Technical Analysis of Ligado Interference Impact on Iridium User Links

September 1, 2016
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1 Background

The Federal Communications Commission has requested comment on Ligado’s proposed out-of-band emissions (OOBE) limits, as described in Ligado’s modification applications for its L-band ancillary terrestrial component (ATC) terminals and base stations. This technical analysis provides an assessment of the harmful interference Ligado’s proposed emissions will cause within the Big LEO band used by Iridium for delivering voice, data and messaging services to end users.

Iridium provides pole-to-pole, true global mobile satellite services through a constellation architecture of 66 satellites in low earth orbit. Since the system was launched in the late 1990s as primarily a provider of voice call services, it has evolved beyond primarily voice to provide a suite of data, two-way messaging, broadcast messaging, netted push-to-talk and broadband services across a wide range of terrestrial, maritime, aviation, machine to machine and government markets.

2 Description of Interference Problem

Ligado’s modification applications provide proposed operational characteristics for ATC base stations and mobile user terminals. Ligado’s proposed operation of user terminals in the 1627.5-1637.5 MHz band, which is immediately adjacent to Iridium’s operations in the 1617.775-1626.5 MHz band, will produce harmful interference to Iridium end users. In some cases, the interference is so severe that Iridium services would be [BEGIN CONFIDENTIAL] [END CONFIDENTIAL]. Ligado’s use of user terminals at 1646.5-1656.5 MHz does not create issues for Iridium.

2.1 Ligado User Terminal Interference into Iridium User Terminals

The potential for Ligado’s proposed operations to cause significant interference into Iridium user terminals manifests itself in two major ways:

- OOBE within Iridium’s frequency band would significantly inhibit Iridium communications; and
- Millions of ubiquitously deployed ATC and/or terrestrial-only LTE or 5G user terminals would greatly increase the probability of these terminals operating near an Iridium terminal.

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All Iridium user terminals transmit and receive in the 1617.775-1626.5 MHz band.\(^3\) Ligado has proposed an OOBE mask that, while purportedly affording protection for some GPS receivers, does not sufficiently protect Iridium receivers in the immediately adjacent band. In the upper portion of Iridium’s band, this OOBE mask has emission levels [BEGIN CONFIDENTIAL]

[END CONFIDENTIAL]

Given that a single Ligado user terminal would produce such harmful levels of interference, the number, density and proximity to Iridium terminals all play a major role in assessing aggregate interference into Iridium terminals.

A more detailed analysis of this interference impact is described in sections 3 and 4 below.

### 2.2 Iridium Would Be Uniquely Impacted by Ligado Interference

#### 2.2.1 Ligado Interference to Iridium is Distinct from GPS

The potential for Ligado ATC interference into GPS receivers has been studied exhaustively for many years. Many (if not most) of these analyses have focused on the “proximity” scenario of a Ligado terrestrial base station or user terminal, in close proximity to a GPS receiver, producing in-band emissions that overload the GPS receiver front end. Though Ligado OOBE into GPS receivers have also been studied, significant concerns remain about GPS receiver overload due to GPS receiver selectivity in Ligado’s transmit bands.

In contrast to the GPS interference problem, Ligado OOBE within Iridium’s band produce interference severe enough to significantly impact Iridium services without having to overload the Iridium receiver RF front end when a Ligado terminal is in close proximity to an Iridium user terminal. While overload of the Iridium receiver front end may result from large numbers of transmitting Ligado terminals in close proximity to an Iridium terminal, the more impactful interference scenario studied in this report is due to Ligado’s OOBE alone.

#### 2.2.2 Ligado is Distinct from Other Mobile Satellite Service Interference

By FCC design, and consistent with sound spectrum management principles, satellite services have been allocated spectrum in adjacent bands with rules to ensure the coexistence of multiple providers. Like all other radiocommunication systems, Iridium is designed to receive and withstand some level of interference from other systems that share the band or reside in adjacent bands. In Iridium’s case, those in band and adjacent band interferers are, like Iridium, mobile satellite service (MSS) systems. Non-geostationary orbit (NGSO) MSS systems Globalstar and Iridium were provided the Big LEO band allocation (1610.0-1626.5 MHz, Earth-to-space, 1613.8-1626.5 MHz, space-to-Earth), and GSO MSS systems such as Inmarsat, Thuraya and Ligado were allocated the adjacent 1626.5-1660.5 MHz (Earth-to-space) band. These allocations were made under the assumption that MSS systems could co-exist. Furthermore, these allocations are generally devoid of other terrestrial transmit services that would be interference threats to these MSS systems. MSS systems and terrestrial mobile systems generally have

\(^3\) Iridium is currently licensed to use this band, but the Iridium system supports transmit and receive in the 1616.0-1626.5 MHz band, and on multiple occasions has been granted STAs to use this extended spectrum to support emergency relief efforts around the world.
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threats to these MSS systems. MSS systems and terrestrial mobile systems generally have contrasting consumer markets and user profiles. Over the last decade these markets and profiles have changed significantly. Terrestrial mobile networks have expanded their coverage areas and have matured through multiple generations of user access technologies (e.g., LTE) that support vastly greater capacities. The deployment of high-capacity 5G networks will further expand and densify terrestrial networks, enabling the use of a substantially greater number of devices.

Likewise, Iridium’s user base characteristics have changed radically since the system was launched in the late 1990s as a voice-only system. Iridium currently supports over 820,000 subscribers, many of them using data messaging services. These data services are leveraged by machine-to-machine (M2M) markets, supervisory control and data acquisition (SCADA) applications, and personal, asset and vehicle/aircraft tracking applications. The Iridium network currently supports millions of these transactions on a daily basis, resulting in these Iridium devices being deployed everywhere throughout the United States, including populated areas.

These Iridium services and user growth trends will continue to expand under Iridium’s second generation system, Iridium NEXT, which was recently licensed by the FCC and is scheduled to begin launching replacement satellites in September 2016. Iridium NEXT will support all legacy services and user equipment while also delivering higher data rate services to meet increasing global throughput demands for land, sea and air mobile communications.

With these issues in mind, Iridium does currently receive interference from Globalstar and Inmarsat MSS systems within the United States. Iridium and Globalstar are co-primary MSS sharers within the Big LEO band and as such are expected to accept limited amounts of interference from each other. These interference levels are manageable due to the low probability of dense numbers of Iridium and Globalstar user terminals being co-located in a small area.

Inmarsat presents a different interference issue for Iridium. Many Inmarsat terminals produce OOBE levels that produce harmful interference to Iridium user terminals when those terminals are co-located. However, most of these Inmarsat terminals have directional (i.e., not omni-directional) antennas that need to be pointed towards the GSO arc with some sidelobe suppression of emissions laterally. Furthermore, there are only several hundred thousand Inmarsat terminals worldwide, making it unlikely that large concentrations of Inmarsat and Iridium terminals would be co-located in a given region.

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3  Ligado Interference Analysis Assumptions, Methodology and Scenario Descriptions

3.1  Interference Analysis Assumptions

This section describes the assumptions regarding Ligado and Iridium system usage and user terminal characteristics as a basis for an interference assessment. Many of the assumptions regarding Ligado system usage are taken from previous studies analyzing potential Ligado interference into GPS.

3.1.1  Single Ligado User Terminal Interference

The foundation for all interference scenarios in this report is based on the individual Ligado user terminal OOBE characteristics. These are provided in Ligado’s modification applications and summarized here.

Ligado user terminals are proposed to have an in-band equivalent isotropically radiated power (EIRP) value of -7 dBW in the 1627.5-1637.5 MHz band. The OOBE mask for these terminals is described as:

- Limit of -34 dBW/MHz between 1625 and 1626.5 MHz; and
- Linearly ramping up from -100 dBW/MHz at 1610 MHz to -34 dBW/MHz at 1625 MHz.

This mask is depicted in Figure 1 below, with OOBE expressed in dBW/30kHz instead of per MHz, because Iridium channels are much narrower than 1 MHz. As Figure 1 shows, the Ligado OOBE at 1618 MHz (near the lower edge of Iridium’s band) is -80 dBW/30kHz and is -49.2 dBW/30kHz at the upper edge of Iridium’s band.

![Figure 1: Ligado Proposed Wideband OOBE Mask](image-url)
Ligado user terminals will operate over a range of transmit powers, depending on the distance between the user terminal’s corresponding base station, propagation conditions and user terminal power control function. Because this study is assessing interference resulting from OOBE, and not receiver overload due to Ligado in-band emissions, Ligado’s proposed OOBE limits are used in this study.

3.1.2 Aggregate Ligado User Terminal Interference

Ligado emissions from a single user terminal produce a significant level of interference into Iridium user terminals, even at substantial separation distances. Understanding the severity and impact of this interference requires taking into account the number, density and proximity of Ligado user terminals operating near an Iridium user terminal.

There has been much debate over appropriate values to assume for number of Ligado LTE users per cell per 10 MHz channel.\(^6\) The Commerce Spectrum Management Advisory Committee (CSMAC) Working Group 1 (“WG-1”) provided a “typical” value of 18 simultaneous users per LTE cell (base station).\(^7\) Other studies have used higher numbers, on the order of hundreds, consistent with LTE technology capabilities. For example, RTCA Special Committee 159 (SC-159) used a “nominal” value of 300 users per cell (while noting that a maximum of 1000 users was possible) when studying the impact of Ligado interference into aeronautical GPS receivers.\(^8\)

For purposes of this paper, we analyze likely interference caused by a single Ligado transmitter and also aggregate interference assuming 18 simultaneous users per LTE cell, consistent with the work of CSMAC WG-1. In addition, Ligado terrestrial user terminals are expected to be used in all types of regions in the United States – urban, suburban and rural. Urban/suburban areas are expected to be covered by base stations with inter-site distances (ISDs) of about 2.0 km (WG-1 used a value of 1.7 km and RTCA SC-159 used a value of 2.2 km), while rural regions are expected to have ISDs of 7 km (a WG-1 value). Inter-site distances of 2.0 and 7.0 km result in cell site radii of 1.0 and 3.5 km, respectively.

The analysis provided herein will take into account this range of potential values, as summarized in Table 1.

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\(^6\) There is even less certainty about what assumptions can be made for future 5G deployments, which makes it difficult to model interference concerns in a 5G environment, but it is equally important to recognize that the transition to 5G also raises concerns.


3.1.3 Iridium User Terminal Receiver Characteristics

Iridium user terminal vulnerability to interference is predicated on user terminal receiver noise floor and antenna pattern, and on user deployment characterization.

Iridium user terminals are represented by various product lines supporting a variety of mobile satellite services, including circuit switched voice and data, data messaging, paging, netted (push-to-talk) communications and broadband communications. The receiver performance across these terminal types, however, may be characterized by a common receiver noise floor, equivalent to -199.6 dBW/Hz. The fundamental Iridium channelization is based on channel spacing of 41.7 kHz, with an occupied bandwidth of 33.5 kHz (irrespective of Doppler shift). Therefore, noise measurement bandwidths of 30 kHz are appropriate for assessing Iridium receiver performance, since this measurement bandwidth is similar to the bandwidth of an Iridium channel. The user terminal noise floor of -199.6 dBW/Hz converts to a per 30 kHz value of -154.8 dBW/30kHz, which is the limit against which Ligado interference will be assessed. Accordingly, interference analyses in this study will be provided in terms of interference to noise (I/N) ratio. The aggregate interference threshold for Iridium transceivers used in this report is I/N = -6 dB (deltaT/T = 25%), or an interference level that results in a decrease in link margin of 1 dB. I/N = -6 dB is a typical value chosen in interference studies,9 but usually in studies where same services (e.g., FSS to FSS) or different services (e.g., FSS to FS) are sharing a common frequency band. In fact, the Iridium system design specification assumes a single entry interference criterion of I/N = -12.2 dB (deltaT/T = 6%). In situations like the one being studied here, an out-of-band interferer like Ligado is often subject to an interference threshold of I/N = -20 dB (deltaT/T = 1%).10 Nevertheless, an I/N = -6 dB will be assumed for the aggregate interference from Ligado terminals.

Iridium user terminals also support a variety of different antenna technologies and forms, but all are generally low gain, hemispherical pattern antennas having gain of unity (0 dBi), averaged over the distribution of elevation angles to the nearest satellite. As a low earth orbiting (LEO) satellite constellation, Iridium users may be communicating with the nearest satellite at any given azimuth, at any given elevation angle down to 8 degrees, and at any given point in time.

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9 See, e.g., Int’l Telecom. Union [ITU], Recommendation S.1432, available at https://www.itu.int/rec/R-REC-S.1432/en see also SC-159 Assessment, supra note 9, Executive Summary (also using a 1 dB increase in noise floor criteria).

10 See, e.g., ITU Recommendation S.1432, supra note 10.
anywhere on earth. As a result, Iridium user equipment must have antennas that can “see” the entire sky. An Iridium user terminal antenna can be expected to have a typical gain of about -3 dBi at 0 degrees elevation, while having peak gain of 3 dBi at higher elevation angles.

Ligado’s proposed OOBE levels vary within the Iridium band. Iridium user services are not segmented within the Iridium band, other than the upper 500 kHz (1626.0-1626.5 MHz), which is a downlink only band used for some Iridium broadcast services [BEGIN CONFIDENTIAL]

[END CONFIDENTIAL] The rest of Iridium’s band is used uniformly for uplink and downlink transmissions for all Iridium services. The particular frequency channel used by an Iridium terminal, for transmit or receive, is directed by the Iridium satellite and is not selectable by the Iridium user terminal. Furthermore, the Iridium user may be handed off to other frequency channels at any point during a transaction due to the dynamic movement of the satellites and corresponding satellite beams on the Earth’s surface.

The last assumption to consider for Iridium transceivers is that these transceivers need to be operating in duplex mode throughout a given communications session in order to maintain the link with the satellite. Regardless of whether communications payload is being transmitted only on the uplink or downlink or in both directions, link maintenance signaling information is continuously being transferred between the user terminal and satellite for all of these cases. For example, when an Iridium user sets up an M2M data session in order to originate data for transmission to the network, that user’s receiver must be operational during the entire session to maintain the link, even if no payload data is being delivered to the user on the downlink. This is important when assessing the impact of interference into the Iridium user device’s receiver; protection of the user terminal receiver is critical to maintaining the communications path.

3.1.4 Signal Propagation Models

This study assumes two different basic propagation models: free space path loss (FSPL), appropriate for short, line-of-sight separation distances between interfering terminals; and a terrestrial propagation model, often used in land mobile applications. While much work has been done in previous Ligado user terminal interference studies attempting to choose appropriate signal propagation models across a range of interference scenarios, no clear consensus exists as to which model is the most appropriate. This study seeks to simplify the analysis such that general conclusions may be drawn.

The FSPL is described by the following well-known expression,\(^{11}\) where \(d\) is the separation distance in meters and \(f\) is the carrier frequency in hertz:

\[
\text{FSPL (dB)} = 20 \log(d) + 20 \log(f) - 147.55
\]

Because this model assumes line-of-sight between the interfering Ligado terminal and victim Iridium terminal receiver, this model is applicable for separation distances less than or equal to 100 meters. It may also be appropriate for longer distances when line-of-sight conditions exist, such as when the interference source or victim receiver is airborne.

The Hata-Okumura median path propagation path loss model is used in this report for modeling losses at longer distances. Both the Ligado and Iridium user terminal heights (above ground) were selected as 2 meters, which provides for a propagation loss significantly higher than the FSPL model.

Because the FSPL model has greater validity for separation distances on the order of 100 meters and less, while the Hata-Okumura model has greater validity for separation distances greater than 1,000 meters, path losses in the range 100 to 1,000 meters were extrapolated between the two models and included with the Hata-Okumura model. The result is shown in Figure 2 below.

![Path Loss Models](image)

**Figure 2: FSPL and Hata-Okumura Path Loss**

### 3.2 Interference Scenarios

Evaluation of the impact of proposed Ligado user terminal interference to Iridium user terminals depends on a number of factors as discussed above, including number and density of Ligado user terminals and signal path loss. These variables are captured in the three interference scenarios below, starting with a baseline interference assessment with a single Ligado user terminal, followed by scenarios involving low and high density Ligado terminal deployment.

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12 The model used in this report is identical to the model used by RTCA SC-159 in their report on LightSquared interference into GPS. See SC-159 Assessment, at 46 & App. B at B-6.
3.2.1 Baseline Interference
The first interference scenario analyzed serves as a baseline assessment in which a single Ligado user terminal is transmitting within line-of-sight of an Iridium terminal. The FSPL propagation model is used in this scenario at various separation distances up to 1,000 meters. As noted in section 3.1.4 above, the FSPL model may be appropriate for separation distances up to 1,000 meters under certain line-of-sight conditions, including the case in which a Ligado user terminal is on the ground and has line-of-sight to an Iridium aeronautical terminal at low altitudes.

In this baseline scenario, as well as all aggregate interference scenarios below, interference is assessed at the upper edge of the Iridium band. The interference decreases as one moves across the band, but remains substantial throughout.

3.2.2 Aggregate Interference: Low Density Ligado Terminal Deployment
This aggregate interference scenario assumes 18 Ligado users per cell/base station (or 6 users per sector) with rural-type inter-site distances of 7 km, consistent with assumptions made in the WG-1 study and report. The resulting Ligado user terminal density is then distributed across multiple interference radii from an Iridium user terminal.

This scenario is analyzed under two propagation conditions: one under the FSPL model and one under the Hata-Okumura model.

3.2.3 Aggregate Interference: High Density Ligado Terminal Deployment
This aggregate interference scenario assumes 18 Ligado users per cell as above, but for smaller urban/suburban inter-site distances of 2 km. Again, the resulting Ligado user terminal density is then distributed across multiple interference radii from an Iridium user terminal.

This scenario is analyzed under two propagation conditions: one under the FSPL model and one under the Hata-Okumura model.

4 Interference Analysis and Impact
4.1 Baseline Interference Results
The baseline scenario demonstrates the severity of interference that Iridium user devices would suffer from Ligado user terminal OOBE transmissions.

In the baseline interference scenario, a single Ligado terminal is assumed at a range of separation distances from an Iridium terminal. The interference power at the Iridium receiver is then calculated under FSPL conditions and compared to the Iridium receiver interference threshold. A positive margin means that the received interference meets (does not exceed) the Iridium receiver interference threshold, while a negative margin means the received interference exceeds the threshold. Any negative margin implies degraded Iridium performance and a reduced link margin crucial for mobile satellite environments. [BEGIN CONFIDENTIAL]

[END CONFIDENTIAL]
The analysis then takes into account the potential of ten simultaneously transmitting Ligado terminals over the same range of separation distances. The results are shown in Table 2 below.

**Table 2: Baseline Ligado Interference Results**

<table>
<thead>
<tr>
<th>Frequency</th>
<th>1626.5 MHz</th>
<th>1626.5 MHz</th>
<th>1626.5 MHz</th>
<th>1626.5 MHz</th>
<th>1626.5 MHz</th>
<th>1626.5 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Ligado user terminal OOBE limit</td>
<td>-49.2 dBW/30kHz</td>
<td>-49.2 dBW/30kHz</td>
<td>-49.2 dBW/30kHz</td>
<td>-49.2 dBW/30kHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Separation distance</td>
<td>10.0 m</td>
<td>100.0 m</td>
<td>1000.0 m</td>
<td>4000.0 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Path loss</td>
<td>56.6 dB</td>
<td>76.6 dB</td>
<td>96.6 dB</td>
<td>108.7 dB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iridium receiver antenna gain at horizon</td>
<td>-3.0 dBi</td>
<td>-3.0 dBi</td>
<td>-3.0 dBi</td>
<td>-3.0 dBi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Received interference power density</td>
<td>dBW/30kHz</td>
<td>dBW/30kHz</td>
<td>dBW/30kHz</td>
<td>dBW/30kHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iridium user terminal noise floor</td>
<td>-154.8 dBW/30kHz</td>
<td>-154.8 dBW/30kHz</td>
<td>-154.8 dBW/30kHz</td>
<td>-154.8 dBW/30kHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I/N</td>
<td>-6 dB</td>
<td>-6 dB</td>
<td>-6 dB</td>
<td>-6 dB</td>
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<tr>
<td>Margin</td>
<td>dB</td>
<td>dB</td>
<td>dB</td>
<td>dB</td>
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</tbody>
</table>

The results show that the interference level from a single Ligado terminal is such that a separation distance of [BEGIN CONFIDENTIAL] 13 [END CONFIDENTIAL] is needed to protect the Iridium receiver. At a lesser separation distance of [BEGIN CONFIDENTIAL] [END CONFIDENTIAL], for example, the interference would exceed the noise floor by [BEGIN CONFIDENTIAL] [END CONFIDENTIAL].

The problem is exacerbated when multiple interfering Ligado terminals are assumed, as can be seen in the last three rows of the table. Figure 3 provides a graphical representation of the interference margin as a function of separation distance, from Table 2.

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13 Only confidential information redacted.
4.2 Aggregate Interference Results

This section looks at multiple aggregate interference scenarios based on previously studied Ligado user terminal deployments. The scenarios assess interference into Iridium user terminals across variables such as Ligado user terminal density, separation distance and propagation path loss.

Each scenario follows the same general methodology to determine aggregate interference from multiple Ligado terminals. First, the Ligado terminal density is found by taking the number of Ligado terminals per cell and dividing by the cell size (assuming a circular cell with diameter equal to the inter-site distance), thus providing the number of Ligado users per square kilometer. This density is then used to find the total number of Ligado terminals within a given interference radius from an Iridium terminal. Because the Ligado terminals are spread uniformly across this interference region, this study uses the following method to distribute propagation losses to groupings of Ligado terminals in order to determine each terminal’s contribution to the aggregate interference.

- Each circular interference region is divided into a series of concentric rings with radii at 0.2 km intervals.
- The number of interfering Ligado terminals within each of these rings is determined and assigned a propagation path loss based on the midpoint between the inner and outer radii of that ring.
- The aggregate interference from the Ligado users within the ring is summed together.
- The same approach is followed for all rings, and the aggregate interference is then determined by summing the interference contributions from each ring.

An illustration of this method is shown in Figure 4 below.

![Figure 4: Methodology for Calculating Aggregate Interference](image)

The aggregate interference is then compared to the Iridium user terminal interference threshold ($I/N = -6$ dB). A positive margin means that the received interference meets (does not exceed) the Iridium receiver interference threshold. A negative margin means the received interference exceeds the threshold. Any negative margin implies degraded Iridium performance and reduced link margin crucial for mobile satellite environment. [BEGIN CONFIDENTIAL]

4.2.1 Low Density Ligado Terminal Results

The results for low density deployment of Ligado terminals under free space path loss and Hata-Okumura loss conditions are shown below in Table 3 and Table 4, respectively.

Results are provided for 1, 5 and 10 km radius interference regions around the Iridium terminal. As described in section 4.2 above, the aggregate interference is integrated over multiple, concentric rings around the Iridium user terminal. However, in the results tables in this and
subsequent sections, a single propagation loss figure is provided that represents a weighted
average of the propagation loss contributions from each ring. In other words, the propagation
loss for each ring radius is determined, then weighted by the number of interfering Ligado
terminals in that ring area. These weighted propagation losses are then summed to provide an
overall weighted average path loss shown in the tables.

[BEGIN CONFIDENTIAL] 14

Table 3: Low Density Ligado Terminal Aggregate Interference Results (FSPL Model)

<table>
<thead>
<tr>
<th></th>
<th>1626.5</th>
<th>1626.5</th>
<th>1626.5</th>
<th>MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>1626.5</td>
<td>1626.5</td>
<td>1626.5</td>
<td>MHz</td>
</tr>
<tr>
<td>Ligado user terminal OOB limit</td>
<td>-49.2</td>
<td>-49.2</td>
<td>-49.2</td>
<td>dBW/30kHz</td>
</tr>
<tr>
<td>Interference radius from Iridium user</td>
<td>1.0</td>
<td>5.0</td>
<td>10.0</td>
<td>km</td>
</tr>
<tr>
<td>Ligado users per cell</td>
<td>18.0</td>
<td>18.0</td>
<td>18.0</td>
<td></td>
</tr>
<tr>
<td>Ligado cell radius</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
<td>km</td>
</tr>
<tr>
<td>Number of Ligado users within interference radius</td>
<td>1.5</td>
<td>36.7</td>
<td>146.9</td>
<td></td>
</tr>
<tr>
<td>Weighted average path loss</td>
<td>88.0</td>
<td>100.4</td>
<td>105.9</td>
<td>dB</td>
</tr>
<tr>
<td>Iridium receiver antenna gain at horizon</td>
<td>-3.0</td>
<td>-3.0</td>
<td>-3.0</td>
<td>dBi</td>
</tr>
<tr>
<td>Aggregate received interference power density</td>
<td></td>
<td>dBW/30kHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iridium user terminal noise floor</td>
<td>-154.8</td>
<td>-154.8</td>
<td>-154.8</td>
<td>dBW/30kHz</td>
</tr>
<tr>
<td>I/N</td>
<td>-6</td>
<td>-6</td>
<td>-6</td>
<td>dB</td>
</tr>
<tr>
<td>Margin</td>
<td></td>
<td></td>
<td></td>
<td>dB</td>
</tr>
</tbody>
</table>

[END CONFIDENTIAL]

14 Only confidential information redacted.
Table 4: Low Density Ligado Terminal Aggregate Interference Results (Hata-Okumura Model)

<table>
<thead>
<tr>
<th>Frequency</th>
<th>1626.5</th>
<th>1626.5</th>
<th>1626.5</th>
<th>MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ligado user terminal OOB limit</td>
<td>-49.2</td>
<td>-49.2</td>
<td>-49.2</td>
<td>dBW/30kHz</td>
</tr>
<tr>
<td>Interference radius from Iridium user</td>
<td>1.0</td>
<td>5.0</td>
<td>10.0</td>
<td>km</td>
</tr>
<tr>
<td>Ligado users per cell</td>
<td>18.0</td>
<td>18.0</td>
<td>18.0</td>
<td></td>
</tr>
<tr>
<td>Ligado cell radius</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
<td>km</td>
</tr>
<tr>
<td>Number of Ligado users within interference radius</td>
<td>1.5</td>
<td>36.7</td>
<td>146.9</td>
<td></td>
</tr>
<tr>
<td>Weighted average path loss</td>
<td>90.5</td>
<td>104.5</td>
<td>110.5</td>
<td>dB</td>
</tr>
<tr>
<td>Iridium receiver antenna gain at horizon</td>
<td>-3.0</td>
<td>-3.0</td>
<td>-3.0</td>
<td>dBi</td>
</tr>
<tr>
<td>Aggregate received interference power density</td>
<td>-154.8</td>
<td>-154.8</td>
<td>-154.8</td>
<td>dBW/30kHz</td>
</tr>
<tr>
<td>Iridium user terminal noise floor</td>
<td>-154.8</td>
<td>-154.8</td>
<td>-154.8</td>
<td>dBW/30kHz</td>
</tr>
<tr>
<td>I/N</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>dB</td>
</tr>
<tr>
<td>Required I/N</td>
<td>-6</td>
<td>-6</td>
<td>-6</td>
<td>dB</td>
</tr>
<tr>
<td>Margin</td>
<td>-6</td>
<td>-6</td>
<td>-6</td>
<td>dB</td>
</tr>
</tbody>
</table>

Table 4 results show again that in a low density Ligado terminal scenario, Iridium transceivers still receive double digit negative interference margins even when assuming the Hata-Okumura propagation loss model. The results for this scenario also show that Ligado aggregate interference into the victim Iridium receiver is the same regardless of the radius of the interference region. Even though larger interference regions imply larger numbers of interfering Ligado terminals near the Iridium terminal, the aggregate interference is dominated by emissions from Ligado terminals closest to the Iridium terminal. In other words, Ligado terminals farther than 1 km away have propagation losses under this model such that their interference does not significantly affect the aggregate interference.

Figure 5 summarizes the low density Ligado terminal aggregate interference margin results.

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15 Only confidential information redacted.
4.2.2 High Density Ligado Terminal Results

The results for high density deployment of Ligado terminals (nominal number of Ligado users per cell in urban/suburban environments) under free space path loss and Hata-Okumura loss conditions are shown below in Table 5 and Table 6, respectively.
Under free space path loss conditions, high density Ligado terminal deployments produce aggregate interference levels exceeding the Iridium receiver threshold in all conditions, regardless of size of interference region. [BEGIN CONFIDENTIAL]

[END CONFIDENTIAL]
As explained in section 4.2.1 above, the aggregate interference under the Hata-Okumura loss model is the same regardless of interference region size.

Figure 6 presents the interference margin results for high density Ligado terminal deployment.
4.3 Ligado Narrowband Interference

In addition to the wideband OOBE limits described above, Ligado also proposes narrowband emission limits that also would produce interference into any given Iridium channel. These narrowband emission limits extend from -110 dBW/700Hz at 1610.0 MHz to -44 dBW/700Hz at 1625.0 MHz. Ligado provides no information on how these spurious or intermodulation emissions are generated, how frequently they occur or how many are generated per 10 MHz Ligado channel. Even assuming that each of these narrowband emissions would only affect one Iridium channel at a time, they are higher power, per Iridium channel, than the proposed wideband OOBE limits and could thus produce more interference than even those levels described in sections 4.1 and 4.2 above.

5 Summary of Findings

Under multiple scenarios, the analyses show that Ligado user terminal interference into Iridium terminals would exceed Iridium interference protection criteria for significant portions of the Iridium user link band.
A baseline assessment of interference from a single Ligado user terminal at various line-of-sight distances resulted in emission levels nearly 50 dB higher than the Iridium receiver noise floor at close distances of 10 meters, and still produced excessive interference at distances up to 1 km away through a significant portion of the Iridium band.

As a result, it is clear that whenever Ligado and Iridium terminals are co-located, with no impact on Ligado operations, Iridium terminals would suffer harmful interference – likely to an extent that would [BEGIN CONFIDENTIAL]

[END CONFIDENTIAL], which are orders of magnitude weaker than the Ligado user terminal emissions.

Moreover, when considering typical Ligado deployment scenarios for small and large base station coverage areas with multiple Ligado terminals, the analyses show that Iridium terminals deployed within these coverage areas would [BEGIN CONFIDENTIAL]

[END CONFIDENTIAL]