nationwide (top figure) and Zoomed View of Chicago, IL (bottom figure) (red=SpaceX Non-Metropolitan, green=other bidders Non-Metropolitan, dark red=Space-X Metropolitan, dark green=other bidders Metropolitan)

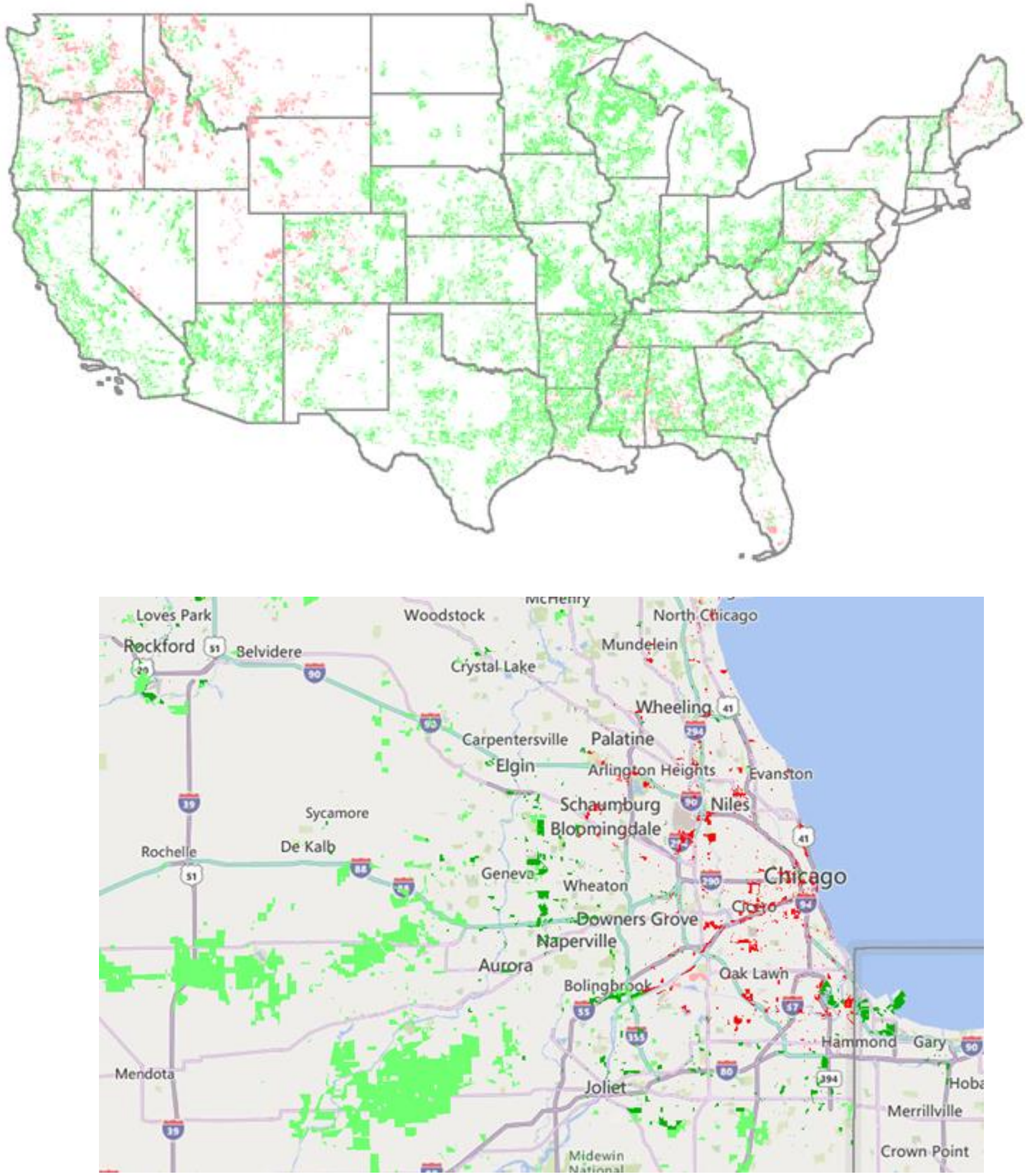


Figure 2-3 and Figure 2-4 illustrate the RKF model's generous distribution of Starlink antennas throughout CONUS and in the Chicago, IL and Milwaukee, WI region.

Figure 2-3: Distribution of Starlink Terminals Throughout CONUS

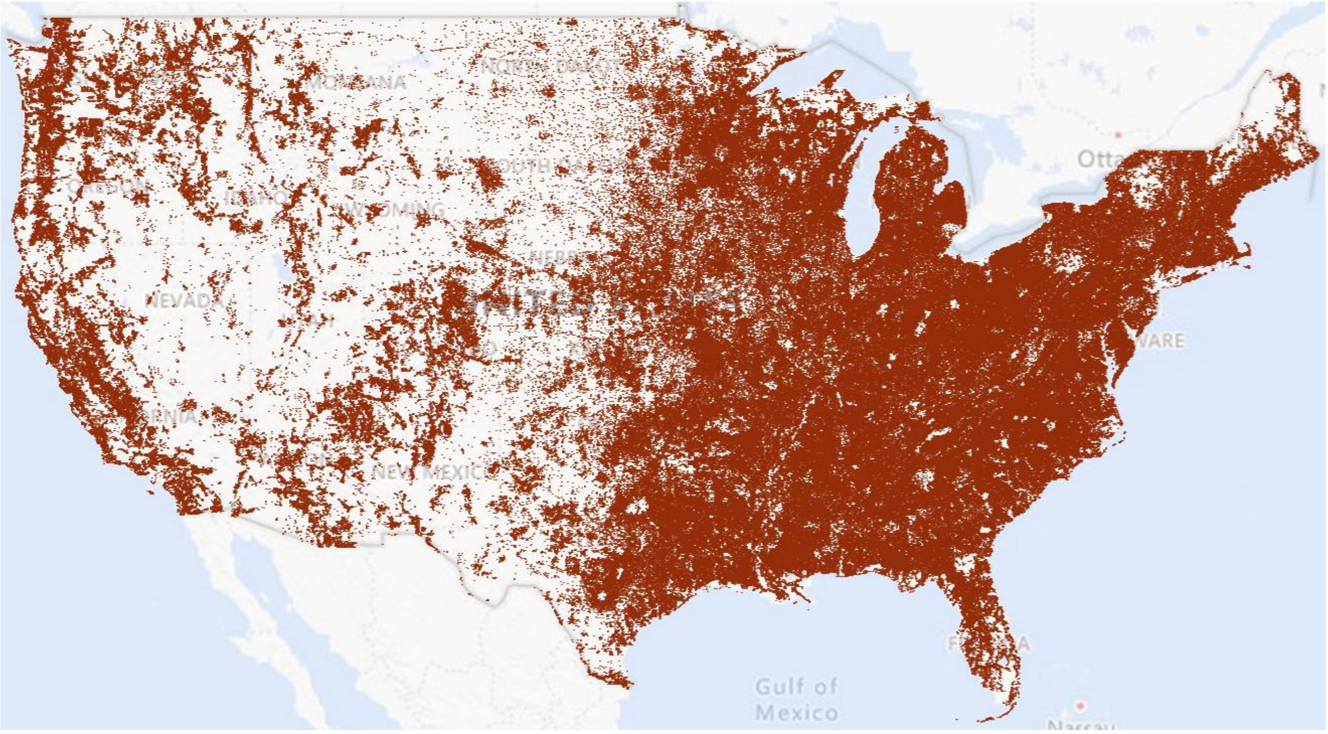
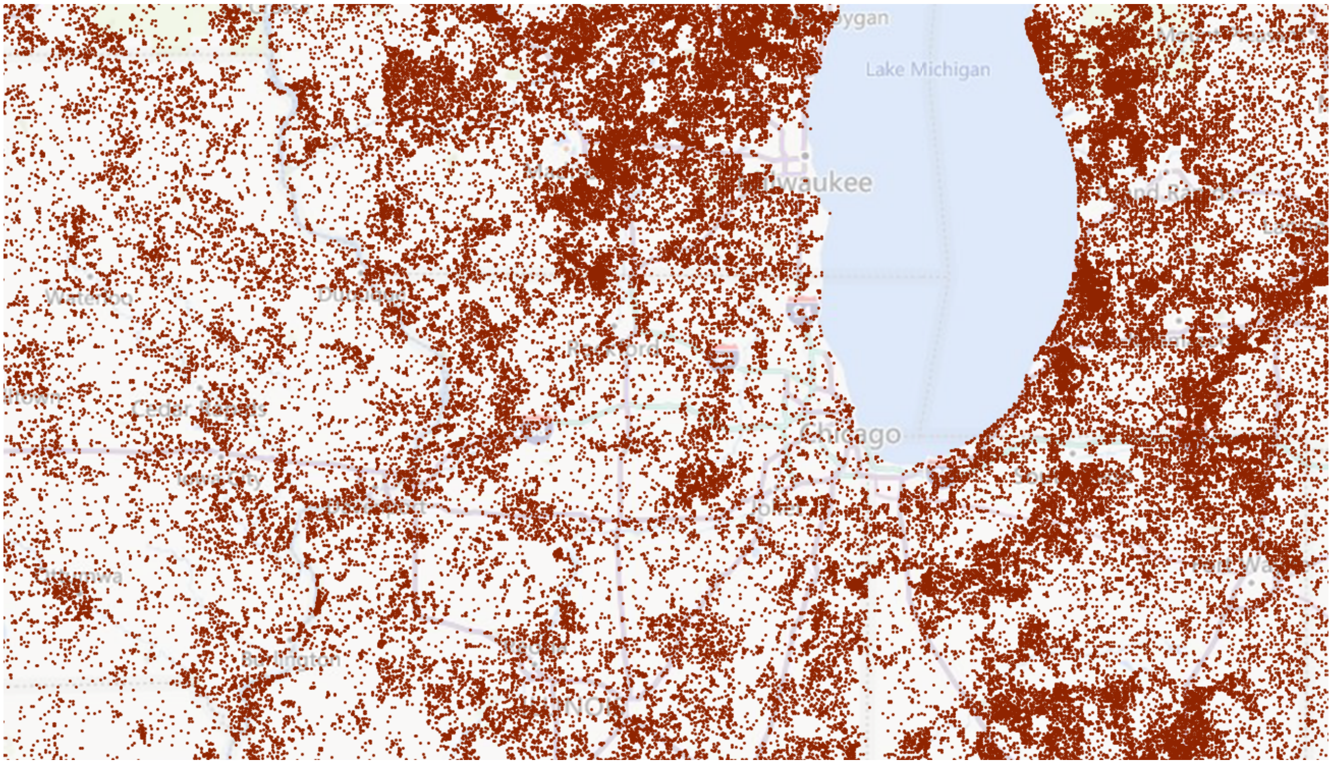


Figure 2-4: Distribution of Starlink Terminals in the Chicago, IL and Milwaukee, WI Region



The satellite terminal deployment assumptions are summarized in Table 2-1 and are designed to (1) be consistent with SpaceX's RDOF obligations, (2) reflect the consumer markets most likely to be served by mass-market NGSO FSS broadband services, and (3) provide a generous number of hypothetical customers (2,500,000). The result of the model is an extensive deployment of Starlink terminals throughout CONUS that include metropolitan areas inside the RDOF blocks as well as rural drops (those with < 600 people per square mile) outside of the RDOF blocks.

Table 2-1: Derivation of Number of Starlink Terminals over CONUS

Case	Percentage of Locations Served	Total Locations in RDOF	Total Assumed Starlink Terminals
SpaceX RDOF Wins: Non-Metropolitan	60%	545,851	327,511
SpaceX RDOF Wins: Metropolitan	15%	97,474	14,621
Other Bidder RDOF Wins: Non-Metropolitan	30%	4,334,999	1,300,500
Other Bidder RDOF Wins: Metropolitan	5%	243,885	12,194
Total within RDOF funded areas			1,654,826
Total to spread in non-RDOF Rural areas in CONUS			845,174
Total within CONUS			2,500,000

2.1.2. Height Distribution

The Starlink terminal comes with a tripod that can be installed on rooftops or in yards, as shown in Figure 2-5.

Figure 2-5: Starlink Terminals on Tripods in Yards and House Rooftop[43]

The Starlink terminals were assigned heights in accordance with the following distribution:

- 80% of the terminals are assumed to be on the ground with an above ground level (AGL) height of 1.5 meters. The high percentage of ground-based installations comes from the assumption that most users will self-install and are therefore unlikely to put the terminal on their roof.
- 20% of the terminals are assumed to be on the house rooftop with an AGL height of 4.5 meters. This is chosen as the average of terminal heights between 3 to 6 meters (one to two stories).

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[43] These images were posted by users on the social media website Reddit.

2.1.3. Other Operating Assumptions

Table 2-2 shows the Starlink terminal receiver's remaining operating characteristics (channel plan, antenna pattern, and receiver noise) used in this study.

Table 2-2: Starlink Terminal Receiver Operating Characteristics

Parameter	Unit	Value
Channel Plan		Eight 240-MHz channels with 250-MHz spacing from 10.7 to 12.7 GHz (see Figure 2-1)
Antenna Diameter	m	0.48
Antenna Pattern		ITU-R Rec. S.1428-1[44] *recommends* 1
Antenna Peak Gain	dBi	33.7 (per S.1428 for 0.48 m dish at 12.45 GHz)
Noise Bandwidth	MHz	240 (occupied Bandwidth)
System Noise Temperature	K	200[45]

The Starlink system uses a total of 2 GHz of Ku-band user downlink spectrum consisting of eight 240 MHz channels with 250 MHz spacing.[46] Only two of the channels overlap the 12 GHz band from 12.2 to 12.7 GHz. Therefore, in the unlikely event of interference from a 5G deployment, the Starlink terminal still has at least three-fourths of the channels available without interference.

As SpaceX has not shared the actual Starlink terminal antenna pattern, the standard ITU pattern for NGSO earth stations as described in S.1428 is used.

Figure 2-6 below shows the Starlink terminal S.1428-1 antenna pattern used.

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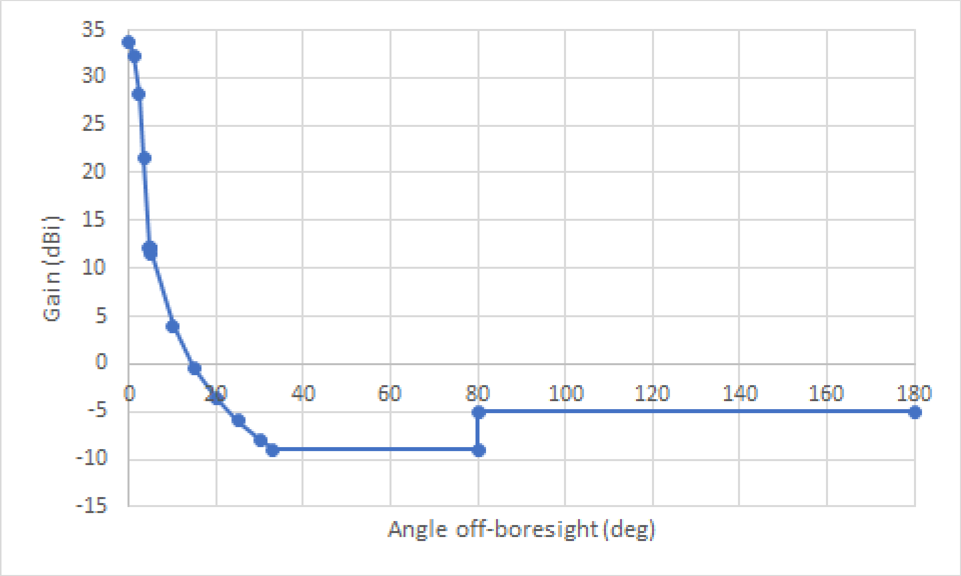
[44] *See* ITU-R S.1428-1, *Reference FSS earth-station radiation patterns for use in interference assessment involving non-GSO satellites in frequency bands between 10.7 GHz and 30 GHz*, International Telecommunication Union, https://bit.ly/3b3jhvH.

[45] *See* ETSI TR 103 399 V1.1.1, *System Reference Document: Fixed and in-motion E/S communicating with Satellites in NGSO in the 11 GHz to 14 GHz frequency band*," European Telecommunications Standards Institute (Apr. 2019), at Table 4, https://bit.ly/3vJl01a.

[46] SpaceX Mod 3 Application, Schedule S.

Figure 2-6: Starlink Terminal Antenna Pattern (ITU-R Rec. S.1428-1)



The Commission granted SpaceX's "Mod 3" application on April 27, 2021, with various conditions. As detailed in Table 2-3, the model simulates the Starlink constellation operating parameters under "Mod 3" as granted by the Commission.[47] Each Starlink terminal in the simulation selects a random pointing direction from a distribution of pointing directions. The distributions of pointing directions are generated using a separate simulation of the latest SpaceX redesign authorization consistent with Table 2-3.[48] In this simulation, the Starlink terminals point toward the satellite that is in view for the longest period of time. The simulations include an 18° exclusion angle to the GEO arc and a minimum Starlink terminal elevation angle of 25° to the satellite. As shown on the chart, most Starlink terminals will have look angles of between 55 and 85 degrees. To make the distributions more manageable in the interference simulations, the pointing distribution is divided into ten latitude regions, within which the distribution of pointing directions does not change considerably. Figure 2-7 shows the cumulative distributions, as a function of the Starlink terminal elevation angles. Each of the ten distributions is labeled with the center point of each latitude range. The actual distributions incorporated in the interference simulations are three dimensional and include both azimuth and elevation angle variations. The Starlink terminal chooses a random pointing direction using the distribution as described in Figure 2-7.

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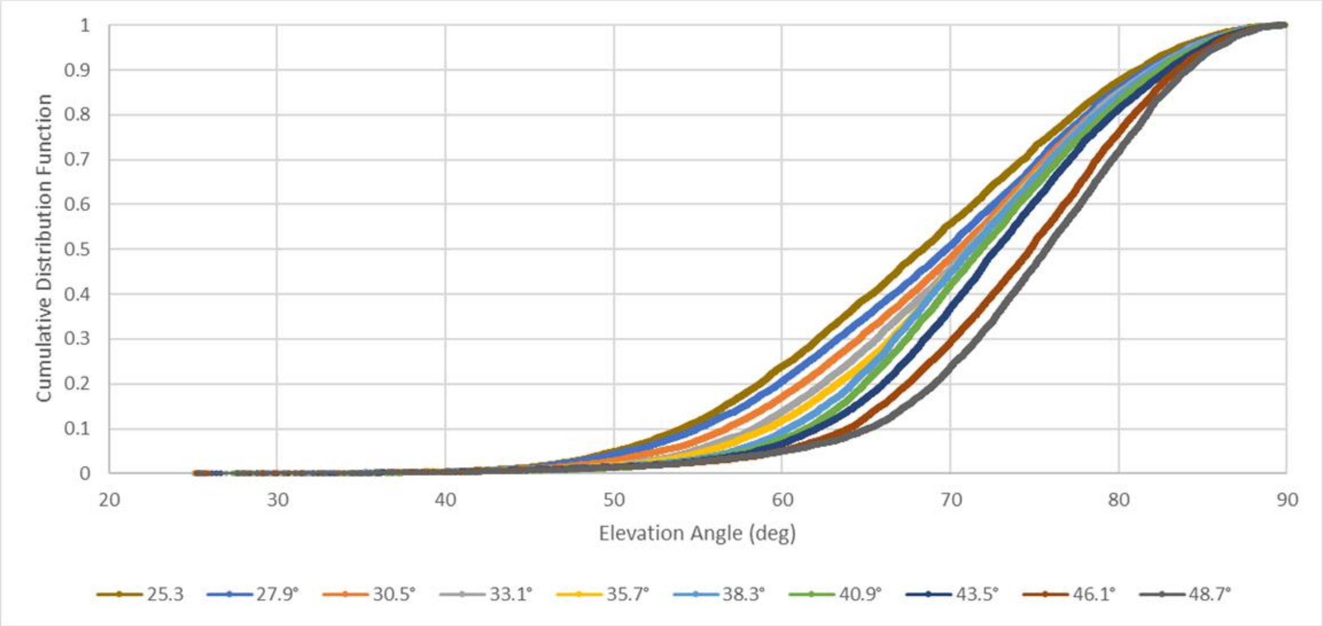
[47] *See* note 49.

[48] *See SpaceX Mod 3 Grant*.

Table 2-3: Simulated SpaceX Constellation Mod 3

SpaceX MOD 3 as Granted[49]					
Planes	72	72	36	6	4
Satellites Per Plane	22	22	20	58	43
Altitude (km)	550	540	570	560	560
Inclination	53°	53.2°	70°	97.6°	97.6°

Figure 2-7: Distribution of Starlink Terminal Elevation Angles at Ten Latitudes (as labeled) over CONUS



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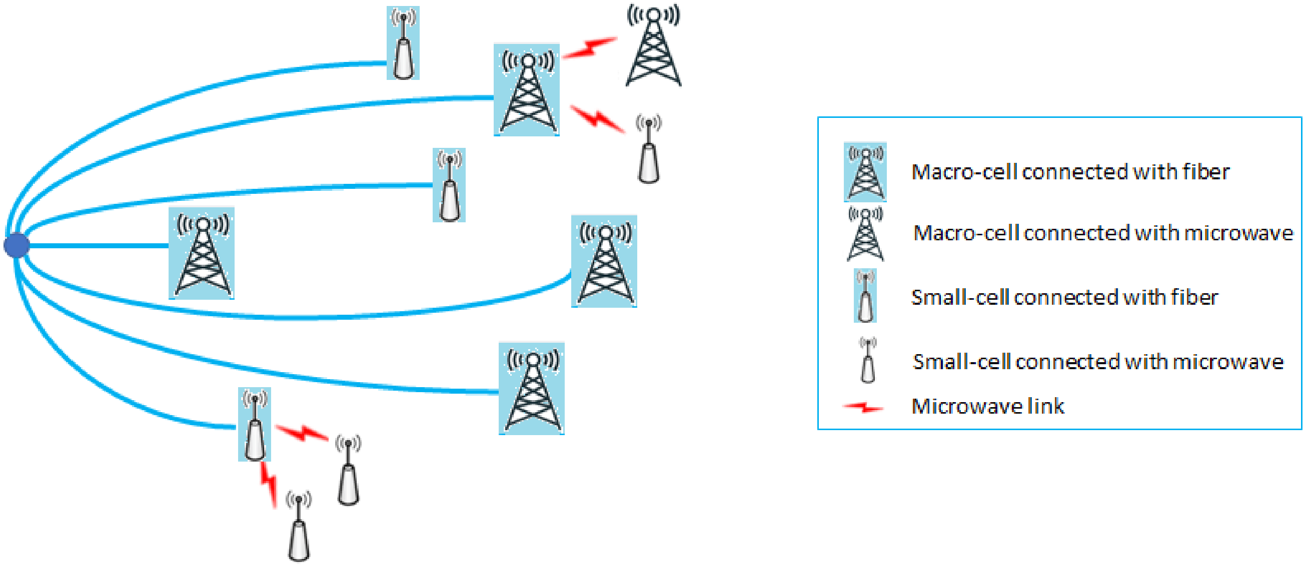
[49] *See* SpaceX Mod 3 Application; *SpaceX Mod 3 Grant*.

2.2. 12 GHz Terrestrial Service Deployment

Figure 2-8 shows a notional 5G deployment in an urban center. The macro-cells are assumed to provide coverage using multiple frequency bands. High-bandwidth Ku-band coverage is provided near the base stations, and other bands support users farther from the base station.[50] Therefore, these macro-cells do not necessarily provide continuous 12 GHz coverage, although in many cases they may. As such, the base stations are not necessarily in a continuous regular hexagonal grid but rather a configuration suitable to provide high capacity service while satisfying the applicable Inter-Site-Distance (ISD) requirements. The 12 GHz band can also be used to provide high-bandwidth small-cell coverage, as shown in this figure. There is a high density of fiber Points of Presence in urban centers. Therefore, as shown in this figure, microwave backhaul links are assumed to be required on only a small number of sites, and to need only one hop to get to a fiber point.

Figure 2-8: Notional 5G Deployment in an Urban Center



To determine the area where 12 GHz terrestrial service would be deployed, the most densely populated census tracts in the United States were first considered. It was noted that census tracts with population density[51] greater than 7,500 people per square mile roughly match the dense urban portions of many cities, so the model uses that figure as a threshold and ensures that these areas were included as areas where 12 GHz was likely to be deployed. However,

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[50] In addition to 49,997 macro-cells, the model also assumed that 89,970 small cells were deployed nationwide between the macro-cell base stations to increase capacity and to provide greater continuity of 12 GHz coverage. Base station transmitters using high capacity 12 GHz spectrum would most likely be deployed as part of a multi-band spectrum strategy and, combined with other bands, would ensure a reliable, seamless user experience.

[51] Each tract is a defined area from which area in square miles is calculated, and the population of each tract is calculated from the 2010 census data. Dividing the tract population by the tract area gives the tract's population density.

population density varies greatly across the United States and the 12 GHz band is expected to also be deployed in many less densely populated urban centers; therefore, the study uses a methodology to ensure that if the "urban" density threshold does not result in an area that encompasses 10% of a market's population, then the most densely populated census tracts in the market are added until the area covers 10% of the market population. As discussed above, MVDDS is geographically licensed using DMAs,[52] but this study uses PEAs for ease of comparison because wireless broadband services are typically licensed on a PEA basis. For the reasons explained above in Section 1.2.1, PEAs were chosen as the basis for 12 GHz deployment.[53] Excluding Alaska, Hawaii, territories and the Gulf of Mexico, there are 406 PEAs in CONUS versus 206 MVDs, and by definition many PEAs include mostly non-urban areas.[54] So RKF's methodology to ensure 10% of the population in each PEA is covered brings 12 GHz 5G service to the most populous parts of many rural markets, as well as to large portions of the largest cities.

Figure 2-9 shows the PEA areas covering CONUS. The 5G network is deployed in the most densely populated areas comprising at least 10% of the population of each PEA. This is consistent with the idea that at higher frequencies, where cell coverage is small, but capacity is high, the 5G network will only be deployed where there is a high population density and high demand. As shown in the three examples in Figure 2-10, for many PEAs, the high population density areas per PEA include isolated towns surrounded by rural areas, such as Bloomsburg, PA; Hastings, NE; and Wenatchee, WA.

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[52] 47 C.F.R. § 101.1401; *see* note 15.

[53] *See What is Geographic Information Systems (GIS)?*, Federal Communications Commission (Nov. 13, 2015), https://bit.ly/2SuOd1F (providing PEA shape files).

[54] *See* discussion in note 15.

Figure 2-9: FCC PEA Boundaries

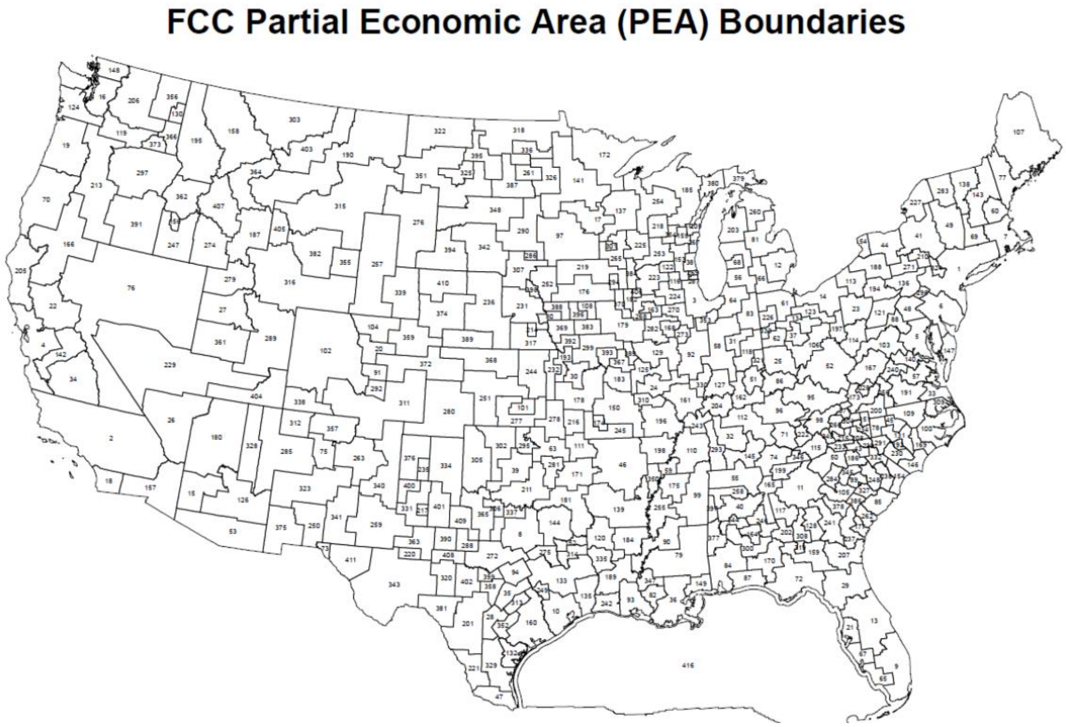
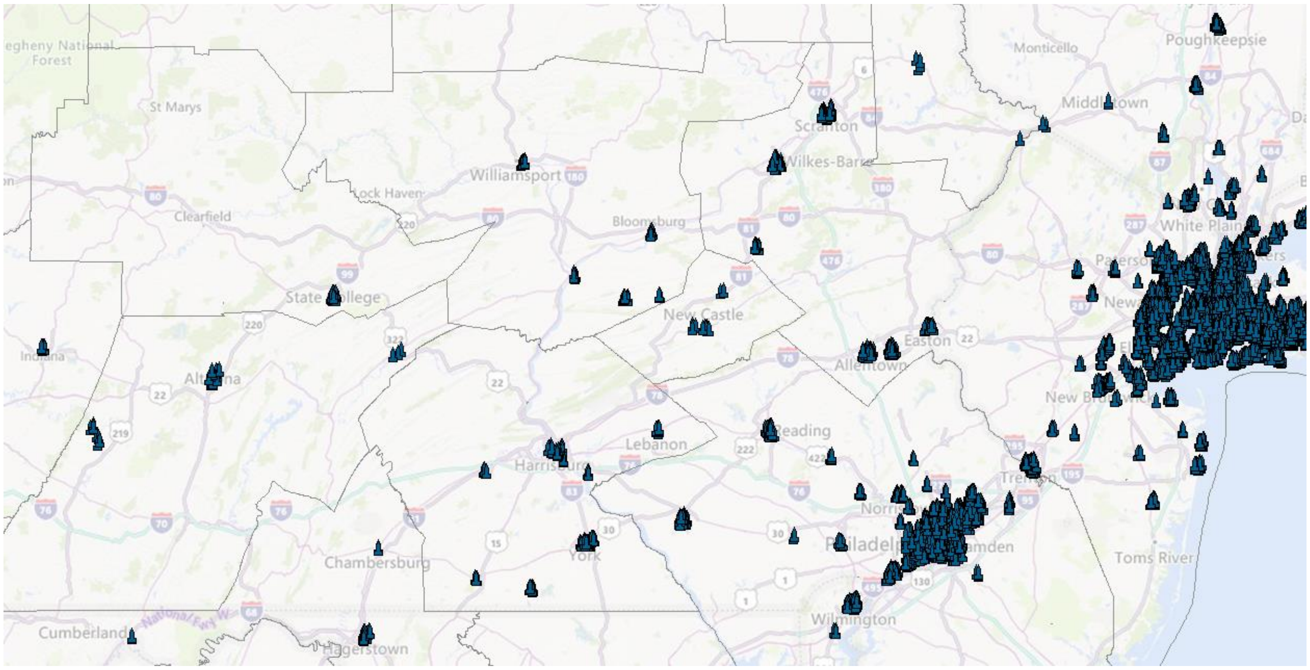
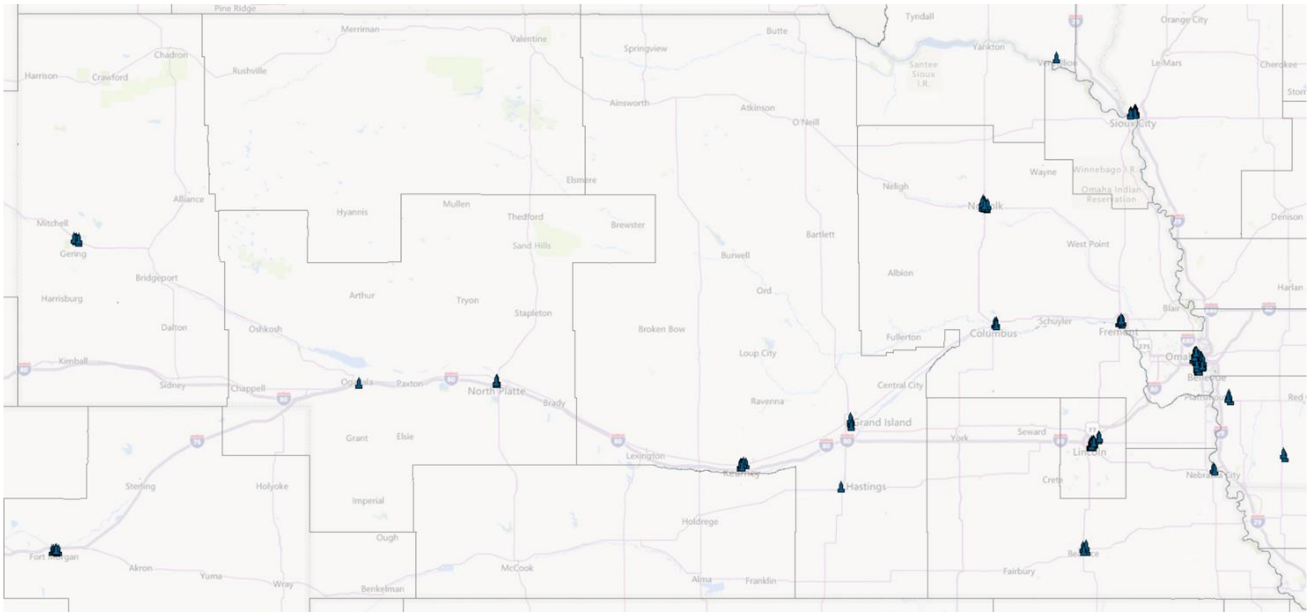
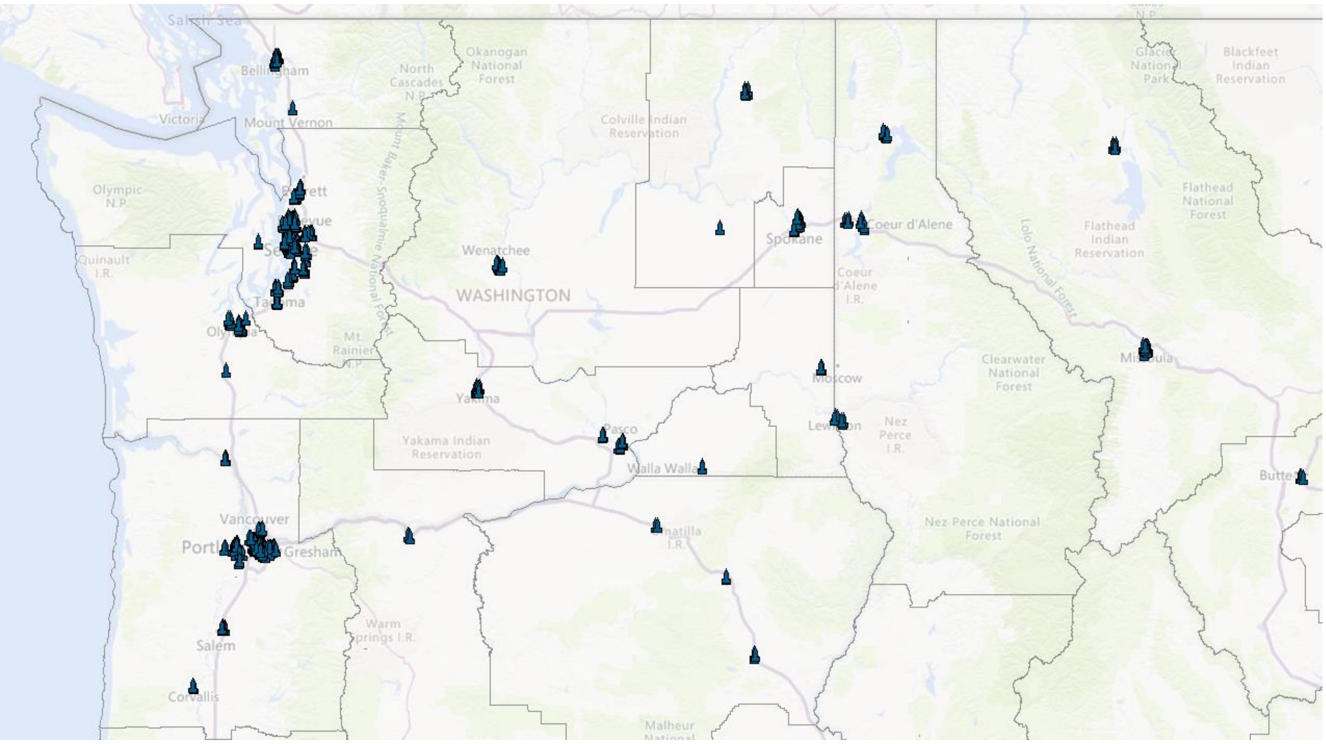


Figure 2-10: 5G Deployment in Top: Eastern PA/NJ/NYC (Bloomsburg, PA); Middle: Nebraska (Hastings, NE); Bottom: Washington State/Northern Oregon/Northern Idaho/Western Montana (Wenatchee, WA)







Version 4.11 of the 2020 Gridded Population of the World (GPW) population-density database is used to determine the morphology classification of the local area so that the appropriate site spacing could be applied.[55] The GPW database has a highest resolution of 30 arcseconds, which corresponds to approximately 1 kilometer, or 927 meters, at the equator.

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[55] *See Gridded Population of the World (GPW), v4*, Socioeconomic Data and Applications Center, https://bit.ly/3h2DF4b.

The GPW population density database is used to classify all points in CONUS region as either urban, suburban, or rural, in accordance with Table 1-1. These classifications in turn are used to determine the macro-cell base stations' deployment-related parameters as expressed in Table 2-4, the locations of the small-cell base stations, the height of the indoor UEs, and the selection of macro-cell base stations without fiber to define the point-to-point backhaul links. In addition, these classifications determine the path loss model to be used as described in Section 3.

2.2.1. Distribution of 12 GHz Macro-Cell Base Stations

In this study, within each PEA, a fixed number of macro-cell base stations are laid down over the 12 GHz eligible areas (as explained above).

Using the census tracts as described in Section 1.2, the total population within all 12 GHz eligible areas of each PEA is calculated and is compared to the population over all 12 GHz eligible areas across all PEAs in CONUS. The ratio is then used to determine the number of macro-cells in each PEA assuming a total of 50,000 macro-cell base stations deployed nationwide. This is indicated in Equation 2-3 below:

Equation 2-3

$$\text{Number of macro-cell BS within a PEA} = 50{,}000 \times \frac{Population\ within\ 12\ GHz{-}eligible\ areas\ of the\ PEA}{Total\ population\ of\ \ 12\ GHz{-}eligible\ areas\ over\ all\ PEAs\ in\ CONUS}$$

Next, those number of base stations are dropped within the 12 GHz eligible areas of each PEA per following methodology:

1. Use 30 arc-second GPW data to calculate the local population density within the 5G area (30 arc-seconds results in roughly 1x1 kilometer tiles).
2. For each tile, determine whether the local area is urban, suburban, or rural based on the following. If the density > 7,500 POPs/miles^2, then the tile is classified as urban. Otherwise, the population density values in the eight surrounding tiles are averaged and this averaged value is compared to the population density thresholds. If the average population density is less than 600, then the tile is classified as rural. If the tile is neither urban, nor rural, it is classified as suburban.
3. Designate the base station as urban, suburban, or rural based on the classification of the tile it is in as determined in step (2) above.
4. Drop the base stations randomly starting with the urban tiles. These tiles have the lowest required separation between base stations.
5. Valid base station locations must satisfy the corresponding (baseline) minimum separation between base stations (referred to as Inter Site Distance (ISD) in this report) as well as the cell size (per Table 2-4 below).
6. Randomly drop the next base station into a valid urban location. If there is no valid urban location, randomly select a valid suburban location, and if there is no valid suburban location, randomly select a valid rural location. If there is no valid rural location, the algorithm has failed with the current ISD values.
7. Repeat steps 4 to 6 until all base stations assigned to the PEA have been dropped. If the algorithm fails in step (6), the ISD separation distances are reduced to the Tier-2 levels in

Table 2-4 and then to the Tier-3 levels if needed. In this case, urban and suburban base station separation distances are reduced simultaneously. This approach recognizes the fact that base stations do not all have the same radius in a given morphology and ensures approximately 50,000 base stations can be deployed.

Using the above methodology, 49,997 macro-cell base stations were dropped over CONUS.[56]

Table 2-4 also shows the base station's assumed height above ground level and its minimum down-tilt level. The minimum down-tilt levels are computed such that a 1.5m UE at the edge of the cell would be within base station's half power beamwidth. The minimum downtilt is also used to compute the maximum UE height within each macro-cell.

Table 2-4: 12 GHz Macro-Cell BS Deployment-related Parameters

	Urban	Suburban	Rural
Minimum separation distance between base stations (ISD) (baseline[57] /Tier-2/Tier-3)	500m/300m/ 200m	1299m/800m/ 500m	1732m
ISD to determine coverage cell size used for UE drops (baseline/Tier-2/Tier-3)	300m/300m/ 200m	500m	1732m
Height above ground	20m[58]	25m[59]	35m[60]
Minimum down-tilt (baseline/Tier-2/Tier-3)	11°/11°/14°	10°	7°

Once the macro-cell base stations are dropped consistent with the methodology described above, their locations are fixed in the simulation. Figure 2-11 shows the location of macro-cell base stations over CONUS.

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[56] Due to rounding the result of equation 2-3 to the nearest integer for each PEA, only 49,997 base stations of the targeted 50,000 were dropped.

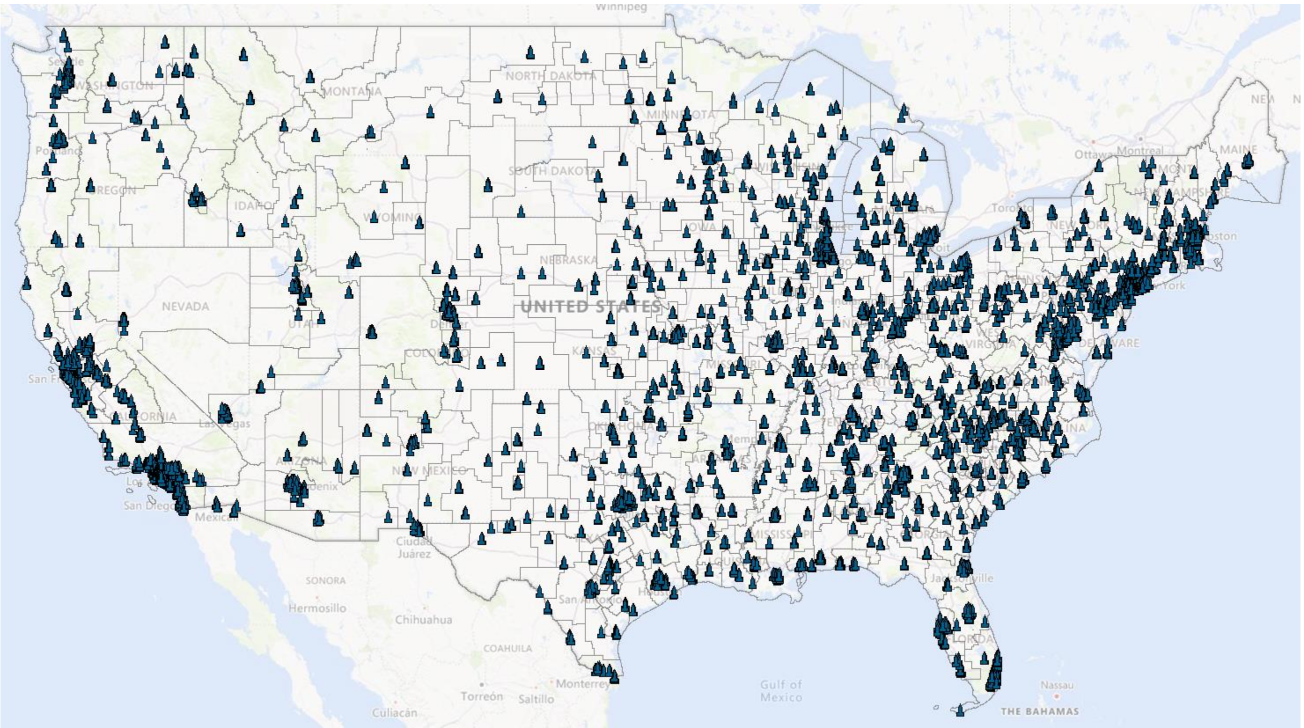
[57] Per ITU-R Rec. M.2135, the assumption is that 12 GHz Base stations will be installed on the same towers as the 2 GHz Base stations. *See* ITU-R Rep. M.2135, *Guidelines for evaluation of radio interface technologies for IMT-Advanced*, International Telecommunication Union, at Table 8-4, https://bit.ly/3nNVghv.

[58] *See* ITU-R Report M.2292-0, *Characteristics of terrestrial IMT-Advanced systems for frequency sharing/interference analyses*, International Telecommunication Union, https://bit.ly/3eheDfQ (noting antenna height for macro urban and suburban for bands between 3 and 6 GHz).

[59] *Id.*

[60] Per 3GPP TR 38.901 V16.1.0 (2019-12). *See Study on channel model for frequencies from 0.5 to 100 GHz*, 3GPP, at Table 7.4.1-1 (Pathloss models), (noting default base station height for Rural Macro-Cell (RMa)).

Figure 2-11: Distribution of 49,997 12 GHz Macro-Cell Base stations over CONUS



2.2.1.1. Macro-Cell Base Station Antenna Pattern, EIRP and Channel Plan

Each macro-cell base station coverage is modeled as a circle with radius equal to the ISD (per Table 2-4) divided by $\sqrt{3}$. The cell is divided into 3 equal sectors (each of 120 degrees).

The base station uses a phased array antenna to beamform a narrow beam toward each UE, allowing a reuse factor of 4 within each sector. On the downlink, each UE is assumed to be allocated 100 MHz. With five 100-MHz channels available (12.2-12.7 GHz), a maximum of 20 UEs per sector, when fully loaded, can be served simultaneously.[61] Figure 2-1 shows the macro-cell base stations channel plan.

Furthermore, it is assumed that base station transmissions are synchronized so that at any given instant (or simulation iteration), either all base stations are transmitting or all the UEs are transmitting. The base stations are assumed to be 50% loaded.

The base station beamforming 3D pattern is modeled consistent with 3GPP specifications pertaining to 5G New Radio operations in the 7 to 24 GHz frequency range, 3GPP TR 38.820, and assumes 256 elements with a peak gain of 27.7 dBi.[62] The antenna pattern was capped at a

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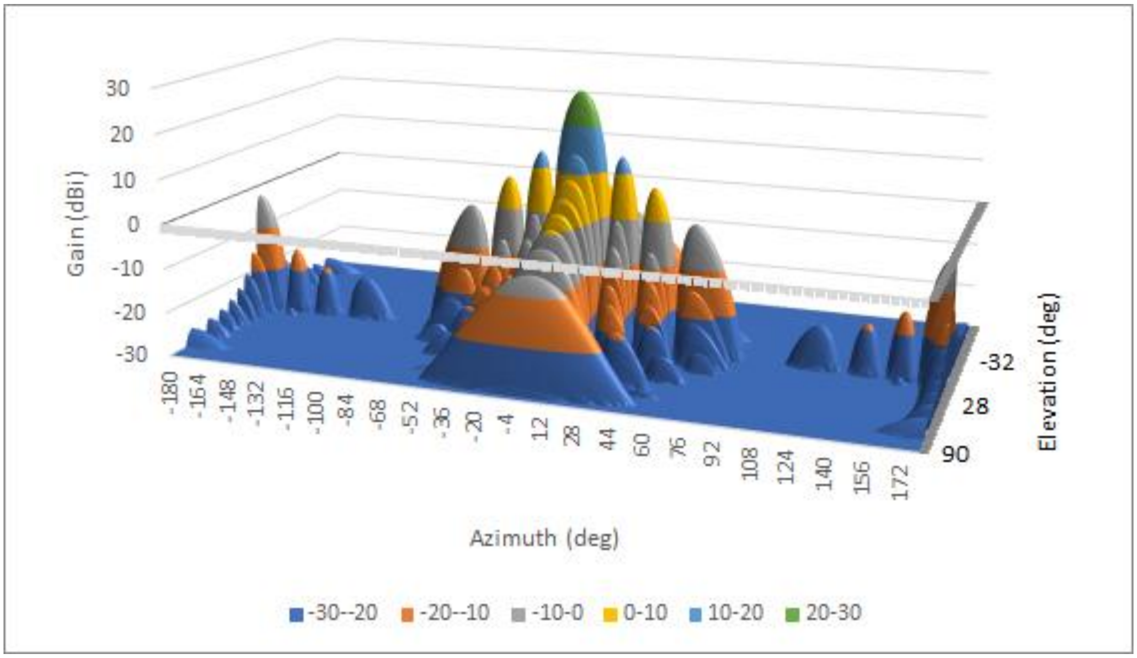
[61] To simulate a 50% loaded system, for simplicity, it is assumed half number of UEs (i.e., 10 per sector) are served simultaneously.

[62] 3GPP TR 38.820 V16.0.0 (2020-06). *See Study on the 7 to 24 GHz frequency range for NR*, 3GPP, at Clause 7.2.4.

minimum gain of -30 dBi. Figure 2-12 below shows the base station antenna pattern. The base station directs a beam toward each UE. In addition, UEs are placed such that the base station's minimum downtilt is as defined in Table 2-4.

Figure 2-12: Base station 3D Antenna Pattern



A macro-cell base station EIRP of 75 dBm per 100 MHz is assumed.[63] This results in conducted transmit power of 41.3 dBW (=75 - 27.7 - 10*log10(4)) per 100 MHz per user.

2.2.2. Distribution of 12 GHz Outdoor Small-Cell Base Stations

In this study, the number of small-cell base stations in each PEA is assumed to be twice the number of urban macro-cell base stations in that PEA, so 89,970 small-cell base stations were also dropped.

As with the macro-cell base stations, each small-cell base station coverage is modeled as a circle with radius equal to the ISD (per Table 2-4) divided by $\sqrt{3}$.

These small-cell base stations are dropped within the 30-arcsec grids that are urban (i.e., with population density greater than 7,500 people per square mile). If the small-cells do not all fit within the urban grids, they are dropped within the suburban and then rural grids (as defined in

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[63] 47 C.F.R. § 30.202(a).

Table 1-1). The small-cell base stations are dropped randomly while maintaining the following minimum separation distances:

To other small-cell base stations: 150m (baseline) /100m (Tier-2) /50m (Tier-3), and

To urban macro-cell base stations: 174m (baseline)/ 115m (Tier-2) / 58m (Tier-3) (=small-cell radius x 2)

Unlike the macro-cell base stations, the small-cell base stations have the same separation distances to another small-cell base station (as explained above) regardless of whether they are located in an urban, suburban, or rural area.

The small-cell separation distance tier level is the same as that of the macro-cell in Table 2-4. In other words, if all the macro-cell and small-cell base stations using the baseline separation distances cannot be deployed, the separation distances for both macro-cell and small-cell base stations are dropped to Tier-2, etc.

Table 2-5 shows the remaining operating characteristics of the small-cell base stations. The small-cell base stations are assumed to have omnidirectional antennas. Only outdoor small-cell base stations are simulated.

Table 2-5: 12 GHz Outdoor Small-Cell Base Station Operating Characteristics

Parameter	Value
Channel Plan and Bandwidth	Ten 25-MHz channels from 12.2-12.45 GHz (see Figure 2-1)
Height, AGL	6 meters (pole mount)
Antenna Pattern	ITU-R Rec. F.1336[64] *recommends* 2.2, average sidelobe pattern for stations with omnidirectional (in azimuth) antennas using the modifications in *recommends* 2.4 for operating with an electrical downtilt
Antenna Peak Gain	15 dBi
EIRP	45 dBm/100 MHz
ISD	150m (tier-1), 100m (tier-2), 50m (tier-3)
Downtilt	5° (tier-1), 7° (tier-2), 11° (tier-3)

Once the small-cell base stations are dropped consistent with the methodology described above, their locations are fixed in the simulation. Figure 2-13 shows the location of small-cell base stations over CONUS.

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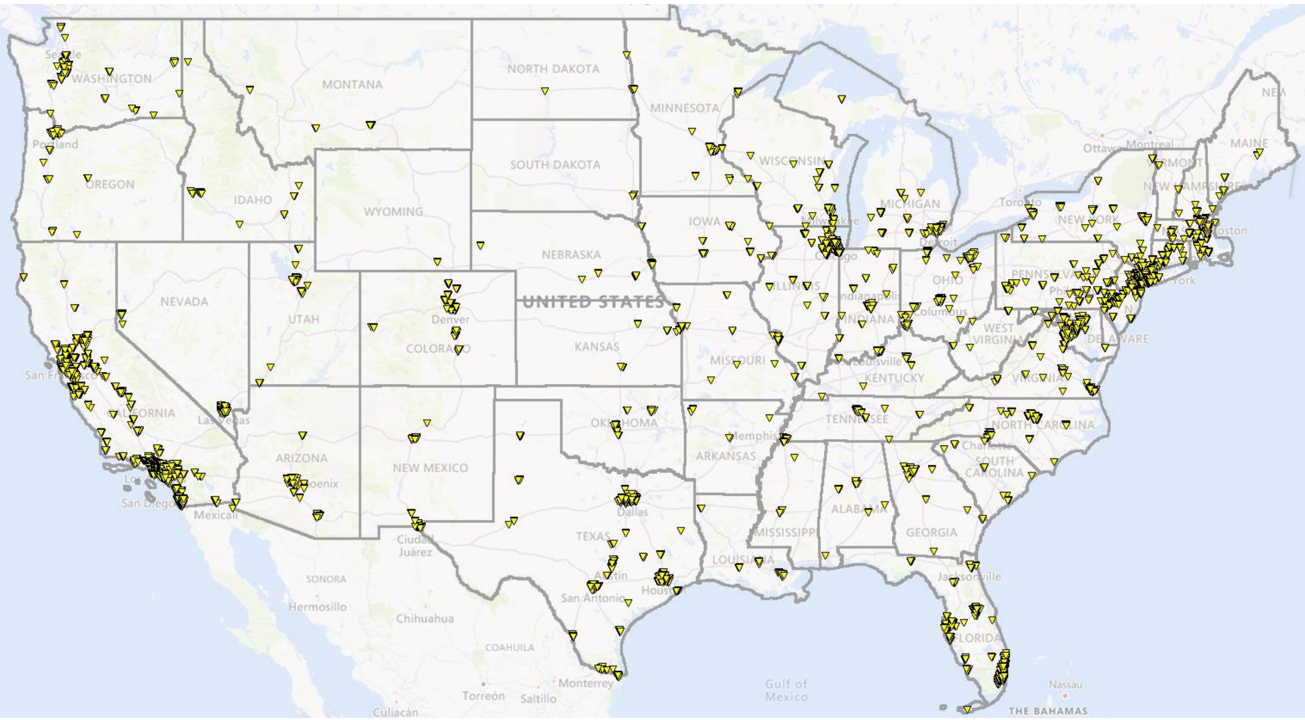
[64] *See* ITU-R F.1336, *Reference radiation patterns of omnidirectional, sectoral and other antennas for the fixed and mobile service for use in sharing studies in the frequency range from 400 MHz to about 70 GHz*, International Telecommunication Union, https://bit.ly/2QURUNI.

Figure 2-13: Distribution of 89,970 12 GHz Small-Cell Base Stations over CONUS



2.2.3. Distribution of UEs in Macro-Cells and Small-Cells

From Figure 2-1, each macro-cell sector is assumed to operate with five 100-MHz channels. With a reuse of four, 20 UEs can operate simultaneously in a macro-cell sector. The model randomly places ten UEs (representing a 50% loaded system) uniformly within each base station macro-cell sector (or 30 UEs over all 3 sectors).

With omnidirectional base station coverage, UEs can't reuse frequencies within small-cells. Instead UEs have to share the channel bandwidth. As a simplification, for this analysis, each UE is allocated 25 MHz. Thus, 10 UEs can be supported simultaneously in the available 250 MHz allocated to small-cells (see Figure 2-1), if the cell is fully loaded. This study assumes the small-cells are 50% loaded and models this by having five simultaneously active UEs.

The UEs are placed uniformly within the base stations' coverage areas. Furthermore, 80% of the UEs are assigned as indoor and 20% as outdoor. Outdoor UEs are assumed to have a height above ground level of 1.5m. For indoor UEs, the height above ground is uniformly distributed between 1.5 meters and the height at which base station's downtilt is the minimum value in Table 2-4 (for macro cell) and Table 2-5 (for small cell). Furthermore, since the uniform distribution of height would highly overestimate the number of tall buildings, UE heights are restricted to 6 floors (16.5m) in urban macro-cells, and 2 floors (4.5m) in suburban and rural macro- and small-cells.

The UE antenna is assumed to be isotropic with gain of -3 dBi and maximum conducted power of 23 dBm. A body loss of 4 dB is assumed for UEs. Each UE's EIRP is computed assuming open loop Transmit Power Control (TPC). The TPC parameters are set to typical parameters (P0=-90 dBm and alpha=0.8). The base station and UEs transmit with a downlink-to-uplink ratio of four-to-one. In other words, the base station transmits 80% of the time, and the UEs transmits 20% of the time. Since the base stations are assumed to be synchronized, interference to the Starlink terminals will be either from the base stations (80% of the Starlink terminals) or from the UEs (20% of the Starlink terminals).

With 49,997 macro-cell base stations and 89,970 small-cell base stations deployed over CONUS, 1,499,910 simultaneously active macro-cell UEs and 449,850 simultaneously active small-cell UEs are simulated.

2.2.4. Distribution of 12 GHz Backhaul

A point-to-point backhaul link is a microwave link from a base station with no fiber access to another base station with fiber access. Figure 2-14[65] indicates that in North America, it is predicted that in 2025, less than 5% of the cell-sites will use microwave backhaul in the 7 GHz to 40 GHz band.

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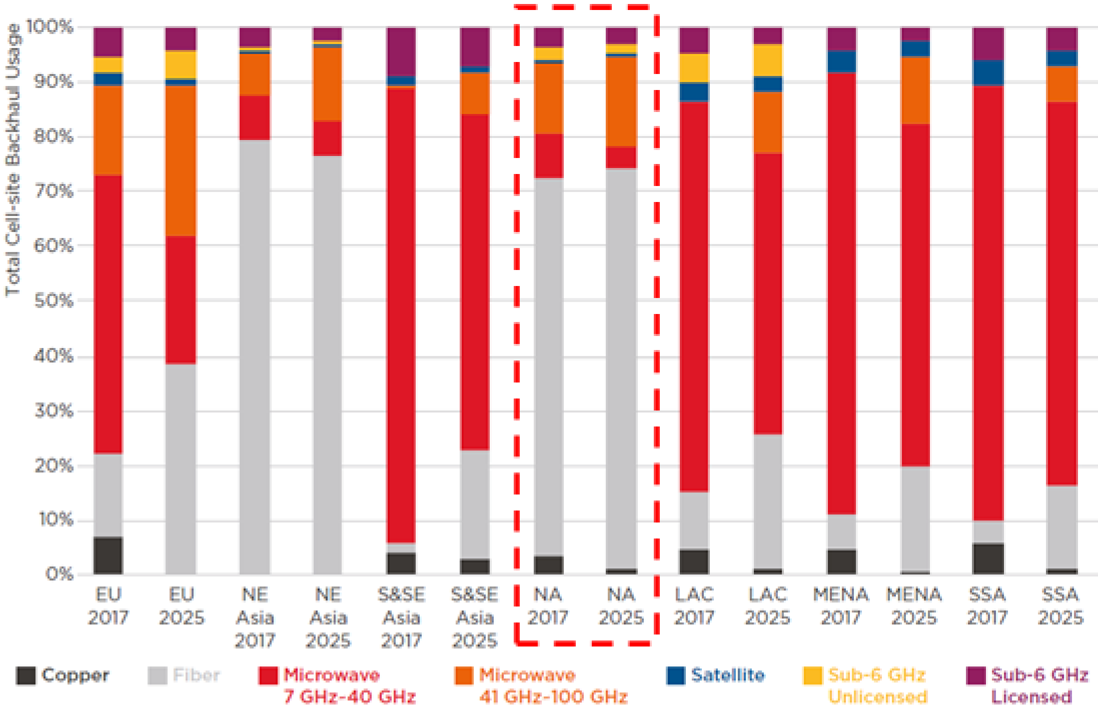
[65] *See* Jake Saunders & Nick Marshall, *Mobile backhaul options Spectrum analysis and recommendations*, ABI Research, at 4 (Sept. 2018), https://bit.ly/3vKW1Lc.

Figure 2-14: Total (macro-cell and small-cell) backhaul by region, historical (2017) and forecast (2025) (NA = North America)



In this study, 5% of all the base stations use point-to-point microwave backhaul. These base stations are selected so that 5% of rural macro-cell base stations, 5% of other macro-cell base stations and 5% of small-cell base stations all use microwave backhaul. Within each group, base stations without fiber access (also referred to as "remote" in this section) were selected at random.

Macro-cell microwave backhaul links connect to the nearest macro-cell base station with fiber access. The small-cells connect either to the nearest small-cell or macro-cell with fiber access. There were a total of 2,500 macro-cell base stations and 4,499 small-cell base stations without fiber access, requiring microwave backhaul via the 12 GHz band.

Figure 2-15 shows the end points of the point-to-point microwave backhaul links chosen. For additional clarity, Figure 2-16 shows a zoom-in of Baltimore, MD showing multiple backhaul scenarios with a green line indicating the 12 GHz link. The scenarios include (1) macro base with fiber (blue tower) to macro base remote (pink tower), (2) macro base with fiber (blue tower) to small-cell remote (pink triangle), and (3) small-cell with fiber (blue triangle) to small-cell remote (pink triangle).

Figure 2-15: End points of 6,999 Point-to-Point Backhaul links over CONUS

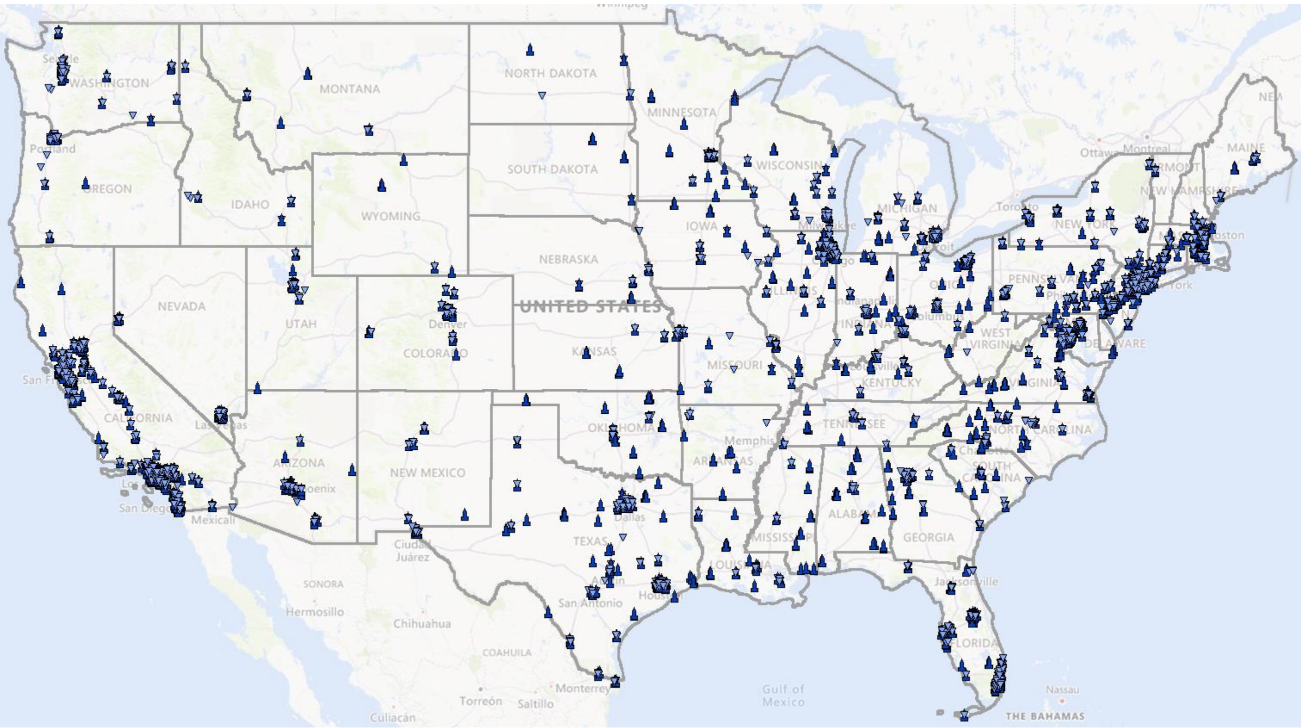


Figure 2-16: Zoom-in of Point-to-Point Backhaul Links in Baltimore, MD (macro-cell BS with fiber (blue tower), macro-cell BS remote (pink tower), small-cell BS with fiber (blue triangle), small-cell BS remote (pink triangle))

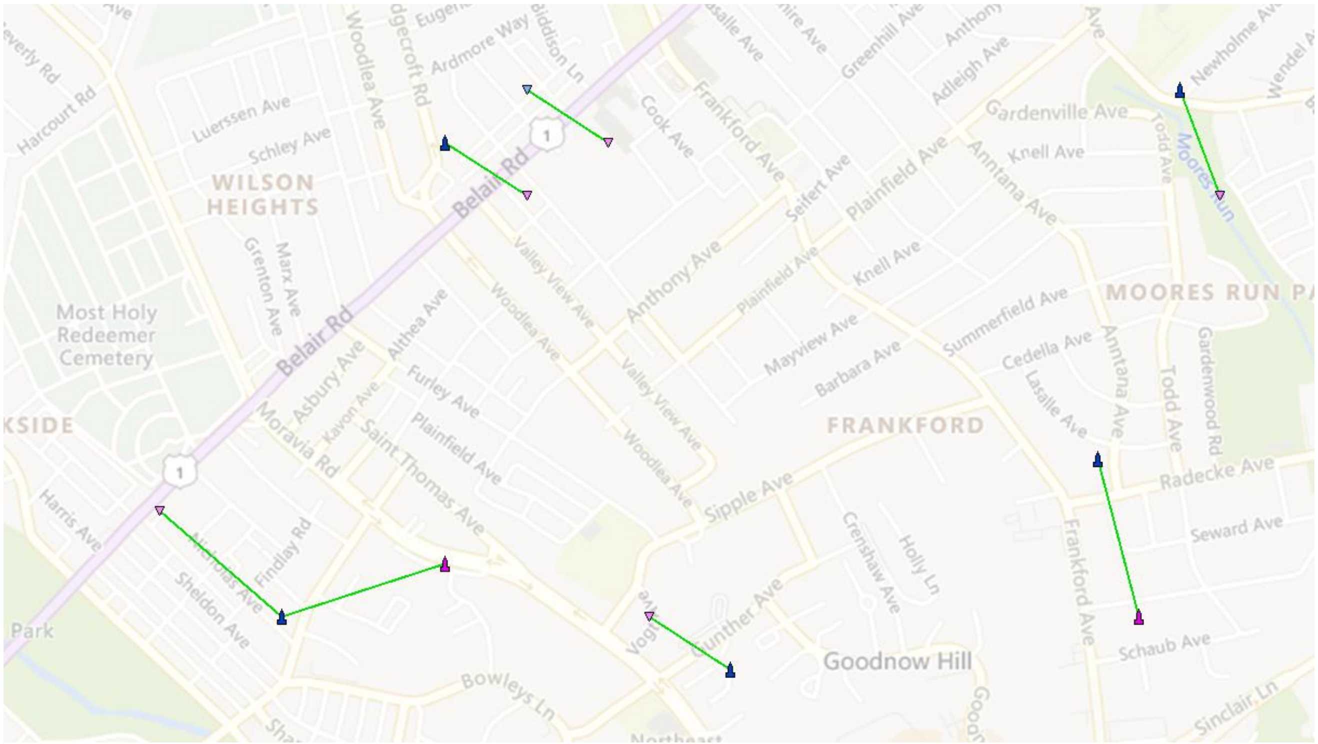


Table 2-6 below shows some of the remaining operating characteristics of the backhaul links. In the table, the downlink is defined as the transmission from the base station with access to fiber to the base station with no access to fiber, and uplink is defined as the reverse direction. Note that since the transmitter and receiver of a point-to-point backhaul link are at the base stations, their height is determined by that of the base station.

Table 2-6: 12 GHz Point-to-Point Microwave Backhaul Link Operating Characteristics

Parameter	Value
Channel Plan and Bandwidth	Per Figure 2-1 macro-cell downlink: 400 MHz (12.2-12.6 GHz) macro-cell uplink: 100 MHz (12.6-12.7 GHz) small-cell downlink: 200 MHz (12.45-12.65 GHz) small-cell uplink: 50 MHz (12.65-12.7 GHz)
Tx/Rx Antenna Pattern	CommScope-HX6-13W[66]
Tx/Rx Antenna Diameter	1.8m (6 feet)
Tx/Rx Antenna Peak Gain	45 dBi
Tx/Rx Feederloss	0 dB
Rx Noise Figure	5 dB[67]
Duty cycle	100% downlink and uplink

A typical 1.8 meter point-to-point microwave antenna in this frequency band, such as one from CommScope HX6-13W was assumed. Figure 2-17 shows the antenna pattern used.

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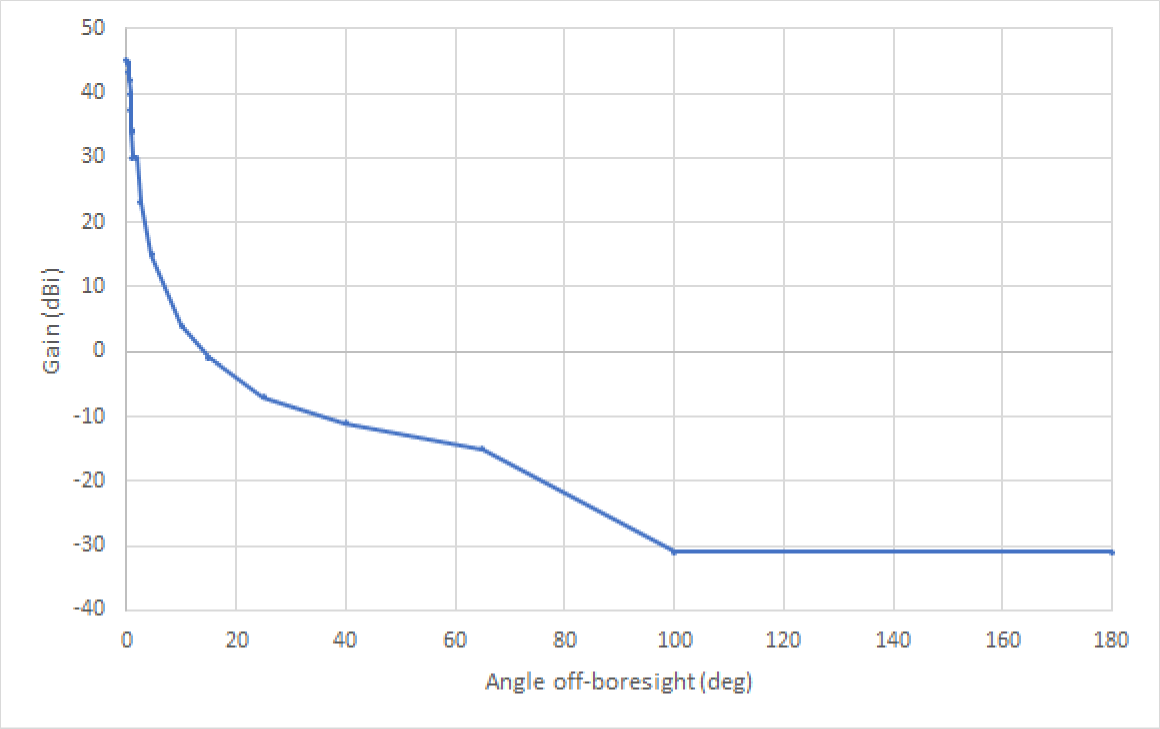
[66] *See* HX6-13W, Commscope, https://bit.ly/33e49HE.

[67] *See* ITU-R Rec. F.758-7, *System parameters and considerations in the development of criteria for sharing or compatibility between digital fixed wireless systems in the fixed service and systems in other services and other sources of interference*, International Telecommunication Union (Nov. 2019), at Table 8, https://bit.ly/3vD6yHW (for 10.7-11.7 GHz).

Figure 2-17: Point-to-Point Backhaul Tx and Rx Antenna Pattern (CommScope HX6-13W)



The point-to-point microwave backhaul EIRP is computed for each link such that the minimum EIRP to transmit a signal with 256-QAM modulation in presence of rain fade is used. However, since maximum EIRP is capped at 85 dBm consistent with section 30.405 of the Commission's rules, it is assumed that when the computed minimum EIRP required exceeds 85 dBm, a lower modulation is used.[68] ITU-R Rec. P.530-17 is used to estimate the rain fade margin required for a target link availability of 99.99%.[69]

The Signal-to-Noise Ratio (SNR or C/N) for the point-to-point link is computed per Equation 2-4 below:

Equation 2-4

$$C/N = EIRP - L_{FSPL} + G_{Rx\ Peak\ Gain} - N$$

where,

- $EIRP$ (dBW) = PtP transmitter EIRP (to be computed)

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[68] 47 C.F.R. § 30.405.

[69] *See* ITU-R Rec. P.530-17, International Telecommunication Union (Dec. 2017), https://bit.ly/3xPYPZh.

- L_{FSPL} (dB) = Free Space Path Loss (=92.45 + 20*log10(center frequency in GHz)+20*log10(Tx-Rx distance in km))
- $G_{Rx\ Peak\ Gain}$ (dBi) = PtP receiver peak gain (=45 dBi)
- N (dBW) = PtP receiver noise power
  - using Equation 2-2 with T = 917.06 K (=*290+290*log10(10^(NF/10)-1*, with *NF* (Noise Figure) = 5 dB). Bandwidth is per Table 2-6 depending on the link.

The point-to-point link's EIRP in Equation 2-4 is set such that C/N in Equation 2-5 is met:

Equation 2-5

$$C/N = SNRreq + \max\{FFM, Rain\ Fade\}$$

where,

- SNRreq (dB) = SNR required for 256-QAM modulation (=29.5 dB[70]). This is used to compute the desired EIRP.

Once the point-to-point backhaul links are established consistent with the methodology described above, their locations and EIRP levels are fixed in the simulation.

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[70] *See* Integra Series Datasheet, SAF TEHNIKA, https://bit.ly/3eP94nY.

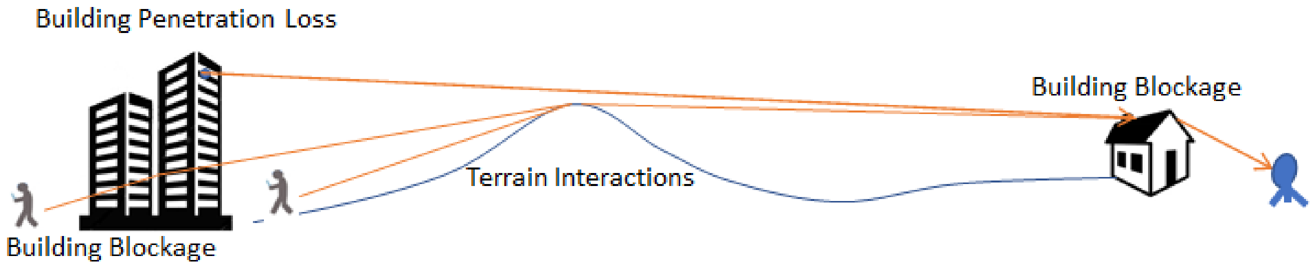
3. Propagation Models

Path loss models are needed in the calculation of UE EIRP determined by applying transmit power control (TPC). Path loss is also required for the interference calculation to Starlink terminals (see Equation 2-3).

Within a sector, for determining UE EIRP, path loss is modeled using 3GPP Specification 38.901. Applicable path loss models in the standard are Urban Macro-Cell (UMa), Rural Macro-Cell (RMa) and Micro-Cell (UMi). UMa is used for both urban and suburban macro-cells, and UMi is used for small-cells.

Figure 3-1 shows possible interference paths from 12 GHz transmitters to the Starlink terminal. Paths from indoor devices will experience penetration losses through buildings. Some paths will then interact with terrain, while others will suffer from local end-point clutter (e.g., buildings and foliage).

Figure 3-1: Typical Interference Paths from 12 GHz Base Station and UEs Towards Starlink Terminal



Paths from indoor 12 GHz UEs experiencing building penetration loss were calculated using ITU-R Rec. P.2109-1 (P.2109).[71] P.2109 is a heuristic model based on many measurements with users located randomly within a building. It considers the elevation angle of the signal leaving the building to the affected receiver. Two types of buildings are defined: traditional and thermally efficient. Penetration losses through thermally efficient buildings is higher than traditional buildings. The study assumes 70% of buildings are traditional and 30% of buildings are thermally efficient.

Table 3-1 summarizes the propagation models used in calculating interference to Starlink terminals from the 12 GHz 5G network. The application of the models depends on the interference source, the cell-site morphology, and the length of the interference path. The methodology used here is similar to the approach used by the Commission in the *6 GHz Report &*

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[71] *See* ITU-R Rec. P.2109-1, International Telecommunication Union (Aug. 2019), https://bit.ly/3nX3C6G.

Order,[72] including propagation models chosen, the method of combining line-of-sight (LOS) and non-line-of-sight (NLOS) equations, and the clutter models used. Appropriate adjustments were made for this frequency band (for instance, use of 3GPP Specification 38.901[73] in place of Winner II[74]).

Table 3-1: Summary of Propagation Models

Slant Range (12 GHz transmitter to Victim Starlink terminal receiver)	Morphology	Propagation Model
Up to 30 meters	Any	Free Space Path Loss (FSPL) per Equation 2-4
30 meters to 1 km	Urban/Suburban Macro-cell BS to UE or Starlink terminal	38.901 UMa
	Urban/Suburban Macro-cell UE to Starlink terminal	38.901 UMi
	Small-cell BS and UE	38.901 UMi
30 meters to 5 km	Rural Macro-cell BS and UE	38.901 RMa
> 1 km	Urban/Suburban Macro-cell BS and UE Small-cell BS and UE	ITM + Clutter at Tx + Clutter at Rx Clutter at Tx or Rx: ● urban/suburban: P.2108 ● rural: P.452 village center clutter Clutter at Tx is only applied when TX is a UE with height = 1.5m Clutter at Rx is only applied when Starlink terminal height = 1.5m
> 5 km	Rural Macro-cell BS and UE	

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[72] *Unlicensed Use of the 6 GHz Band, Expanding Flexible Use in Mid-Band Spectrum Between 3.7 and 24 GHz*, Report and Order and Further Notice of Proposed Rulemaking, 35 FCC Rcd. 3852 (2020) ("*6 GHz Report & Order*").

[73] *See 5G; Study on channel model for frequencies from 0.5 to 100 GHz (3GPP TR 38.901 version 16.1.0 Release 16)*, European Telecommunications Standards Institute (ETSI) (Nov. 2020), at Table 7.4.1-1 (Pathloss models) and Table 7.4.2-1 (LOS probability).

[74] See Pekka Kyösti et al., *WINNER II Channel Models Part 1*, European Conference of Postal and Telecommunications Administrations (Feb. 4, 2008), https://bit.ly/3nHBGn9.

First, FSPL is used for distances below 30 meters.

When the 12 GHz transmitter is in an urban or suburban location (as defined in Table 1-1), for distance between 30 meters and 1 km, the combined LOS/NLOS 3GPP Specification 38.901 path loss model is computed using Equation 3-1 below. When the 12 GHz transmitter is in a rural area (as defined in Table 1-1), this model is used for distances between 30 meters and 5 km.

Equation 3-1

$$PL_{38.901}\,(dB) = PL_{LOS}\,(dB) \times Prob_{LOS} + PL_{NLOS}\,(dB) \times \{1 - Prob_{LOS}\}$$

Where,

- PL_{LOS} and PL_{NLOS} are the LOS and NLOS Path Losses per Table 7.4.1-1 in 38.901
- $Prob_{LOS}$ is the LOS Probability per Table 7.4.2-1 in 38.901

The path loss models used for PL_{LOS}, PL_{NLOS}, and $Prob_{LOS}$ are UMa, RMa or UMi, depending on whether the 12 GHz transmitter is a base station or UE, macro-cell or small-cell and whether it is in urban, suburban, or rural area (see Table 3-1). Note that the 38.901 UMa, RMa and UMi path loss models all include a random lognormal shadowing term.

For distances above 1 kilometer (for urban/suburban 12 GHz Tx) or 5 kilometers (for rural 12 GHz Tx), the Irregular Terrain Model (ITM)[75] is used. ITM is a general-purpose radio propagation model for frequencies between 20 MHz and 20 GHz that can be applied to a large variety of engineering problems. The model, which is based on electromagnetic theory and statistical analyses of both terrain features and radio measurements, predicts the median attenuation of a radio signal as a function of distance and the variability of the signal in time and in space.

The ITM, along with Shuttle Radar Topography Model (SRTM) 3-arc seconds terrain database, is used to model terrain interactions. The ITM uses the SRTM 3-arc seconds terrain elevation data along with diffraction theory to calculate the path loss when there is terrain blockage.

The end-point clutter models follow the models adopted in the *6 GHz Report & Order* by the Commission, which is applied at the transmitter and/or receiver if the terminal is in the clutter (assumed when height above ground is 1.5 meters).

As indicated in Table 3-1, local end-point clutter is added using Recommendation ITU-R Rec. P.2108 (06/2017) Prediction of Clutter Loss (P.2108), Section 3.2 (for terrestrial paths). However, this is a statistical clutter model for urban and suburban areas. As such, when the end-

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[75] See Sheryl Genco, *NTIA Trusted Propagation Models Help Expand Commercial Wireless Services*, National Telecommunications and Information Administration (Oct. 16, 2020), https://bit.ly/3b1p7xJ.

point clutter is in a rural area, P.452 village center clutter (using P.452 Table 4 and Equation 57) is applied when the elevation angle of the signal path from the Starlink terminal to the 12 GHz transmitter is less than or equal to the clutter elevation angle of 2.86 degrees and the distance is greater than 700 meters. This corresponds to an average distance from the clutter of 70 meters and average clutter height of 5 meters.[76]

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[76] Clutter elevation angle is the elevation angle of the signal going above clutter with P.452 nominal height, h_a and nominal distance to Starlink terminal of d_k (see Figure 3 in P.452).

4. Sharing Results & Conclusions

4.1. Result Summary

The RKF analysis produces a cumulative distribution function (CDF) to assess the probability of interference to Starlink earth terminals from a national deployment of terrestrial 12 GHz operations, including base stations, small-cells, backhaul, and user equipment. Figure 4-1 shows the complementary CDF of aggregate I/N levels at the 2,500,000 Starlink terminals over CONUS, which RKF simulates in groups of 2,500 terminals over 1,000 iterations.

To generate the CDF, 2,500,000 Starlink terminals are randomly dropped over CONUS. Each Starlink terminal selects one of the eight available channels to operate on according to the frequency plan (see Figure 2-1) and UEs are deployed randomly within their base stations' coverage areas and also select a random channel according to their frequency plan. In 80% of the Starlink terminal drops, the interference from base station transmissions is simulated, and in 20% of the drops, the interference from UE transmissions is simulated. Finally, the point-to-point backhaul transmissions are simulated for all Starlink terminals.

Table 4-1 summarizes the large number of 5G transmitters that were deployed over CONUS from which the interference to the Starlink terminals were computed.

Table 4-1: Summary of the Number of 5G Interference Sources Deployed over CONUS and Their Variability in the Simulation

	Number	Variability in each Simulation iteration
Macro-cell base stations	49,997	Frequency channel Pointing direction (to UE)
Macro-cell user equipment	1,499,910 (=49,997 BS x 10 UEs/sector/BS x 3 sectors/BS)	Location within the cell Frequency channel
Small-cell base stations	89,970	Frequency channel
Small-cell user equipment	449,850 (=89,970 BS x 5 UEs/BS)	Location within the cell Frequency channel
PtP microwave backhaul	6,999	Frequency channel
Total 12 GHz 5G transmitters	2,096,726	

Figure 4-1 shows the individual I/N statistics resulting from 49,997 fixed macro-cell base stations (gray curve), 89,970 fixed small-cell base stations (yellow), 1,949,760 UEs deployed in macro-cell and small-cell (blue), and 6,999 point-to-point backhaul links (orange). The top figure shows the y-axis in linear scale, and the bottom figure shows it in log-scale to make visible the points above -8.5 dB I/N. Table 4-2 shows the exceedance probabilities from each of these curves. As indicated, the transmissions from 49,997 macro-cell base stations over CONUS result in 0.881% of the 2,025,000 (=81% of 2,500,000[77]) Starlink terminals having an aggregate I/N greater than -8.5 dB. Similarly, the transmissions from 89,970 small-cell base stations over CONUS results in 0.093% of the 2,025,000 Starlink terminals having an I/N exceeding -8.5 dB. The transmissions from 1,949,760 mobile UEs result in only 0.0043% of the 475,000 (=19% of 2,500,000) Starlink terminals having an exceedance. Finally, the transmissions from 6,999 point-to-point backhaul links result in 0.00004% of the 2,500,000 Starlink terminals having an exceedance. Considering the aggregate I/N statistics from all the 5G macro- and small-cell base station transmissions as well as the point-to-point links (in the base station downlink iterations), -8.5 dB I/N exceedance occurs for 0.888% of Starlink terminals.

Put differently, more than 94% of 2,500,000 Starlink user terminals receive 5G signals at power levels *a million times below their noise floor* (-60 dB). The log-scaled chart provides a “zoom in” on the remaining 5.6 percent of terminals. Of that fraction, only a small portion have a -8.5 dB I/N exceedance. And given the many assumptions that tend to overstate the degree and likelihood of potential emissions, the real-world risk of harmful interference is likely much lower than the model simulates. These results suggest there are ample opportunities for sharing between NGSO FSS and terrestrial 12 GHz infrastructure.

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[77] The model assumes a four-to-one downlink-to-uplink ratio (i.e., 80% of the time, base stations are transmitting, and 20% of the time, UEs are transmitting), but due to variation inherent to probabilistic analysis, the downlink-to-uplink ratio was about 81-to-19 (i.e., 81% of the time, base stations are transmitting, and 19% of the time, UEs are transmitting).

Figure 4-1: Probability of Aggregate I/N exceeding x-axis at Starlink Terminal Locations over CONUS (top figure – linear-scale; bottom figure – log-scale)

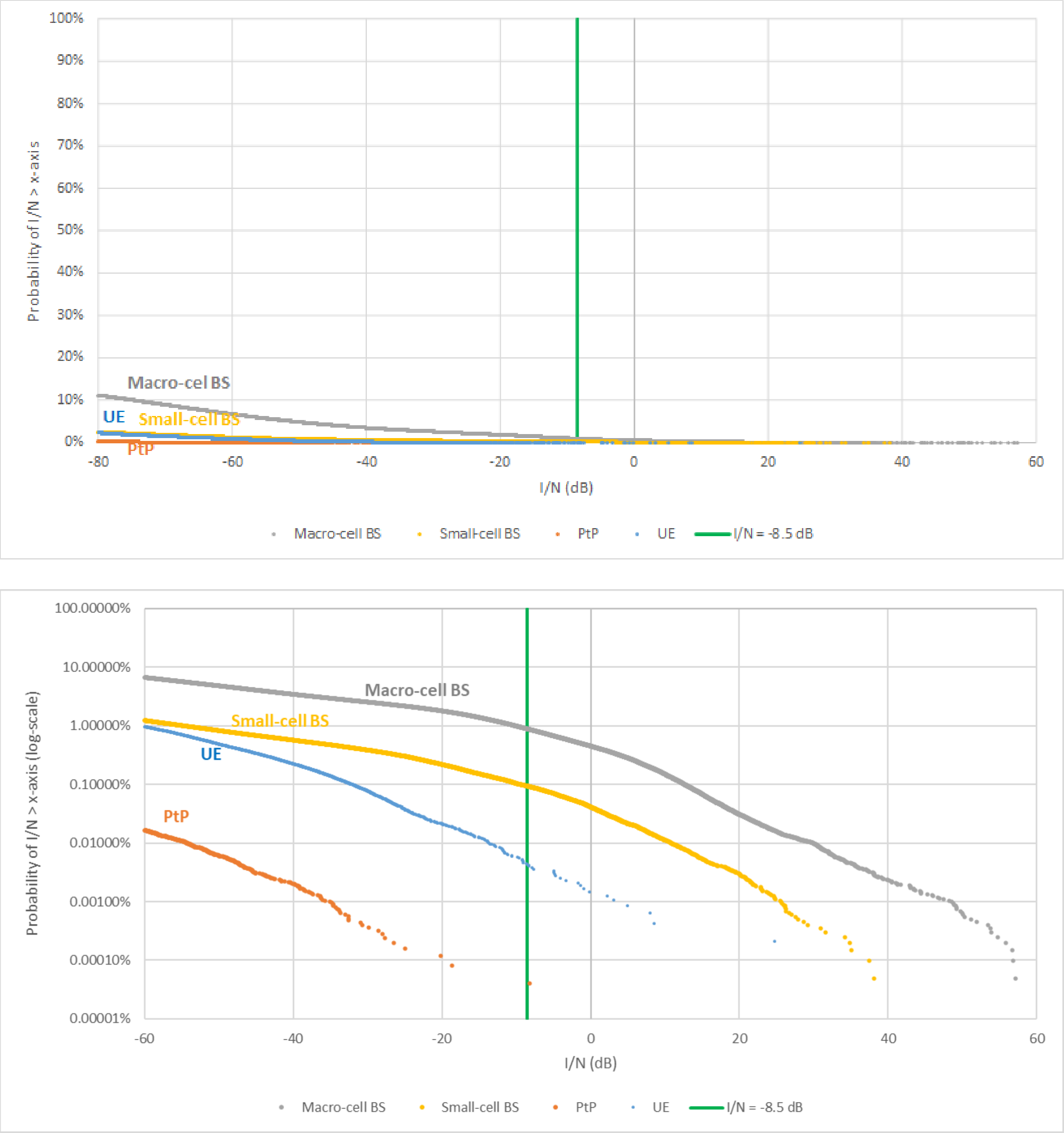

Table 4-2: I/N Exceedance Probabilities from Each Category of 5G Transmitters and the Total

5G interference source	% of Starlink terminals with -8.5 dB I/N exceedance
Macro-cell base stations	0.881% (out of 2,025,000 Starlink terminals)
Small-cell base stations	0.093% (out of 2,025,000 Starlink terminals)
Macro-cell and Small-cell user equipment	0.0043% (out of 475,000 Starlink terminals)
PtP microwave backhaul	0.00004% (i.e., 1 out of 2,500,000 Starlink terminals)
Total from macro- and small-cell base stations and PtP in the base station downlink iterations	0.888%[78] (out of 2,025,000 Starlink terminals)

The simulation results indicate that the 12 GHz base stations (versus the UEs and point-to-point links) are the dominant sources of interference. This is expected since the base stations are higher up from the ground – by at least 18.5 meters (=20-1.5) for the macro-cell and by 4.5 meters for the small-cell base stations – than the outdoor user equipment and hence can have line-of-sight to the Starlink terminals more often than a UE device would. The transmissions from the indoor user equipment at higher floors go through additional attenuation from the building resulting in lower I/N levels. In addition, the high I/N levels are caused by base stations that are very close to the Starlink terminal and/or when the Starlink terminal is within the base station's main beam, which can be easily addressed through coordination with little negative effect on either the 12 GHz terrestrial network or the NGSO operator.

An interference event from a single transmitter source is referred herein as a single-entry event. Due to the large number of simulated interference events, in the simulation, detailed link budgets were maintained only for single-entry interference events with I/N>-15 dB. These tabulated results are discussed below.

Figure 4-2 shows the Starlink terminal angle off boresight towards the 12 GHz transmitter (base station, UE, or point-to-point backhaul) (x-axis) versus the corresponding antenna gains (y-axis) for the interference events with single-entry I/N > -15 dB. As expected, the Starlink antenna gain in the direction of the 5G transmitter is low due to the minimum elevation angle restriction of the Starlink terminal. Note that low probability worst-case minimum elevation angle conditions

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[78] This figure is computed for the 2,025,000 Starlink terminals that were subject to 5G base station downlink transmissions, by adding the I/N from the individual 5G sources (i.e., macro- and small-cell base stations and point-to-point backhaul) linearly, then taking the 10*log10 of the total to convert to dB, and finally computing the percentage of those Starlink terminals that had total I/N > -8.5 dB.

(discrimination angle as low as 11.8 degrees) from the Starlink terminal to the 5G transmitter, which result in higher Starlink terminal gain towards the 5G transmitter, were simulated.

Figure 4-2: Starlink Terminal Antenna Gain Versus Angle Off-boresight Towards 12 GHz Transmitter

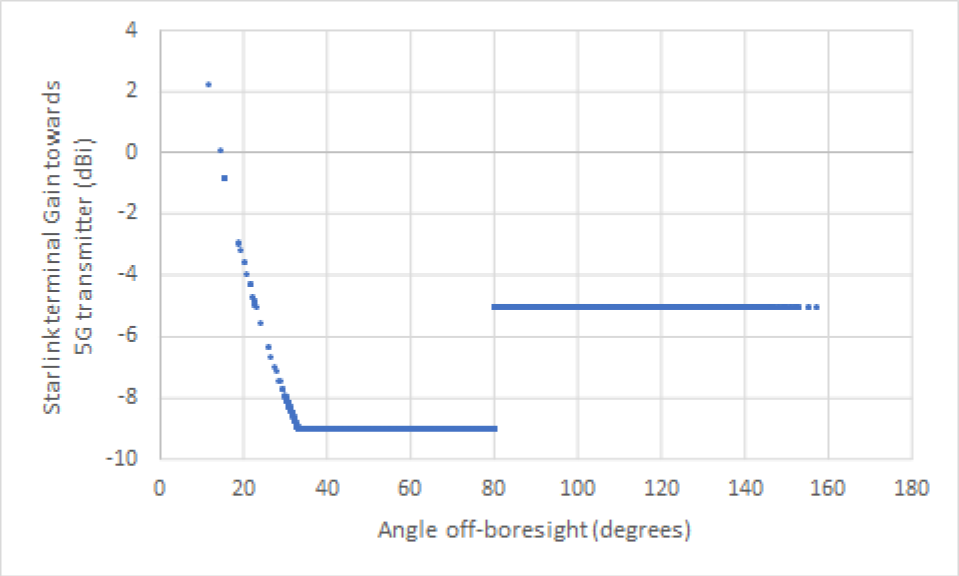


Figure 4-3 shows an EIRP distribution of macro-cell and small-cell UEs from one of the iterations of this simulation. This chart includes the EIRP levels from 1,949,760 UEs. As expected, indoor UEs have a higher probability of higher EIRP levels to compensate for the building penetration loss.

Figure 4-3: EIRP Distribution of 1,499,910 Macro-cell UEs and 449,850 Small-cell UEs over CONUS

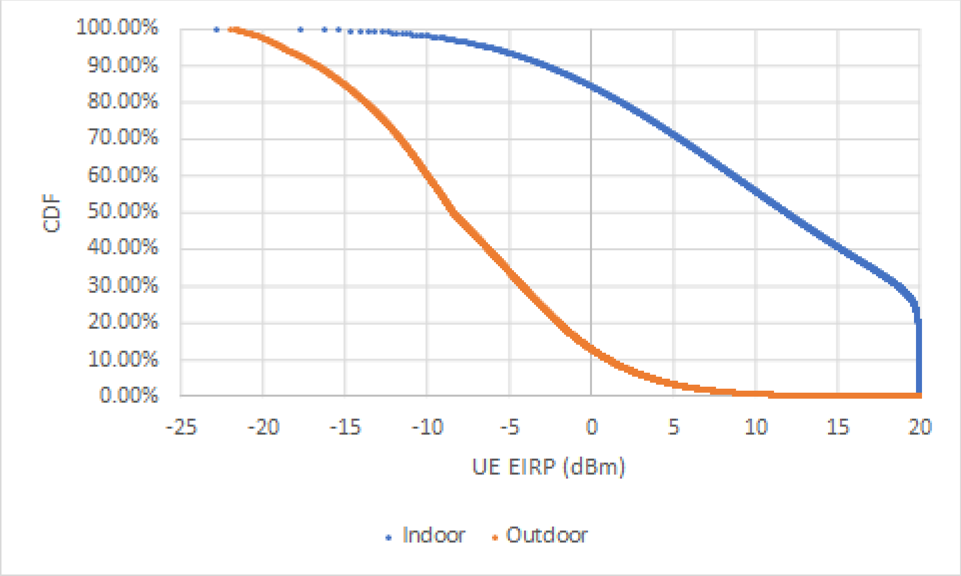


Figure 4-4 and Figure 4-5 show the distribution of 12 GHz macro-cell and small-cell base station (respectively) boresight azimuth and elevation angles (or, in the case of terrestrial 12 GHz base stations, downtilt) for interference events with single-entry I/N > -15 dB. The results confirm that all pointing directions were simulated.

Figure 4-4: 12 GHz Macro-cell Base Station Boresight Elevation Angle (y-axis) Versus Azimuth (x-axis)

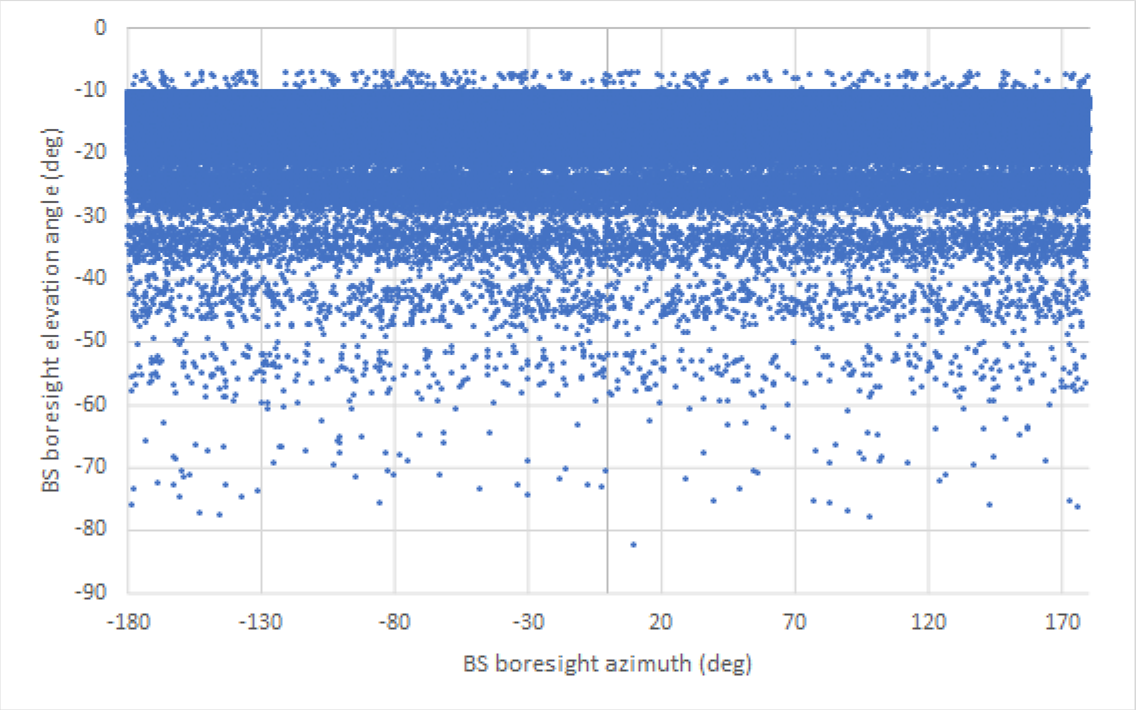
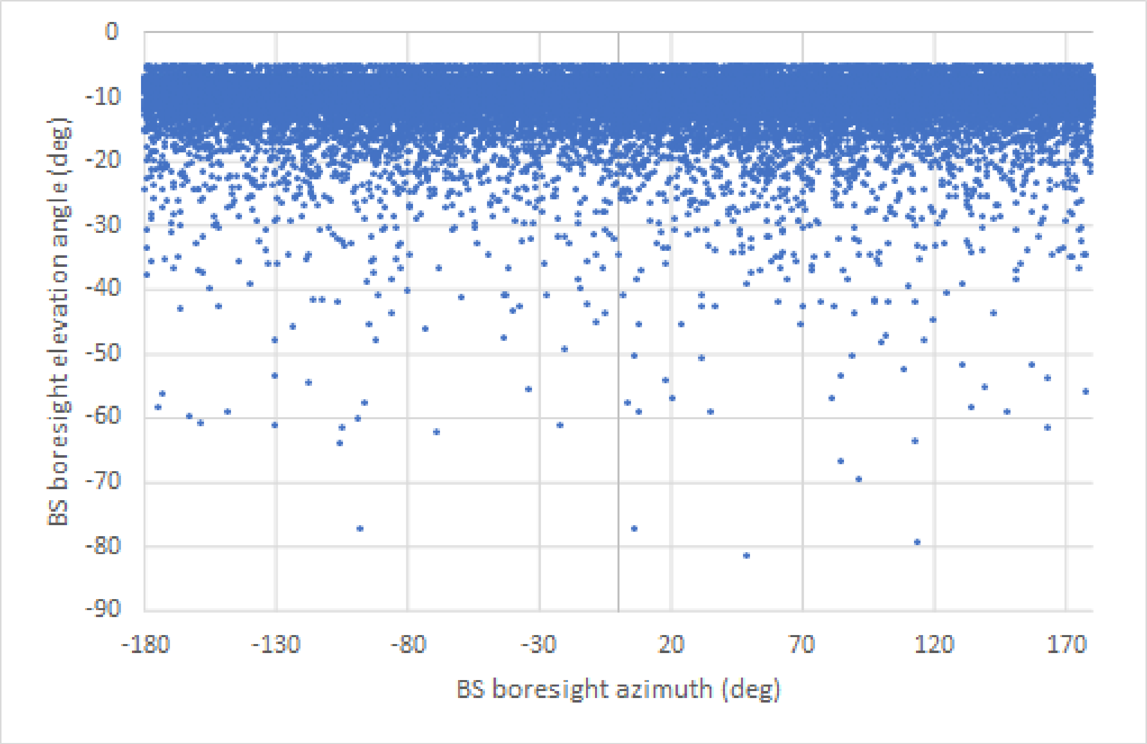


Figure 4-5: 12 GHz Small-cell Base Station Boresight Elevation Angle (y-axis) Versus Azimuth (x-axis)



As mentioned earlier, high I/N interference events occur when the 5G transmitter is close to the Starlink terminal and/or when the Starlink terminal is within the 5G transmitter's main beam (in the case of the base station).

4.2. Conclusions

Uncoordinated 5G broadband can coexist with Starlink NGSO FSS operations. RKF uses algorithmically populated models for siting terrestrial 5G and NGSO FSS infrastructure throughout CONUS. The 5G network's deployment closely replicates existing terrestrial mobile network infrastructure deployed by the major national wireless providers. RKF's Starlink user terminal deployment model is informed by, and corresponds to, the RDOF deployment areas SpaceX has committed to serving and mirrors the deployment model satellite operators and analysts anticipate will maximize the value proposition NGSO FSS can offer consumers.

RKF then uses the terrestrial and satellite network models to assess the potential for sharing in the 12 GHz band between a diversified and robust set of 5G network operations and a much larger-than-anticipated number of Starlink terminals that receive signals from the NGSO FSS satellites SpaceX intends to deploy. RKF finds the potential for Starlink terminals to receive emissions in excess of a nominal I/N value of -8.5 dB will occur in only 0.888% of Starlink terminals deployed over CONUS. Moreover, this figure very likely overstates the interference potential of 5G networks into the NGSO FSS terminals because RKF's modeling uses conservative assumptions biased against a finding of coexistence and incorporates none of the site coordination measures operators routinely employ.

Few, if any, of the 0.888% of nominally affected Starlink terminals will experience service interruption, or even service degradation, in actual practice for several reasons. *First*, the study uses a variety of conservative assumptions that tend to overstate the likelihood of exceeding nominal interference thresholds for the satellite terminals. *Second*, the model does not implement any of the case-by-case mitigation measures that operators routinely employ to mitigate the potential for interference in the ordinary course of business (and that – if needed – are particularly easy to implement before systems are widely deployed). *Third*, the Starlink terminals have access to 1,500 megahertz of spectrum that is not co-frequency with the 5G infrastructure and UE envisioned for deployment in the 12 GHz band; these additional frequencies provide an operational safe harbor for Starlink users in the unlikely event that a nominal interference event were to occur. RKF's findings are clear: licensed 5G services can successfully coexist with authorized NGSO FSS operations in the 12 GHz band.

RKF's analysis concludes that the impact of a nationwide deployment of licensed 5G services on Starlink NGSO FSS is minimal to non-existent. Several factors account for the highly favorable coexistence environment in the 12 GHz band. *First*, NGSO satellite constellations that are designed to provide broadband internet access typically include thousands of satellites; therefore, user terminal operation is typically limited to comparatively high elevation angles. *Second*, both the base stations and user equipment that comprise terrestrial 12 GHz systems are all relatively close to the ground and therefore operate at low elevation angles. *Third*, 12 GHz base stations often utilize antenna downtilt to avoid self-interference, which also further limits the risk of interference to NGSO user terminals. *Fourth*, 5G macro-cell base stations in 12 GHz will use beamforming, which further focuses their radiated energy on the UEs being served. *Fifth*, the primary markets for NGSO user terminals are in less densely populated areas, whereas 12 GHz terrestrial systems will be primarily deployed in areas of greater population density. *Sixth*, both NGSO systems and 12 GHz terrestrial systems are designed to operate in – and mitigate – an interference-prone environment.

Taken together, these and other factors allow RKF to conclude that 5G operations and NGSO FSS operations can successfully coexist in the 12 GHz band.

APPENDIX 1 - STANDARDS, RECOMMENDATIONS & PROPAGATION MODELS USED

During the performance of this study, the following sources were used:

1. Recommendation ITU-R SF.1006-0 (04/1993), "Determination of the interference potential between earth stations of the fixed-satellite service and stations in the fixed service"
2. Recommendation ITU-R S.1428-1 (02/2001), "Reference FSS earth-station radiation patterns for use in interference assessment involving non-GSO satellites in frequency bands between 10.7 GHz and 30 GHz"
3. ETSI TR 103 399 V1.1.1 (2019-04) Technical Report, "System Reference Document: Fixed and in-motion E/S communicating with Satellites in NGSO in the 11 GHz to 14 GHz frequency band"
4. Report ITU-R M.2135-1 (12/2009), "Guidelines for evaluation of radio interface technologies for IMT-Advanced"
5. 3GPP TR 38.820 V16.0.0 (2020-06), "3rd Generation Partnership Project; Technical Specification Group Radio Access Network; NR; 7 - 24 GHz frequency range (Release 16)"
6. Recommendation ITU-R F.1336-5 (01/2019), "Reference radiation pattern of omnidirectional, sectoral and other antennas for the fixed and mobile services for use in sharing studies in the frequency range from 400 MHz to about 70 GHz"
7. Recommendation ITU-R F.758-7 (11/2019), "System parameters and considerations in the development of criteria for sharing or compatibility between digital fixed wireless systems in the fixed service and systems in other services and other sources of interference"
8. Recommendation ITU-R P.530-17 (12/2017), "Propagation data and prediction methods required for the design of terrestrial line-of-sight systems"
9. Recommendation ITU-R P.2109-1 (08/2019), "Prediction of building entry loss"
10. WINNER & Information Society Technologies, WINNER II Channel Models Part 1
11. 3GPP TR 38.901 V16.1.0 (2019-12) Technical Report, "3rd Generation Partnership Project Technical Specification Group Radio Access Network Study on channel model for frequencies from 0.5 to 100 GHz (Release 16)"
12. Irregular Terrain Model (ITM)
13. Recommendation ITU-R P.452-16 (07/2015), "Predication procedure for the evaluation of interference between stations on the surface of the Earth at frequencies above about 0.1 GHz"
14. Recommendation ITU-R P.2108-0 (06/2017), "Prediction of clutter loss"