Shannon

INTERFERENCE MITIGATION

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I. Introduction

The following analyses are updated from the interference mitigation analyses Lynk initially submitted to the Commission in July 2018. Like then, Lynk's engineering and spectrum team computed that the probability of harmful interference will be non-existent regarding the testing under the current experimental request. The analyses below address GSM use, but the corresponding LTE analyses would result in the same answer of no harmful interference because the signal energy levels scale accordingly due to the LTE eNodeB and GSM BTS effectively having equivalent EIRP.

The Lynk system uses a specific GSM or LTE channel licensed to a specific operator in any given test area. The downlink signal that reaches the Earth from the spacecraft is very low with respect to terrestrial towers, and is intended to be the "tower of last resort". Therefore, the spacecraft's transmission will not successfully compete or interfere with terrestrial communications because this low signal power level and geospatial and protocol factors will preclude harmful interference in all instances. Out of an abundance of caution, Lynk will select testing sites in quiet areas/zones—i.e., locations outside cell tower coverage. Furthermore, Lynk will conduct the tests with the express cooperation and participation of the terrestrial licensee. Lynk's primary objective is to accumulate data to validate these assumptions and provide a design baseline for enhancements to the Lynk's network for delivering and improving cellular service for the public good.

While the methodology presented below was applied to U.S. data, the methodology as well as the numerical and analytical conclusions are valid internationally.

II. Proximity Interference Analysis

This interference analysis considers any competition with terrestrial towers in three separate cases with respect to the area illuminated by the satellite—i.e., Urban, Suburban/Rural, and Remote User. The analysis considers geospatial, frequency, time and protocol aspects to harmful interference and applies these processes sequentially to establish the conclusion. On the next page, Figure 1 summarizes the interference analysis in a process flowchart in which each subsequent individual process further reduces the chance for harmful interference. The flowchart reads from top left to bottom right, and it uses color-coded columns to indicate the dimension being analyzed along that point in the process flow line. Later in the Monte Carlo interference analysis, the exact probabilities for the possible outcomes within this process flow are numerically computed.

In conclusion, no matter which case is considered, there is no chance of harmful interference. Furthermore, as described in the separate Detailed Description of Testing & Operations Attachment, since the proposed testing will only occur for up to two minutes during any testing session, the probability that Lynk will interfere with any user's cellular device on the ground is incredibly low, and the probability that Lynk will impact the user's service is essentially zero.

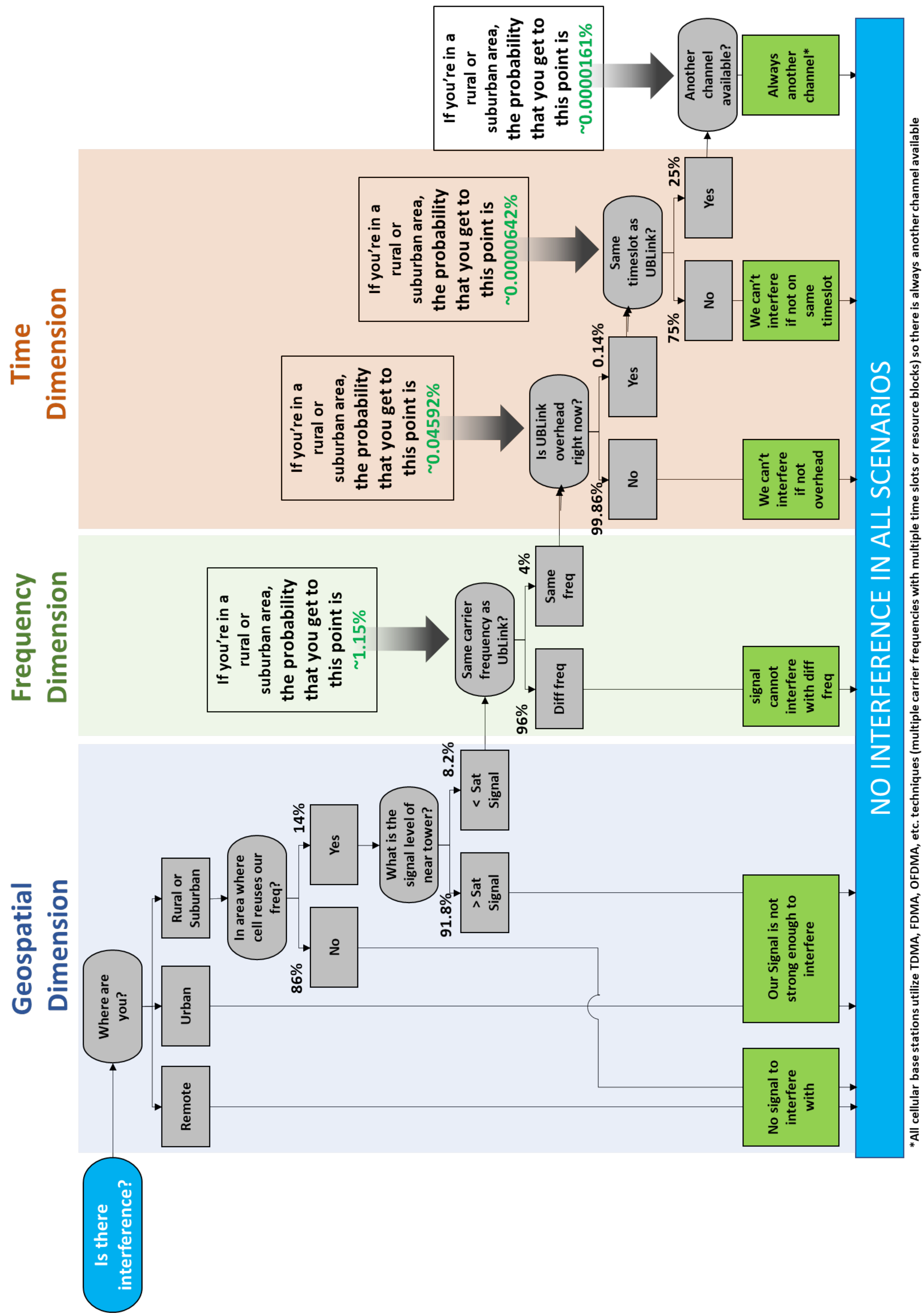

Figure 1 - Process flow chart illustrating that under no scenarios will the Lynk payload create harmful interference.

A. Urban User Interference Potential

Urban environments contain many closely spaced towers to provide ample performance in the presence of significant multipath, shadowing, and attenuation. Additionally, towers are spaced closely to leverage frequency re-use as well as to support numerous subscribers and substantial bandwidth demands. Furthermore, urban deployments of cells are often heterogenous in nature, where cell coverage often involves substantial overlap and interference is avoided using spectral orthogonality among overlapping cells. Typically, higher frequencies are deployed on smaller cells. The only locations in urban geographies where cellular signals drop to levels comparable to those from Lynk's satellite payload are when attenuation from obstructions, multipath, building penetration, etc. occur. At these locations, any signal losses due to attenuation will equally impact the signal from Lynk's satellite payload where it will be reduced to well below the thermal noise limit. **Hence, there is no material case in which a customer in an urban location will suffer impeded service due to the presence of the satellite's signal.**

B. Suburban/Rural User Interference Potential

The terrestrial cellular network is designed to deploy the use of its spectrum to users across three dimensions for maximum throughput: space, time, and frequency. In other words, the spectrum is deployed geographically via expansive frequency re-use and then each cell channelizes communications across the domains of frequency and time using multiple access schemes. Consequently, interference must occur at a particular place and time as well as on a particular carrier frequency, which will only be possible if the terrestrial cellular network cannot automatically reallocate the communications to another available channel.

A satellite payload poses the greatest risk of impacting the service of suburban and rural users because cellular base station coverage areas in these places are generally larger and more spread out, creating more opportunities for these users to operate at the edges of cellular service. Fortunately, at these edges there is usually very few, if any, mobile devices, and thus ample excess capacity. This is known to be the case because economics drive the MNOs to expand their coverage capability until there is too limited population density to merit the investment. In other words, the edge of cellular coverage is intentionally designed to occur in geographies with limited population density.

The following four-pronged analysis details that suburban and rural geographies will experience no harmful interference from Lynk's satellite payload by evaluating the probability of interference from the Lynk payload on a terrestrial cellular network across the three dimensions: space, time, and frequency. Notably, the potential for interference along any one of the three dimensions is unlikely by itself, and when all three dimensions are invoked at the same time, which is highly unlikely, there may be a potential for interference for any given cellular device user in the real world. As shown in <u>Figure 1</u> above, there is approximately 0.0000161% probability that the Lynk payload will create interference to a suburban or rural user's *initial* chosen carrier, and even then, the GSM or LTE device uses a protocol to automatically select another carrier should this extremely unlikely event occur.

Therefore, the following four-pronged analysis shows the final likelihood of actual harmful interference impacting service in suburban and rural geographies as zero.

1. Spatial/Geospatial Impact on Potential Interference

Across the U.S., the analysis finds approximately 1.15% chance of any interference regarding the dimension of space.

The cellular network structure relies on a frequency re-use pattern to avoid self-interference from adjacent cells operating at the same frequency. Since the Lynk's test satellite operates on a single 200 kHz carrier frequency, only a fraction of the towers within the footprint have the potential to be impacted. Typical frequency re-use schemes in suburban and rural geographies are on the order of every seven or nine towers. Hence, the percentage of towers within a footprint that could even share the same co-channel with Lynk's payload would be on the order of 14% in a worst-case scenario as shown in Figure 1 above.

Of the 14% of cellular tower coverage areas, Lynk's payload could only impact the cells at the edge of the tower coverage area. As a result, the central regions of suburban and rural locations and those that abut higher density regions (e.g., urban) would see no impact. Figure 2 on the next page illustrates this, where the design of cell edges for suburban and rural towers are indicated in cases of overlap and no overlap. In geographies where cells overlap, interference is mitigated, but those cells that represent the edge of regional cellular coverage (or stand-alone) are subject to possible interference from Lynk's payload. The only areas that could be impacted within these cells are the slice between the peak signal level from the satellite (approximately -80 to -95 dBm) and -105 dBm, which are generally areas of overlap with adjacent cells. However, at the very edge of regional cellular coverage, these may be the only signals available in some geographies, where very few or no people live or traverse. Below -105 dBm in the GSM protocol, the phones will not work, and so there can be no interference. At or above the satellite signal expressed in dBm—i.e., the upper limit of the payload downlink signal energy—the tower dominates.

Section III, below, contains a Monte Carlo simulation analysis related to the potential geospatial interference factors during the test. The analysis illustrates that the percentage of all land area in the United States that might have access to a signal from only one tower and where the signal from that one tower is between the signal energy received from the satellite and -105 dBm is less than 8.2%. In other words, the theoretical possibility of interference is at most 8.2% of the U.S. geography.

In sum, only 14% of towers representing the 8.2% of the U.S. geography that could possibly experience interference will use the same group of carrier frequencies as Lynk's satellite payload. **Consequently, as shown in Figure 1 above, the probability that there could be potential interference from Lynk's payload solely based on the geospatial criteria is at most 8.2% X 14% = 1.15%.**

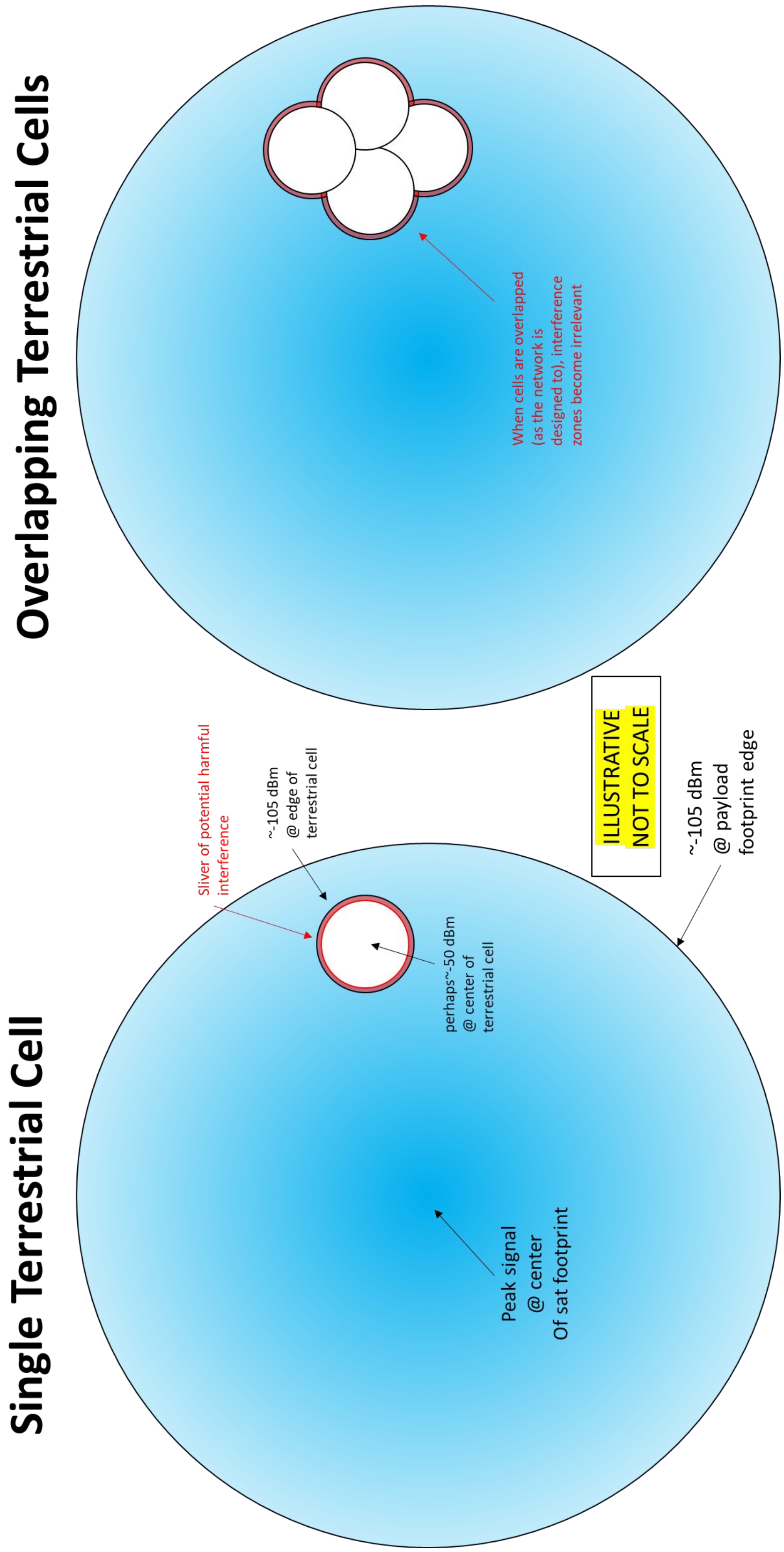

Figure 2 - Illustration of how cellular overlap defends against harmful interference from Lynk's payload signals. The only areas of possible interference are geographies where there is no continued build out of towers.

2. Time Impact on Potential Interference

The Lynk payload can potentially interfere only 0.035% of the time across the proposed testing period. For any given test site, Lynk's payload will be operational for about twenty minutes over the span of ten days of testing, which represents 0.14% of the total time over those days. Furthermore, the signals from the payload will operate using the frame structures of the GSM protocol, meaning that the signals from the transmitter will occur in bursts in an individual timeslot across eight potential timeslots in the TDMA frames. Notably, the broadcast control channel ("BCCH") will always occupy the first timeslot. Since Lynk's satellite will only communicate with no more than one GSM mobile phone at any given point in time (to move a message from one mobile phone to the other), the downlink carrier frequency will remain quiet on at least six out of the eight downlink timeslots. Therefore, from the perspective of the timing dimension, the probability that there will be interference during the payload's transmissions is 25%. In other words, there is a 25% chance that a burst from the payload on the downlink channel will coincide with a burst from a terrestrial cellular tower on the downlink channel during the exact timeslot. **Thus, the temporal probability that there is interference is 25% X 0.14% = 0.035%.**

3. Frequency Impact on Potential Interference

The probability of potential interference on a spectral dimension is likely not higher than 4%. A typical cellular tower utilizes at least 5 MHz of spectrum. For any given cellular tower below the spotbeam of Lynk's payload that operates across 5 MHz of spectrum, 200 kHz represents 4% of the spectrum on any given tower in the GSM case.

4. All 3 Dimensions Impact on Potential Interference

There is zero chance that Lynk's testing will interfere with a user's device based on the concatenated probability of a user's device meeting all of the following criteria:

a. operating on a cell tower in a rural area near the test site with a cell signal lower than the signal from Lynk's payload,
b. on the exact frequency Lynk is using for a test, and
c. at the exact time that Lynk's payload is overhead

The numerical value is 1.61 in 10 million (1.15% X 0.035% X 4% = 0.0000161%). Unlikely as that is, the GSM and LTE protocols are designed to be resilient to various issues with individual carriers that may temporarily degrade performance of an individual user device with individual carriers—e.g., switching to a non-impacted carrier. Consequently, should this highly unlikely event occur, the device and its base station will simply move to another available carrier. Moreover, the user density is very low at the fringes of the cellular network, assuring plentiful supply of alternative carriers and making the final probability of harmful interference zero.

C. Remote User Interference Potential

There is no potential of Lynk causing interference under the requested testing authorization. Remote users, by definition, are those who reside in regions in which there are no towers sufficiently close to produce service. These users are enabled by the Lynk service without which they would have either no or unusable connectivity, creating no interference concern.

III. Monte Carlo Interference Analysis

A. Sourcing the Data

The following Monte Carlo numerical analysis utilizes location data of cellular towers throughout the United States. The locations are recorded in the FCC Universal Licensing System Database and extracted for various uses on the Homeland Infrastructure Foundation-Level Data ("HIFLD").[1] The cellular tower location data is comprised of 23,499 transmitters represented in an equal number of rows. Notably, some of the towers contain multiple transmitters. Moreover, the data does not contain every cellular tower in the United States, but it is likely representative of macro cells, which is sufficient for this analysis because micro, pico, and femto cells do not represent likely candidates of harmful interference from Lynk as they are predominately located in either urban settings, indoors, or underground and perform over very short distances, or operate on different bands.

B. Analyzing the Data

Lynk analyzed the data supporting the Monte Carlo numerical analysis by porting a CSV file into in the MATLAB environment and creating location vectors for each tower. Using the latitude and longitude of the towers, a WGS84 Earth model is assumed to calculate the corresponding ECEF locations of the cellular towers in 3-D space to account for the curvature of the Earth—see Figure 3 on the next page.

To examine the distribution of towers that might be impacted by the satellite payload, an analysis was conducted using the positions of each cellular tower to calculate the distance to its nearest neighboring tower. Figure 4 on the next page represents the probability distribution function of the distance to the nearest tower for cellular towers.

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[1] *See* Cellular Towers, Homeland Infrastructure Foundation-Level Data (HIFLD), at: https://hifld-geoplatform.opendata.arcgis.com/datasets/cellular-towers?geometry=-82.962%2C37.982%2C-81.901%2C38.171; *see also* https://www.arcgis.com/sharing/rest/content/items/0835ba2ed38f494196c14af8407454fb/info/metadata/metadata.xml?format=default&output=html (containing the meta-data for the analyzed cellular tower dataset, which was last updated December 20, 2016, by a Senior Engineer at the FCC).

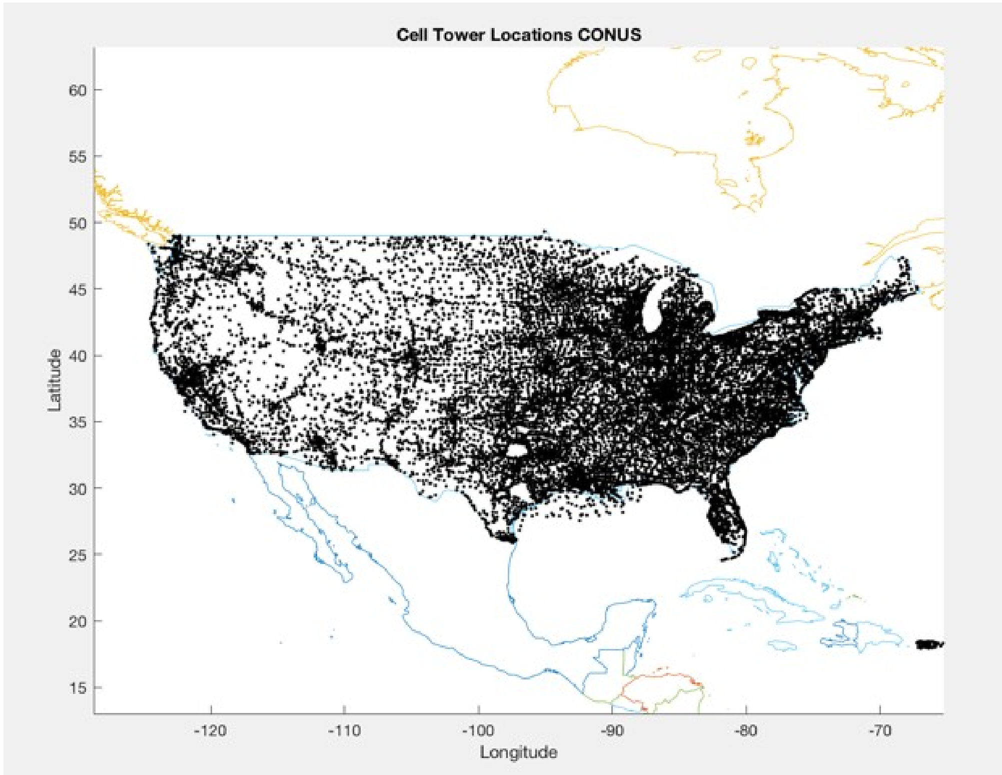

Figure 3 - The latitude and longitude positions of each cellular tower site in the FCC database.

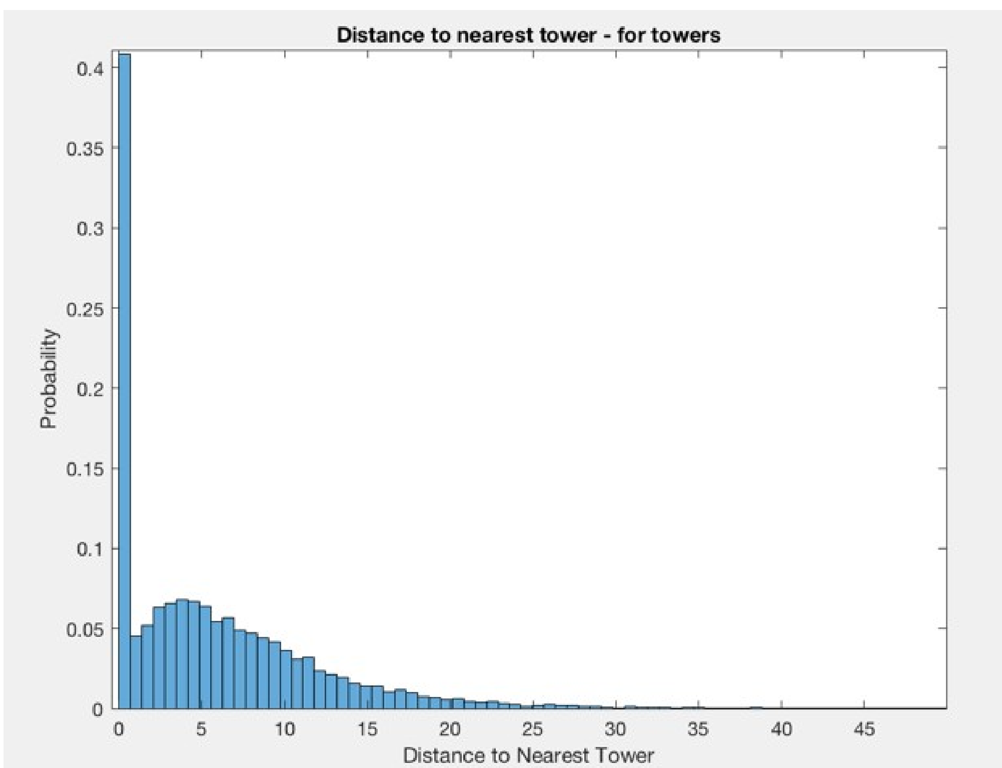

Figure 4 – Provides the probability of the distance to the next nearest cellular tower for any given tower in the FCC database.

1. Monte Carlo RF Propagation Simulation

To generate a model for the strongest signal levels at any point across the country, Lynk utilized the tower location data and a U.S. border file for the locations of U.S. borders. Lynk then developed a Monte Carlo algorithm to generate nearly one-million points across the United States, in which each point is a location randomly generated in latitude and longitude. The latitude and longitude positions are used to calculate ECEF positions for every Monte Carlo point.

The following assumptions (code snippet taken from analysis script) were made for critical signal propagation characteristics:

[redacted]

The path loss exponent of 2.8 was determined to be well aligned with the suburban/rural Hata model, which seemed suitable for the current analysis.

The Monte Carlo simulation points are used as the anchors for a long loop. For each point in the simulation set, the nearest cellular tower is computed. Given the distance to the nearest tower, the strongest signal energy is computed using a simplified exponential path loss model. The EIRP from the base station is assumed to be decremented by the calculated path loss estimate. Also, for each point, the second nearest tower is also computed, along with its distance and the signal energy from it.

Once the loop is executed, the one-million simulation points all have a corresponding set of four conditions:

- distance to nearest tower,
- approximate signal energy from nearest tower,
- distance to second nearest tower, and
- approximate signal energy from the second nearest tower.

2. Plotting a Revealing Story

The following plots tell a revealing story: Most geographies in the United States have existing cellular coverage signal levels via a plurality of towers that prevent interference from any signal from the Lynk transmitter.

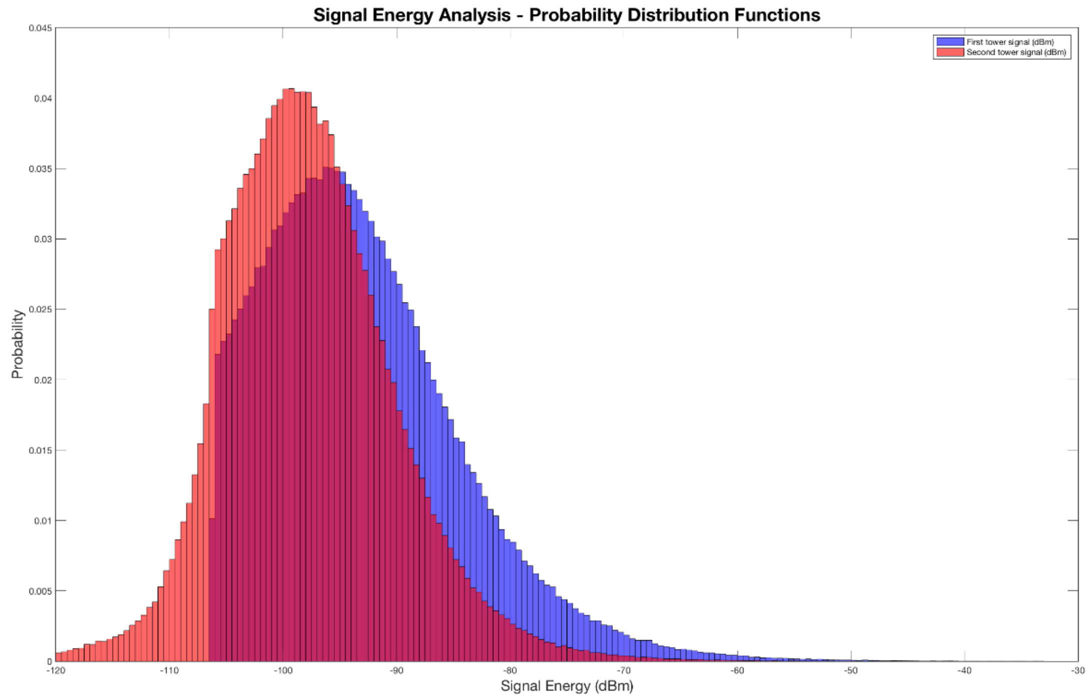

Figure 5 - The probability distribution function of the signal energies calculated across all the Monte Carlo points in the simulation, where the: Blue Histogram represents the signal energy from the nearest, first tower to the Monte Carlo location point; and the Red Histogram represents the signal energy from the second nearest, second tower to the Monte Carlo location point.

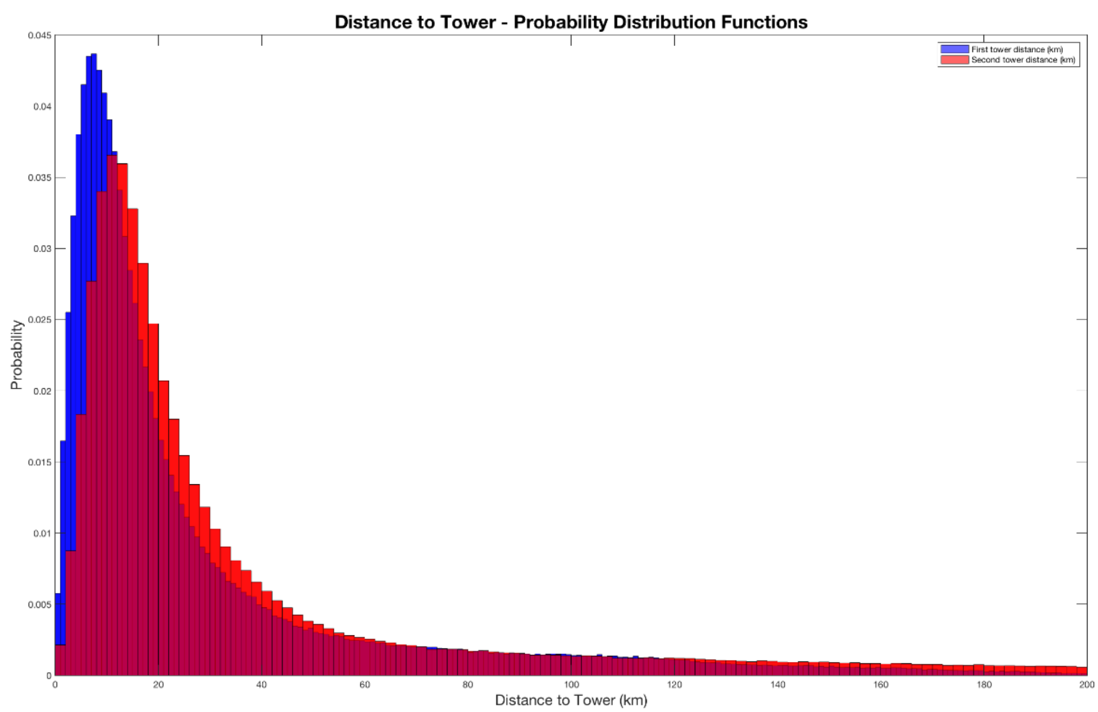

Figure 6 - The probability distribution function of the nearest tower and second nearest tower to all Monte Carlo simulation points, where the nearest tower is in blue and the second nearest tower is in red.

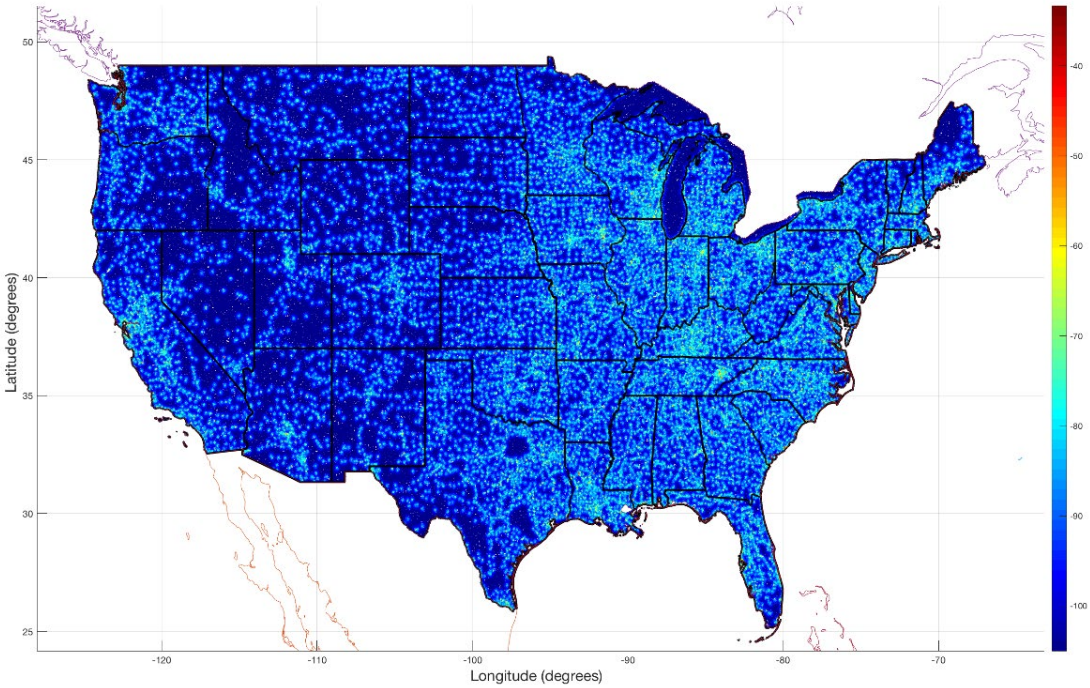

Figure 7 - The resulting cell signal across CONUS from the Monte Carlo simulation, where each point plotted is color-coded based on its signal energy ranging from -105 dBm to the highest signal energy calculated in the simulation (deep blue means no connectivity).

C. Conclusion

The percentage of points that meet all the following corresponding conditions to each point in the Monte Carlo simulation is less than 8.2%:

1. The signal energy level from the nearest tower is greater than -105 dBm;
2. The distance to the nearest tower is less than 35 km;
3. The signal energy level from the second nearest tower is less than -105 dBm; and
4. The distance to the second nearest tower is less than 35 km;
5. The signal energy level from the nearest tower is higher than that of the highest signal energy level in the satellite payload spotbeam.

Figure 8 below represents the percentage of points in the Monte Carlo simulation as a function of varying signal energy level in fifth condition described above. The plot illustrates that increasing the EIRP of the satellite payload has incremental impact on the interference analysis. Consequently, the first four conditions alone bound the potential for interference to $\leq$ 8.2% for the Spatial/Geospatial factor in the interference analysis above.

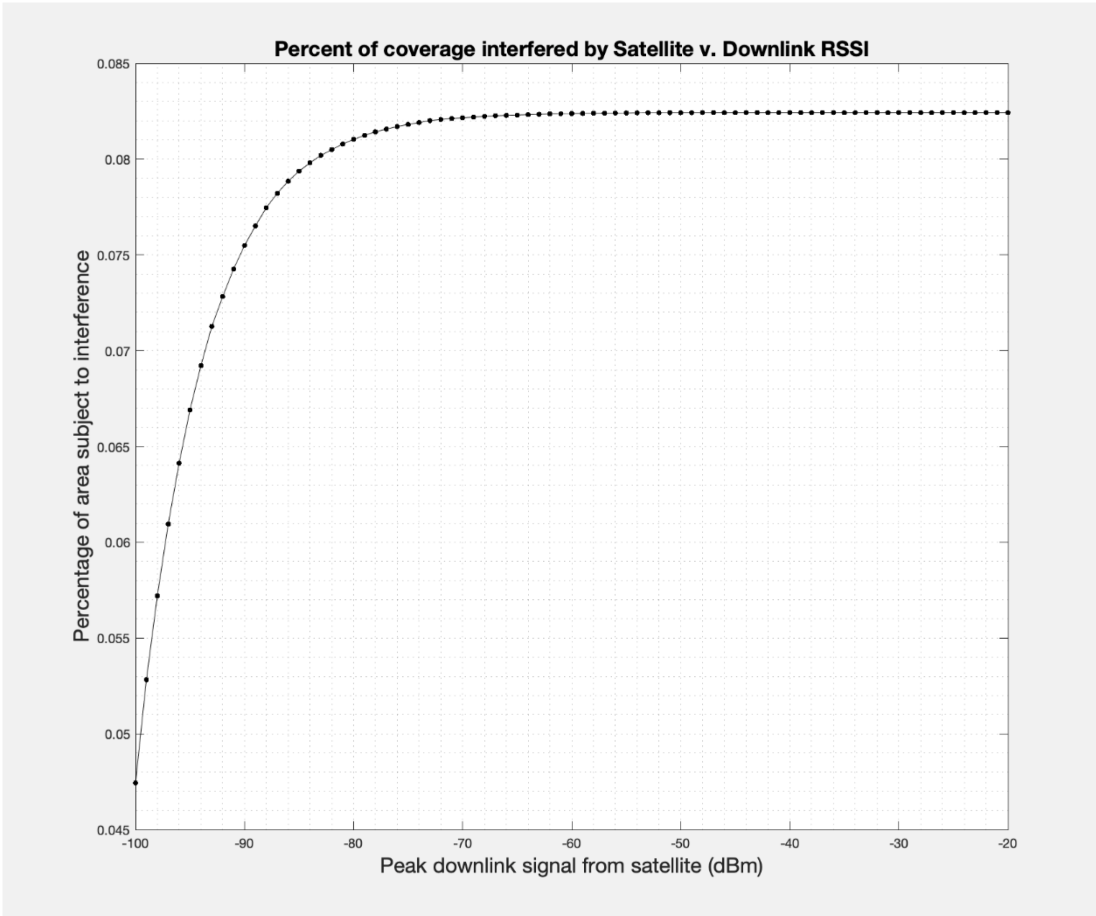

Figure 8 - Plot showing the percentage of U.S. geography with existing cellular coverage that "could" experience interference as a function of the downlink RSSI from the satellite; as EIRP on the satellite (gain and transmit power) increases, the downlink RSSI increases linearly.

Note that the calculation details are listed below and are based on a total number of points in the simulation equaling exactly 967,104.

1. Number of points in coverage = 299,127
2. Number of points out of coverage = 667,977
3. Percentage of America Geographically "Covered" per this model = 69.07%
4. Percentage of America Geographically "Not Covered" per this model = 30.93%
5. Percentage of all land area with possible interference from Lynk and *no access to a second tower* ≤ 8