X-BAND, K-BAND, AND FUTURE MILSATCOM REQUIREMENTS: AN OUTING IN TRADE SPACE

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ABSTRACT

The current US wideband Milsatcom system, DSCS, uses X-band to provide service to all types of wideband users. However, in the near future, the community will have both X-band and Ka-band frequencies available. The question arises, which frequencies are best for which missions? This paper presents a quick-look analysis of two alternative approaches, relying on reasonable and consistent, if somewhat arbitrary, assumptions. In the first, tactical services are supported by a transponded X-band payload. In the second, we use Ka-band to support the tactical users, and argue that this payload should be processed. In both cases the frequency not chosen for the tactical mission is assigned to primarily support infrastructure users. This paper concludes that for comparable levels of coverage, connectivity, link availability, and radiated satellite power, the achievable tactical capacity of each satellite could be several times higher using the processed Ka-band approach.

INTRODUCTION

Projected military communications requirements, as specified in the Emerging Requirements Data Base (ERDB), will exceed 40 Gbps in 2010. Of this total, a detailed requirements analysis [1] has determined that more than 17 Gbps of tactical and infrastructure requirements must be met with dedicated military satellite communications systems, with over 15 Gbps nominally assigned to an X/Ka wideband system.

In addition to capacity, Milsatcom users require coverage, which addresses their chances of being supported as opposed to merely supportable; connectivity, which refers to communications with the desired party versus merely anyone; and link availability, which is the fraction of time that attenuation from rain will not exceed the allocated link margin. Jamming will be discussed separately.

Figure 1. Paths through the Trade Space

Future wideband systems will use both X-band and Ka-band payloads to provide these services to different types of users. Which payloads should be optimized for which missions? We will perform quick-look design trades leading to notional designs, as shown in Figure 1. We will start from two points. In the first, tactical service is provided with an X-band payload, and the Ka-band payload is oriented towards infrastructure support. In the second approach, the Ka-band payload is to be used to support the tactical requirements, while the infrastructure users remain at X-band. It is our primary goal to determine which, if either, approach provides more tactical utility. We will use common assumptions whenever possible to simplify the comparison. We do not claim that our designs are optimal; however, we believe that they are reasonable, and that the lessons learned in comparing them may be of value to the designers and users of systems such as the X/Ka Gapfiller and Advanced Wideband.

For simplicity, we will consider a tactical operating theater to be about 4° across (about 4000 km at 40° N). Most tactical users will be in this area, but there will also be a considerable number in a larger "extended theater" and in transit; links with the terrestrial infrastructure must also be supported. We will design our notional satellites
so that each can support two such theaters simultaneously.
The current DSCS system has uplink and downlink rain margins of 2 dB, for an end-to-end availability of 99.0%,
based on the Crane Rain model [2] D2 region with a 10°
elevation angle. The link margins for our notional designs
will be set to match these. Our approach will be to
emphasize capacity to tactical users in theater first, and
then provide as much capability to other users as a
moderate amount of payload power will allow. We will
reuse frequency spatially, but will not use the X-band
cross-polarization spectrum for interference reasons.

**APPROACH 1: TACTICAL USERS AT X-BAND**

Approach 1 will employ X-band to service tactical users.
The X-band frequency has the primary advantage of low
rain margins, which makes it practical to provide
extended coverage. As Figure 1 shows, our first decision
involves choosing a tactical antenna. Earth coverage
horns (ECHs) and gimbaled-dish antennas (GDAs) are
both very useful, but the former requires too much power
to support tactical users at acceptable availabilities and
the latter has coverage and/or connectivity problems when
used alone or with ECHs. A cellular approach (Figure 2)
at X-band is not attractive, because in order to get cells
small enough to be useful the diameter of the antenna
would have to be fairly large (17 feet for 0.5° beams).
Smaller antennas with larger cell sizes may actually have
significantly less aggregate theater capacity than a single
beam, due to bandwidth constraints on the cell (Figures 2a
and 2b). Figure 2d shows that very small cells can result
in a single user per cell. Figure 2c represents a middle
ground. Thus, since we will not use the cellular approach
here, on-board processing need not be considered, and the
associated weight, power, and messaging overhead can be
avoided.

We choose multibeam antennas with beam forming
networks (MBA/BNF) for the X-band payload in this
approach, similar to that used on the DSCS III spacecraft,
but with multiple beam forming networks for gain pattern
optimization. BFNs can provide connectivity to out-of-
theater users, since the gain pattern need not be contiguous; however, connectivity between users on
different BFNs/channels is limited. This problem can be
mitigated using an analog, reconfigurable filter-switching
system, perhaps using established or developing surface
acoustic wave (SAW) technology, to route portions of the
uplink bandwidth to different downlink channels.

For simplicity, we will reserve 100 MHz of the X-band
spectrum for those infrastructure users who require Earth
coverage; the remaining 400 MHz will be subdivided into
tactical channels. We will use 300 MHz to support the 4°
theater, and the remaining 100 MHz for extended 7°
theater. BFNs allow some spatial frequency reuse; we will
assume that each of these tactical bands can be used
twice, if spatial isolation permits, and will budget satellite
power accordingly. (Note: we will use the two 100 MHz
channels in Approach 2 also, to simplify comparison.)

We will consider 7.8' T3 terminals in the central theater
and 7.0' WSC-6 terminals in the extended theater. In the
central theater, the modems will use 8PSK, which is the
highest mode being considered at this point for either
COTS or UM tactical performance. Using link parameters
taken from reference [3], the amount of power that the X-
band transponders must emit to reach the bandwidth limit
the 300 MHz tactical channels is 205 watts, which
supports 384 Mbps (about 45 - 8 Mbps users). We use the
more robust QPSK mode for the extended theaters and
100 watts of satellite power; this supports 70 Mbps of
ship-to-ship traffic, or about 45 - T1 users in each area.

<table>
<thead>
<tr>
<th>Modulation Mode</th>
<th>Coding (Inner/Outer)</th>
<th>bps/Hz</th>
<th>E_b/N_o</th>
</tr>
</thead>
<tbody>
<tr>
<td>QPSK</td>
<td>1/2*0.9</td>
<td>0.71</td>
<td>6.0</td>
</tr>
<tr>
<td>8PSK</td>
<td>2/3*0.9</td>
<td>1.28</td>
<td>6.5</td>
</tr>
<tr>
<td>16 QAM</td>
<td>3/4*0.9</td>
<td>1.93</td>
<td>9.0</td>
</tr>
<tr>
<td>32 QAM</td>
<td>3/4*0.9</td>
<td>2.41</td>
<td>10.0</td>
</tr>
<tr>
<td>64 QAM</td>
<td>3/4*0.9</td>
<td>2.90</td>
<td>13.0</td>
</tr>
</tbody>
</table>

Figure 3. Modem parameters considered. [4]

The Ka-band payload would be used primarily to support
infrastructure users. The more widely dispersed
infrastructure users, such as those belonging to the
Diplomatic Telecommunications Service (DTS), will be
supported using the previously-reserved 100 MHz Earth coverage X-band channel. The Ka-band payload would then be optimized for the highest data rate infrastructure users. This would require these users to incur the costs of acquiring and fielding fixed Ka-band terminals.

In order to maintain the link availability, the Crane Rain model indicates that we will need about 12.5 dB and 6.5 dB of rain and atmospheric margin on the uplink and downlink, respectively. The size of these margins makes it difficult to support large beams, especially when combined with more bandwidth-efficient modems. For instance, in a 4° beam, a 30-foot Ka-band terminal must transmit about 2000 linear watts to a satellite in order to link at 155 Mbps to another 30-foot terminal. Also, about 180 watts of satellite power per 100 MHz of bandwidth is required to achieve the bandwidth limit.

If we consider 1° beams for this payload, the terminal power required to support 155 Mbps using 64 QAM is reduced to about 35 linear watts, and about 16 linear watts per 100 MHz on the spacecraft is needed to bandwidth-limit the channel. The 1° beams could be implemented in several ways; we select a GDA design. We will consider six diplexed 1° (3.3 feet) GDAs. The routing of signals between Ka-band antennas, and between the X- and Ka-band payloads, can also be accomplished in several ways. As in the tactical payload, we choose the reconfigurable analog filter-switch approach because of its flexibility, and because the limited amount of connectivity required should not overly stress the technology.

We will assume 500 MHz of the Ka spectrum is available for this mission using 64 QAM. The filter-switch approach, in theory, would allow this frequency to be reused as many times as one has antennas; We will assume that only two channels are be completely full (e.g., Washington and Landstuhl), while the others are half full. The effective bandwidth is thus 2000 MHz, with a bandwidth-limited capacity of about 5.8 Gbps. The radiated power required to bandwidth-limit all six uses of the spectrum is about 480 linear watts.

The X-band support to the infrastructure users is quite important, as it provides service outside of the spot areas. Assuming 16 QAM modems in GSC-52 terminals, 100 linear watts will bandwidth-limit this channel at 192 Mbps, supporting about 125 simultaneous T1 users.

To summarize this path, we have arrived at a design satellite that supports tactical users at X-band and infrastructure users largely at Ka-band, with no on-board processing. Not counting the GBS and any other payloads, Approach 1 requires about 610 X-band watts and 480 Ka-band watts of transmitted power. Each bandwidth-limited satellite will support about 0.9 Gbps of tactical service and 6.0 Gbps of infrastructure service with very good coverage, connectivity, and link availability. We note that the majority of the infrastructure support is only between the 1° Ka-band spots. A notional block diagram appears below as Figure 4.

![Payload design based on Approach 1.](image)

**APPROACH 2: TACTICAL USERS AT KA-BAND**

Approach 2 will employ Ka-band to service tactical users. We will try to provide the same level of coverage, connectivity, and link availability as in Approach 1, in order to simplify the comparison; e.g., the tactical Ka-band payload must two 4° and two 7° theaters. We will assume that the tactical terminals of Approach 1 are modified to support Ka-band service; informal interaction with a terminal manufacturer suggests that a 100 linear watt Ka-band amplifier can be added in place of C-band with minimal impact to the terminal configuration.

Analysis shows the difficulty of trying to service tactical terminals in a 4° Ka-band spot. A 7.8' terminal using 8PSK modems at 30 GHz requires 4,500 watts of transmitted power to communicate with a similar terminal at 8 Mbps, and the satellite requires 250 watts per 100 MHz to reach the bandwidth limit; this is not practical. Thus, to use Ka-band to support the tactical mission, we are forced to use a large collection of smaller beams in order to increase the uplink and downlink gains. Routing by on-board processing appears to be the only practical way of achieving the required connectivity; we note that most commercial Ka-band systems will use this approach.

Let us consider an antenna comprised of 61 - 0.5° elements (diameters 4.5' at 30 GHz, 7.5' at 20 GHz)
arranged as shown in Figure 5 to form a circular coverage area of 4°, matching the coverage of Approach 1. We will employ a cellular technique, dividing an arbitrarily-assumed 400 MHz of Ka bandwidth into four equal sub-bands of 100 MHz each (A, B, C, and D). This allows a considerable amount of frequency reuse, but also introduces additional noise since some signal from the nearest neighbors of the same frequency can be present.

To close at 8 Mbps, we find that the modified STAR-T must emit only 9.5 linear watts. On the downlink side, we can ignore the uplink noise, as it has been processed out; we need only 5.5 watts per 100 MHz to reach the bandwidth limit of the channel. For simplicity, we will not consider a beam-switching network, in which a limited number of transponders can be switched to a larger number of beams. Instead, we will consider a single 5.5-linear-watt SSA in each of the 61 transmit horns, for a total radiated power of 335 watts per antenna. We will need two such antennas to provide the same dual-theater coverage as Approach 1. Ideally, these antennas will each occupy a different 400 MHz portion of the Ka spectrum, allowing them to be overlapped if necessary (note that Approach 1 cannot support this). We postulate an additional two 1° Ka-band spot beams for out-of-theater connectivity. If the gateway terminal is 30°, then 11 watts of radiated power per beam will fill a 100 MHz channel (290 Mbps, not counted toward tactical total).

We will retain the two X-band 100 MHz, 7° beams to provide extended theater coverage, although now we will require that they operate in a processed fashion also so as to be able to communicate freely with the tactical users (it makes no difference to a processing payload if not all users are at the same frequency). This then adds another 200 watts to the amount of tactical radiated power.

What is a realistic capacity estimate for the cellular design? This is often calculated as the maximum capacity per cell times the number of cells; however, users are unlikely to be distributed uniformly over the theater and resources cannot be moved from an underutilized cell to an overloaded one. For simplicity, and in the absence of actual terminal laydowns, we will proceed as follows. First, we assume that half of the cells will not be used. Second, we add 8 Mbps users randomly to the remaining cells until one cell fills up, stop, and count the total users supported. We repeat this process several times and average. The mean number of simultaneously supportable 8 Mbps users is 249 in our case, yielding a total capacity of about 1990 Mbps per antenna. With two such antennas, the tactical service provided is about 4 Gbps per satellite, plus the additional 140 Mbps from the extended theater coverage at X-band. This is about four times the tactical capacity of Approach 1, with the same degree of coverage, connectivity, and link availability. Note that the advantages of this approach vanish if we broadcast the same information to all users; our design is most useful for point-to-point or "narrowcasting."

The penalties of this approach are the acquisition of an on-board processor, and modifications to the tactical terminals. Experts engaged in the space processor efforts for commercial applications express confidence that such a system can be developed in the Gapfiller timeframe, and estimate that it will require less than 2000 watts of spacecraft power (not to be confused with radiated power) and weigh less than 400 lbs [5]. Terminal manufacturers state that they believe that T3 terminals modifications to support operation on a commercial-like processed satellite would add about 10-20% of the cost to each terminal.

We will assume that 300 MHz of the X-band spectrum is available to support fixed users using MBA/BNtechnology; the remaining 100 MHz will be reserved for Earth coverage, using the same design as in the first approach. The power required to achieve the bandwidth limit of GSC-52 terminals with 32 QAM modems is about 252 transmitted watts, assuming two-times frequency reuse, and yields 1.45 Gbps. Coupled with the ECH channel, we achieve a total of about 1.6 Gbps of infrastructure support per satellite with 552 watts of radiated X-band power. This compares to 6.0 Gbps and 480 watts in Approach 1, but most of this was only between a limited number of points. This approach does not require the infrastructure users, who have recently modernized their X-band terminals, to acquire Ka-band terminals. A notional block diagram appears as Figure 6.
SUMMARY

One of the key questions facing the Milsatcom community is how best to utilize the Ka-band frequencies that will soon be available in the face of heavy requirement growth. This paper has investigated two approaches, emphasizing tactical user satisfaction. We followed a series of design choices through the trade space, and developed two designs whose key features are summarized in Figure 7. While both starting points lead to workable solutions, one interesting fact emerged: that for essentially the weight, power, and cost associated with an on-board processor and some modifications to the new generation of deployable terminals, tactical capacity can be increased by about a factor of four with equal levels of coverage, connectivity, and link availability. Jamming issues are addressed differently in the two cases, but also appear to lead to comparable performance. We believe that there is a strong case to support further exploration of a processed design for Gapfiller and Advanced SHF/Ka, as it may offer significant advantages to tactical users while providing substantial service to fixed users.

REFERENCES


JAMMING CONSIDERATIONS

Use of the Universal Modem can mitigate jamming effects. However, while the UM hardware could be modified to support 8PSK (currently unfunded), this mode is not intended to provide antijam capabilities. At the very least, the total capacity will drop by about one-third as the modem drops from 8PSK to QPSK. Also, the UM waveform was designed to operate over a transponder system, as in Approach 1. In Approach 2, however, the satellite is processed, which implies that the processor will have to track each frequency-hopping user on the uplink and downlink. This is not a task expected to be required of commercial satcom processors, and additional costs will probably result. We recommend an investigation into impacts to the spacecraft to implement de-hopping and re-hopping, and as well as investigations into the utility of alternate (perhaps purely COTS) modems and waveforms.

Approach 1 can use BFNs to form nulls, which can defeat most jammers outside of a standoff distance on the order of perhaps 800 km (smaller separations may be possible with automated and dynamic power control of the tactical terminals [6]). However, the cellular design of Approach 2 does not lend itself to nulling at all, as nulls are formed from phase differences between neighboring horns receiving the same frequencies, and the cellular antenna by design does not receive the same frequencies in neighboring feedhorns. By the same token, however, a jammer should only be able to disrupt the cell it is in and perhaps its nearest neighbors, an area 500 - 1500 km across. As always, the use of jammer location electronics on the spacecraft can help address the jamming issue through the conops of counterforce.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Approach 1 Tactical @ Transponder X</th>
<th>Approach 2 Tactical @ Processed Ka</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tactical Capacity</td>
<td>0.9 Gbps</td>
<td>4.1 Gbps</td>
</tr>
<tr>
<td>Infra Capacity</td>
<td>6.0 Gbps</td>
<td>1.6 Gbps</td>
</tr>
<tr>
<td>Radiated Power</td>
<td>1190 W</td>
<td>1242 W</td>
</tr>
<tr>
<td>Spacecraft Impacts</td>
<td>Minimal</td>
<td>On-board Processing</td>
</tr>
<tr>
<td>Terminal Impacts</td>
<td>Replace / Augment Infrastructure Terminals</td>
<td>Modify Tactical Terminals</td>
</tr>
</tbody>
</table>

*Most between limited number of fixed points

Figure 6. Payload design based on Approach 2.

Figure 7. Summary of Key Parameters.