Ka and Ku Operational Considerations for Military SATCOM Applications

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During last year’s MILCOM event (MILCOM 2011), McLain et al [1] presented a paper that provided a comprehensive comparison of Ku, commercial Ka and military Ka-band efficiencies against a number of parameters; including terminal size, regulatory restrictions, and performance in the presence of rain. This comparison showed that each band has its strengths and weaknesses, depending on the application for which it is being used (aeronautical, maritime, land based), terminal size, and operational environment (mobile and fixed).

This paper provides an expanded comparison of Ku and Ka-band, focusing on operational aspects and other key considerations; including coverage resilience, operational flexibility, regulatory impacts and potential regulatory changes that would improve commercial Ka-band performance, as well as the use of hybrid (multi-band) systems to further improve performance when operating in adverse weather conditions.

Index Terms - SATCOM, Mobile terminal, Ka, Ku, L, Inmarsat, Boeing, iDirect, rain fade

I. INTRODUCTION

Ku-band and Ka-band systems differ in many respects, including transponder bandwidth, beam size, transponder connectivity, topology (mesh vs. hub-spoke) and associated payload complexity and cost. Both Ku and Ka-band systems are used for multiple applications, including Mobile Satellite Services (MSS), Fixed Satellite Services (FSS), and Broadcast Satellite Services (BSS). Although Ku-band systems are deployed extensively throughout the orbital arc today, the number of Ka-band systems is increasing at a rapid pace. In this paper we compare Ku and Ka-band systems on a practical level for mobile, fixed and mission critical applications. System utility and performance are evaluated to address market needs including global, regional, and concentrated coverages and environments.

II. COVERAGE RESILIENCE

Wideband satellite communications has experienced significant growth over the last several years, providing sizable increases in coverage and connectivity across large geographical regions while enabling mobile data rates greater than or equal to T1 across the globe. The geographical coverage provided by Ku-band systems has increased substantially over time with overlapping, multi-satellite coverage in most densely populated areas of the world and significant coverage over ocean regions. Figure 1 shows a composite worldwide Ku-band coverage map (orange outline). This capability, characterized by many overlapping coverages, is provided by over 260 Ku-band satellites on-orbit with an average spacing of 1.5 degrees over the United States, Europe, Southeast Asia and the Middle East. This results in a robust capability with multiple sources of Ku-band coverage available in a single service area. The communications resilience afforded by this overlapping capability has not gone unnoticed by the world’s military as it seeks to diversify fleet assets in space and on the ground. This resilient coverage is considered a strategic feature of the Ku-band fleet.

Commercial Ka-band systems are also starting to provide large coverage footprints that currently focus on landmasses, with continental coverage currently available in North America (Viasat-1 and Anik F2), Europe (KaSat), and Southeast Asia (ABS-7), as well as in highly populated areas of Africa and the Middle East (Hylas-2, Yahsat 1A,1B, and AMOS-2).

Similar to the coverage expansion experienced by Ku-band, the United States, Europe and South East Asia will soon have overlapping Ka-band coverages, as systems such as Jupiter-1, Thor 7, and Jabiru-1 become operational. Other regional coverage systems in the planning stages include Yahsat 2, Hylas-3 and NBN. Figure 1 provides a graphical depiction of the Ka-band coverage provided by operational and soon-to-be-deployed satellite systems (denoted by blue contours).

Ka-band systems will require additional time to provide the same overlapping coverage around the globe that Ku-band enjoys today. However, two major systems that are currently under development, Inmarsat-5 and O3B, will serve to accelerate this Ka-band coverage build out by providing large wide-area coverage. The Inmarsat-5 Global Xpress service will provide ubiquitous commercial Ka-band coverage in the +/- 70

Figure 1. Composite Ku/Ka-band Coverage Map.
degree latitude range starting in 2014 while O3B will provide comprehensive coverage in the +/- 45 degree latitude range, focusing on select population centers in underserved markets, starting sometime after 2015. Figure 2 provides a representative coverage map for Inmarsat-5, including six dual commercial/military Ka-band beams that can be pointed anywhere within the satellite’s Field of Regard (FOR).

Inmarsat-5 is especially well suited to provide coverage along heavily travelled air and maritime routes (see Figure 3), effectively bridging the high-capacity continental Ka coverages, shown in Figure 1. This off-continental coverage offers consistently higher performance than what Ku-band typically provides (in excess of 52 dBW), bringing state-of-the-art performance to every portion of the globe.

Although further build out of Ka systems across the orbital arc is still required in order to match the widespread coverage of Ku-band systems, the number of deployed Ka-band systems is increasing at a rapid pace. The number of Ku-band systems, on the other hand, is quickly approaching the point of saturation of the orbital arc, at which point new deployments serve largely to replenish existing systems. Figure 4 provides a summary of currently planned Ku-band and Ka-band systems, based on published ITU frequency coordination filings [2]. This figure shows that the trend rate of planned Ka-band systems has been higher than Ku-band over the past 5 years. This trend is expected to continue for the foreseeable future, as demand for Ka-band capacity continues to increase.

Despite the substantial amount of available coverage, current Ku-band systems have performance shortcomings when compared to Ka-band. Despite the large number of Ku-band systems already deployed, these systems do not provide the ubiquitous coverage required by many users, often necessitating a patchwork of satellites and systems to provide continuous coverage over extended geographical areas, and to platforms moving across coverage boundaries. With more orbital slots available to accommodate new Ka-band payloads than Ku-band payloads, it is possible for a single satellite operator, or service provider, to field a Ka-band constellation with global coverage, whereas accomplishing this in Ku-band would prove difficult. Inmarsat-5 is an example of such a planned Ka-band deployment, as depicted in Figure 2.

Further, when we consider Ku-band systems offering EIRP > 52 dBW, the Ku-band coverage, previously shown in Figure 1, is significantly reduced from the orange outline to the blue contours, as shown in Figure 5. To achieve this higher coverage/performance level over large geographical areas, Ku-band users must reserve transponder space on several overlapping satellites; resulting in an expensive solution and...
the underutilization of satellite assets.

The difference in performance between Ku and Ka-band is even more pronounced in the return link (Spacecraft G/T), which is critical for platforms with large uplink data rate requirements (e.g., military ISR platforms and oil and gas, mining and exploration platforms).

Commercially-provided Ka-band satellite systems enable operational flexibility by servicing both commercial and military Ka-band networks. With the increased budget pressures, more and more users are migrating toward military Ka-band in order to take advantage of the substantial bandwidth that WGS offers. But realistically, not all military users will have access to the WGS system, as these steerable beam systems quickly become beam limited, and user’s needs are prioritized, leaving many potential users without access.

A number of systems that provide compatible military Ka-band capability are currently available or nearing service; including Inmarsat-5 High Capacity Payload (HCP), Yahsat (1A, 1B), ABS-7 and Hylas-2. These systems can serve as augmentation to the WGS constellation and provide resilient military Ka-band coverage while still using ARSTRAT certified terminals without modifications. The adjacency of commercial and military Ka-band frequencies also fosters the development of hybrid terminals that cover the extended commercial/military Ka-band range. Existing military Ka-band terminals can be minimally modified, via RF and baseband upgrade kits, to enable commercial Ka-band service to Government users when military Ka-band service via WGS is not available.

Another key Ku/Ka comparison metric is capacity density. Ku-band has the inherent ability to pool power within a coverage area due to its large beams and output multiplexing (OMUX) capability. Since Ka-band OMUX losses are higher, Ka-band systems tend to support fixed-power multi-beam architectures to deliver high-efficiency power without pooling power within a beam. One answer to this potential shortcoming is to augment multi-beam structures with steerable beams. Many new Ka-band systems offer steerable beams providing very high capacity density anywhere within the satellite’s FOR. The use of agile structures, such as phased arrays, to provide steerable beams in an inexpensive manner will be critical to the success and evolution of Ka-band systems in the future.

III. REGULATORY IMPACTS TO KU AND KA-BAND

As pointed out in McLain’s paper [1], the current ETSI EIRP Spectral Density (ESD) mask for commercial Ka-band is 14 dB below the ETSI Ku ESD mask [4] and 22 dB below military Ka-band ESD mask defined by MIL-STD-188-164 [7]. This mask may prove to be more stringent than necessary and careful work is needed over the coming years as data from fielded Ka-band systems is collected to arrive at a mask that balances the needs of all interested parties.

Figure 6 provides a comparison of ESD mask restrictions defined in the ETSI [4][6], ITU-R [5], MIL-STD [7], and FCC CFR [8][9] regulatory standards. A primary reason for setting stringent restrictions on the commercial Ka-band ESD is to enable commercial Ka-band satellites to achieve 2 degree separation across the orbital arc, given the higher anticipated Ka-band satellite frequency reuse. An influencing factor in the definition of the generic Ka-band Off-axis Power Spectral Density (PSD) limits is ITU-R S.524-9 Annex-I, Section 4 [5].

This recommendation attempts to statistically quantify the uplink C/N degradation caused by off-axis radiation by the Earth Station for satellite orbital separation of 2 degrees and 3 degrees. The off-axis limit of $19 - 25 \times \log (\Phi) [\text{dBW}/40 \text{kHz}]$ from 2 degrees to 7 degrees was first adopted by ITU-R S.524-9 to restrain harmful interference on a statistical basis. This limit was subsequently adopted by FCC 25.138 and later by ETSI EN 303 978.

Figures 7 and 8 illustrate the impact that ESD mask restrictions have on Ka-band data rates for two representative small terminals; a 45 cm circular aperture terminal and a 30 cm circular aperture terminal, using two different waveforms; iDirect (MF-TDMA) and MIL-STD-188-165 (SCPC). These figures also show the potential increase in uplink data rates for the 30 cm terminal with a 6 dB increase in ESD mask power allowance. The 45 cm antenna terminal performance, using a MIL-STD-188-165 modem (Figure 8a), is transmit-EIRP limited with an offered data rate about 2x higher than the one using an iDirect waveform (Figure 7a). The iDirect waveform, however, is more flexible and can spread the power densities as necessary to work within the ESD limits for the smaller 30 cm terminal (Figure 7b), whereas the MIL-STD-188-165 modem lacks this flexibility and cannot provide link closure with the same 30 cm antenna (Figure 8b). For both waveforms, a 6 dB increase in ESD mask would allow high data rate transmission with a 30 cm terminal, as shown in Figures 7c and 8c.

Ka-band does provide a 6 dB C/I advantage compared to Ku-band due to improved sidelobe performance, but this is not enough to justify a 14 dB difference in ESD mask. Applying the general radiation pattern provided in ITU Radio Regulations Appendix 8 [10] for a 1 meter transmit antenna size, the uplink C/I advantage with equal transmit power is 6 dB due to higher Ka-band Gmax (20 Log (30 GHz/14.5 GHz)). An identical sidelobe pattern of 29 - 25 LOG $\theta$ exists in the 0,
sidelobe roll-off region for both Ka and Ku-band beginning at a nominal 2° off-axis angle.

This C/I advantage represents a relative improvement in access to the orbit-spectrum resource for Ka-band systems and is instrumental in achieving adjacent satellite ITU frequency coordination. Figure 9 illustrates that for the same size antenna aperture (e.g. 45 cm) terminal transmit power is more focused, minimizing the amount of interference broadcast to adjacent satellites due to the higher directivity achieved at higher frequencies (Ka).

Additional interference and statistical analyses need to be performed as real Ka-band systems are deployed. Ka-band usage data can be used to refine the ETSI standard to equalize the financial impacts, as well as operational valuing of Ka and Ku-band in the future. Operational valuing of the ETSI standard would allow, for example, Ka-band to provide increased uplink capacities that leverage the very high, multi-beam G/T performance, especially for Government users.

IV. ENVIRONMENTAL ANALYSIS AND HYBRID SOLUTIONS

Ka-band performance under various environmental conditions can vary depending on terminal, weather characteristics and desired availability. Antenna performance dictates system resource utilization and available margin to meet link requirements. This section characterizes link performance by region using throughput as a metric. Typically, satellite service providers look at attenuation and availability separately; however, combining performance and availability into a single set of curves provides a better representation of performance. In fact, an interesting pattern emerges that suggests great benefit to bundling more robust services like L-band with Ka-band services to provide a hybrid all-weather, high-data-rate data delivery system, as discussed below.

The signal-to-noise ratio (C/No) achieved by a military Ka-band uplink in clear sky is 4 to 5 dB higher than that of Ku-band. Since antenna directivity varies inversely as the square of the RF wavelength, the spacecraft antenna G/T for military Ka-band is roughly 5 dB higher than for the same size Ku-band antenna. On the other hand atmospheric losses due to gas absorption in Ka-band range from 0 to 1 dB higher than in Ku-band, depending on location. The received isotropic power (RIP) for Ka-band differs from that of Ku-band only by this 0 to 1 dB difference, since the directivity gain in EIRP of the terminal antenna is offset by an equal but opposite increase in isotropic area. Combining the RIP and G/T terms, the net result is a 4 to 5 dB higher C/No for Ka-band than for Ku-band. Details of this analysis are shown in Table 1, which is calculated at a location with high Ka-band atmospheric losses. This matches the conclusion drawn by McClain [1].
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To analyze the effect of weather we take a closer look at the link degradation caused by rain. For the sake of simplicity and for descriptive purposes, the ITU rain zone model in Rec. ITU-R 837-1[11] is used. In this model, the Earth is divided into different “rain zones,” where each zone corresponds to a certain probabilistic spread of rain rates (measured in mm/hr). Rain zones range from Zone A, in which the rain rate exceeds 8mm/hr less than 0.01% of the time, to Zone P, in which rain rates can approach 145 mm/hr. For ka-band, link availability correlates strongly with rain rate statistics for a particular rain zone. For example, if an area can withstand up to 30mm/hr of rain before going down, then it will have 99.99% availability in Zone G because in this zone the rain rate is less than 30mm/hr 99.99% of the time. Figure 10 displays consolidated color-coded areas of the world with different rain rates.

Figure 11 shows comparative data rate performances for (a) a smaller terminal (45 cm) and (b) a larger terminal (1.3 m) operating in a Ka-band system versus the same sized terminals operating in Ku-band and L-band. As illustrated here, the data rates achievable in clear-sky conditions are 2 to 4 times higher for Ka than for Ku for most locations in the world. As rain rate increases, the achievable data-rate advantage of Ka-band over Ku-band decreases. For very high rain rates, the achievable Ka data rate crosses below that for Ku. It is noteworthy that this crossover point for small-aperture terminals occurs at around 400 to 800 kbps, independent of rain region. These data rates are within the capability range of L-band systems, which are resilient to high rain rates.

For drier regions of the world (Areas 1 and 2 in Figure 10), this crossover in achievable Ka/Ku data rate happens 1% of the time for both small and large antennas (Figure 11a and b, blue and green curves).

For wetter regions of the world (Areas 3 and 4 in Figure 10), this crossover happens less than 3% of the time for both small and large antennas (Figure 11a and b, yellow and pink curves).

For the wettest pockets of the world (Area 5 in Figure 10), this crossover happens approximately 20% of the time for small antennas and approximately 5% of the time for large antennas (Figure 11a and b, blue and green curves).

Thus, for a fixed antenna size, Ka-band yields higher data rates than Ku-band at least 97% of the times for Areas 1 through 4 of Figure 10. For Area 5 (orange), both Ka and Ku-band have severely-degraded performance (data rates limited to less than 500 kbps) at least 20% of the time for small-aperture terminals. To avoid complete loss of service during periods of heavy rain, a service provider may offer a bundled L-band service with Ka-band or Ku-band as the primary service and the ability to fall back to L-band service when the Ka-band or Ku-band data rates fall significantly below 500 kbps. As noted earlier, L-band is resilient to rain outages, and thus is a good candidate to offer backup service in case of severe Ka or Ku rain outage. A Ka-band/L-band service bundle provides worldwide availability greater than 99.5% while reaping the benefits of Ka-band performance in clear sky conditions.

The goal is for hybrid terminal solutions to allow for the rapid or seamless switching between the L-band and K-band services. Seamless handoff is defined as a handoff where an insignificant number of IP packets are lost when transitioning SATCOM links from satellite to satellite, or from system to system, where the satellite’s orbital slots differ. Seamless handoff can only be accomplished when two simultaneous SATCOM links can be established between the mobile platform and the ground network at a common data rate. Figure 12 depicts one such hybrid terminal solution that consists of a Ka-band satellite and terminal, an L-band satellite

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Military Ka Terminal 1</th>
<th>Commercial Ku Terminal 1</th>
<th>Comment</th>
<th>Delta = Ka – Ku</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Frequency</td>
<td>GHz</td>
<td>30.5</td>
<td>14.25</td>
<td>Uplink Frequency</td>
<td></td>
</tr>
<tr>
<td>b. Net Terminal EIRP</td>
<td>dBW</td>
<td>47.0</td>
<td>40.4</td>
<td>45 cm antenna, 10W</td>
<td></td>
</tr>
<tr>
<td>c. Weather Loss</td>
<td>dB</td>
<td>0</td>
<td>0</td>
<td>Clear sky</td>
<td></td>
</tr>
<tr>
<td>d. Atmosphere Loss</td>
<td>dB</td>
<td>-2</td>
<td>-1</td>
<td>Gas Absorption, etc. per ITU-R P. Rec.676</td>
<td></td>
</tr>
<tr>
<td>e. Range at 15 deg Elev.</td>
<td>Km</td>
<td>40061</td>
<td>40061</td>
<td></td>
<td></td>
</tr>
<tr>
<td>f. Range Loss</td>
<td>dB/m^2</td>
<td>-163.0</td>
<td>-163.0</td>
<td>= -10<em>log10(4</em>π*R^2)</td>
<td></td>
</tr>
<tr>
<td>g. Receive Power Flux Density at SC</td>
<td>dBW/m^2</td>
<td>-118.0</td>
<td>-123.6</td>
<td>= b+c+d+f</td>
<td></td>
</tr>
<tr>
<td>h. Isotropic Area</td>
<td>dB-m^2</td>
<td>-51.1</td>
<td>-44.5</td>
<td>= 10*log10(4</td>
<td>π</td>
</tr>
<tr>
<td>i. Received Isotropic Power (RIP)</td>
<td>dBW</td>
<td>-169.2</td>
<td>-168.2</td>
<td>= g+h</td>
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<tr>
<td>j. Boltzmann Constant, kB</td>
<td>dBJ/K</td>
<td>-228.6</td>
<td>-228.6</td>
<td></td>
<td></td>
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<tr>
<td>k. Spacecraft G/T</td>
<td>dB/K</td>
<td>11</td>
<td>6</td>
<td></td>
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<tr>
<td>l. Uplink C/No</td>
<td>dB-Hz</td>
<td>70.4</td>
<td>66.4</td>
<td>= i-j+k</td>
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Figure 10. ITU Rain Rate World Map (1=lowest, to 5=highest, rain rate)
and terminal, and their associated ground networks, all coupled to form a single integrated system.

Typically, handover between the systems is implemented by using IP routing protocols which make informed routing decisions to switch between systems based on metrics such as cost of an associated link or whether a particular link is ‘up’ or ‘down’ as assessed through expiration of timers.

Hybrid solutions available today are able to perform the handover functionality; however, the handovers are not yet seamless and need refinement to ensure handover within the 400 to 800 kbps crossover band for all rain scenarios. Some challenges to overcome include:

- The Ka-band link may never be assessed as ‘down’, because data is still able to transit the link
- Standard IP routing protocols are not developed to make decisions on satellite specific metrics, including satellite link quality (C/No) measurements
- Current handover solutions are unable to perform application-specific handovers, such as to switch high-priority traffic to L-band link for maximum reliability, while servicing best-effort applications on Ka-band

Future hybrid solutions need to enable seamless switching between bands using a number of optimized methods; any single solution may not be ideal for all circumstances. An end-to-end seamless handover solution should include the following characteristics and considerations:

- Handover decisions based on SATCOM-specific metrics. (e.g., C/No, Modulation and Coding scheme)
- Application-specific routing (e.g., mission-critical applications serviced on L-band and all other applications on Ka-band)
- Backhaul of traffic across both satellite systems to a single provider edge point of presence. (to minimize jitter and latency as well as terrestrial circuit costs)
- Synchronization of Cryptographic and Wide Area Network Optimization (WANO) state across multiple links (i.e., a single crypto device should be able to service multiple WAN links without having to be reconfigured).

V. CONCLUSION

The use of Ku-band and Ka-band systems will proliferate as opportunities and applications demand. The real question is how to get the most out of what each technology has to offer.

This paper has addressed the three primary differentiators between Ka and Ku-band systems: coverage, regulatory limits, and environmental performance.

With respect to coverage, Ka-band systems currently enjoy an satellite EIRP advantage, and if it were not for the ESD limits, would enjoy an equal G/T advantage. The ability of Ku-band satellites to take advantage of larger satellite reflector technology to support higher power levels and greater frequency reuse will be limited by adjacent satellite interference. Higher power levels in a co-frequency co-coverage sharing environment will require new frequency coordination agreements due to increased interference-to-noise levels (I/N) into adjacent satellite victim Ku-band terminals. Since there are many incumbent notified Ku-band systems with small average satellite spacing, the increased I/N levels will inhibit the ability to deploy the new reflector technology and higher power levels.
From a regulatory perspective, additional practical and statistical analyses are needed to understand the viability of utilizing small terminals for Ka-band operations. The inherent wavelength advantage of the Ka band provides opportunities and advantages for introducing very small terminals (sub 45 cm), opening new possibilities to support ISR missions, exploratory systems, report-back, and imaging applications from very small platforms at very remote locations.

This paper also presented weather as a differentiator. Ku-band does enjoy an inherent availability advantage over Ka but the higher gain of equivalent size Ka-band antennas, along with the use of modern waveforms, hybrid systems, and site diversity moderates any difference in Ku-Ka availability. Hybrid systems, and their inherent diversity, will support mission critical military/government, aeronautical and maritime applications. L-band can provide reliable 400 to 800 kbps service during times when Ka-band is unavailable, while commercial Ka-band can itself act to bridge gaps in military spot beam coverage.

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