Waveform Design For Ka-band SATCOM High Data Rate Links

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Abstract

This paper presents a methodology for the design of waveforms for high data rate communications in the Ka- frequency band. Key points involving power and bandwidth efficiency design tradeoffs are taken into consideration along with multiple access options, satellite communications payload constraints, and terminal limitations. A baseline waveform design, based on several data modulation / coding and multiple access selections, is presented and shown to meet the data rates needs for the applications of interest.

I. Introduction

It is projected that there will be an ever-increasing need for RF bandwidth to support command and control (C2), intelligence, surveillance, and reconnaissance (ISR), and other defense-related operations in the post-2015 time frame. A significant portion of these requirements will be for SATCOM capacity, needed to support beyond-line-of-sight (BLOS) wideband and narrowband communications. Wideband communication links will be required for the distribution and dissemination of sensor products from ISR platforms as well as for range extension of in-theater communication systems. Driving a significant portion of the future bandwidth needs are C2 and ISR communication links required to support distributed operations with BLOS reach back capability. The required ISR bandwidth projections needed to support these operational needs are generally viewed as stressing the capacity of future MILSATCOM systems planned for the time frame beyond 2015.

In order to satisfy the ever growing SATCOM bandwidth needs, and because of the overcrowding of the radio frequency spectrum, the Ka frequency band is becoming one of the most sought after portions of the spectrum, and there is an increasing demand for it by both military and commercial users of satellite communications. The Ka-band offers considerable amounts of bandwidth (about 1 GHz on the uplink and downlink for each commercial and military systems), and the technology development for its use has been progressing very rapidly. There have been many filings in the USA, Europe, Japan, and other countries, requesting orbital slot assignments to operate national and global communication systems in this frequency band.

In this paper we present a methodology for the design of waveforms to support high data rate communications over Ka-band SATCOM links along with key design points involving bandwidth and power efficiency tradeoffs, payload and terminal limitations, and operational requirements. We first present the general guidelines and capabilities required to satisfy typical ISR communications as well as other C2 communications applications. All this results in very high data rate needs, in the range of 250-300 Mbps along with requirements on satellite beam coverage and capacity to support typical terminal types and operational scenarios of interest. In turn, all these constraints and requirements result in a design envelope for the waveform, within which tradeoffs can be made in order to obtain an overall optimal design. Because bandwidth is always at a premium, and because of satellite and terminal power limitations, it is of utmost importance to use waveforms with the best bandwidth and power efficiency that is possible, i.e., waveforms that approach the Shannon bound performance as much as possible. However, since bandwidth and power efficiency have an inverse relationship, a judicious tradeoff is necessary in order to achieve an overall best solution. In this paper we examine various data modulation, forward error-correction, and multiple-access choices that provide the required communication capabilities for typical high data rate communication applications of interest.

This paper is organized as follows. In section II, we briefly review the general requirements of a Ka-band service/datalink in terms of desired data rates, satellite beam coverage needed, and overall system capacity. In section III, we present a general Ka-band SATCOM link analysis to determine the signal-to-noise ratios that are available for communications for typical system parameters and characteristics of interest. In Section IV, we introduce a high level waveform design in terms of modulation, error-correction coding, and multiple access, and we also discuss some of the power and bandwidth tradeoffs that are necessary in order to obtain an effective overall design. Finally, Section V summarizes some of the major constraints and results of the paper.

II. Ka-band ISR Communications

As stated previously, wideband communication links will be required for the distribution and dissemination of sensor products from ISR platforms and to support distributed operations with BLOS reach back capability. The platforms of interest are typically airborne ISR platforms, and a typical operational scenario of interest is shown in figure 2.1

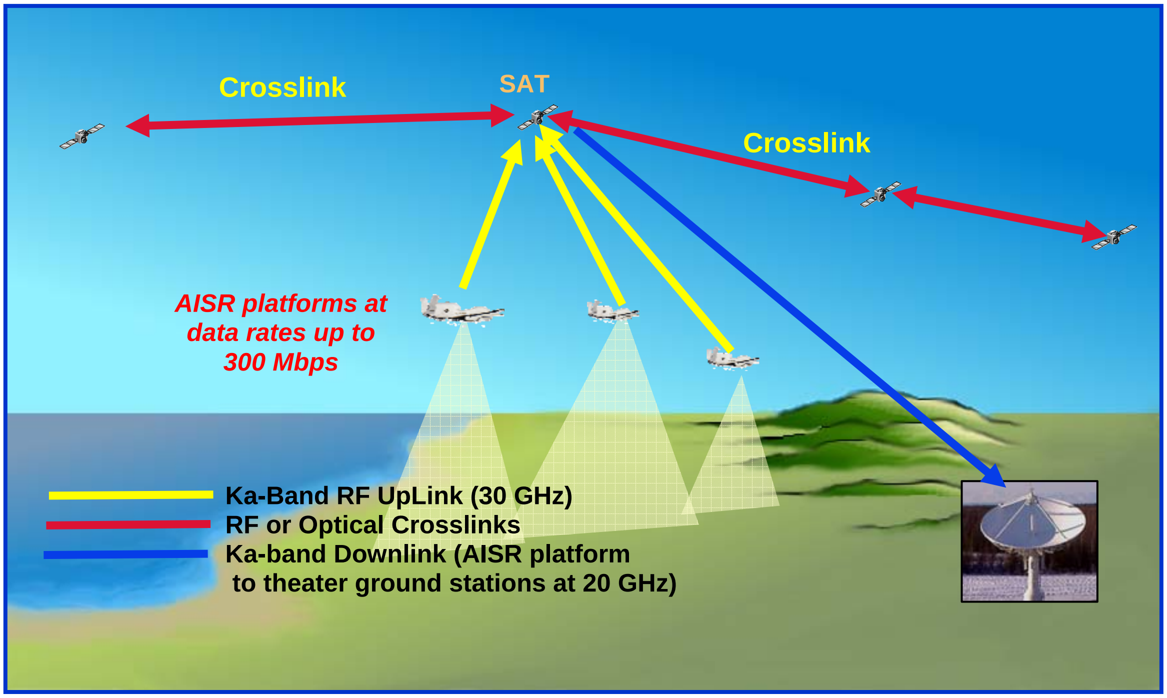

Figure 2.1. Airborne ISR Operational Scenario

As can be seen from figure 2.1, an airborne platform collects ISR sensor data, and sends it via Ka-band SATCOM links to C2 and processing centers, which are typically outside the theater of operations.

The required data rates depend on the type of sensors used by the airborne ISR (AISR) platform, but they are typically in the range of 50 Mbps to 300 Mbps, corresponding to the Common Data Link (CDL) data rates. In this paper, we will assume that a maximum data rate of 300 Mbps is needed. Also, we will focus on the uplink, and assume that full on-board processing is done at the satellite, i.e., the uplink signal is demodulated and decoded to obtain the original sensor data (information bits). The uplink data is then sent to the crosslink or downlink on-board processors for transmission to C2 or processing centers. It is also assumed that the satellites are in geosynchronous orbits.

II.1. Beam Coverage

In order to support distributed operations, the satellite uplink beams have to cover rather large areas, typically on the order of 2000 km to 3000 km across. A large area can be covered with one very large area beam, e.g., an earth coverage beam, or by using several spot beams of relatively small size. Figures 2.2 and 2.3 show the type of coverage provided by beams which vary in size from one to four degrees.

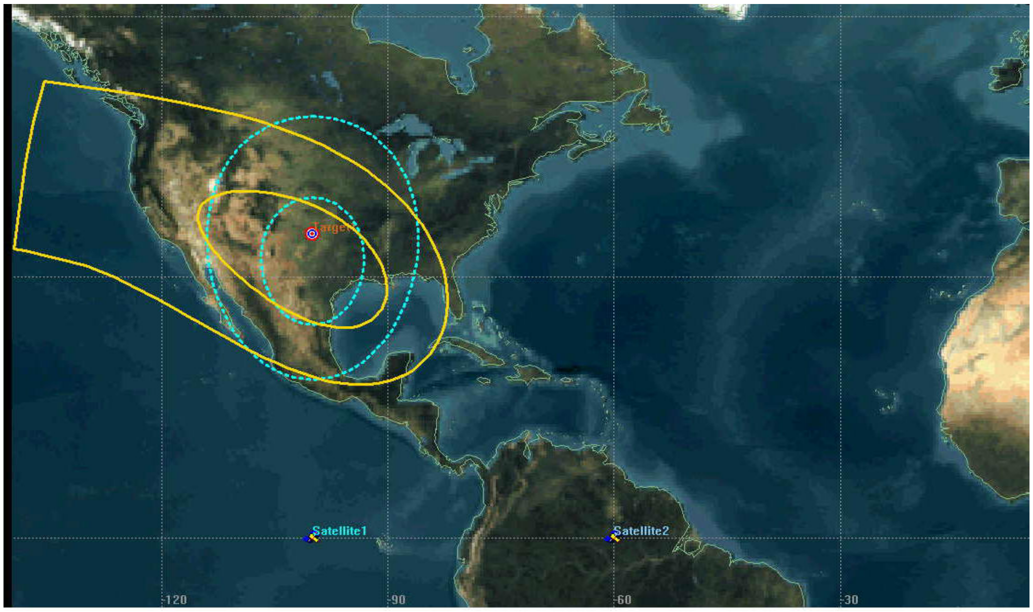

Figure 2.2. Coverage of 2- and 4-degree Spot Beams

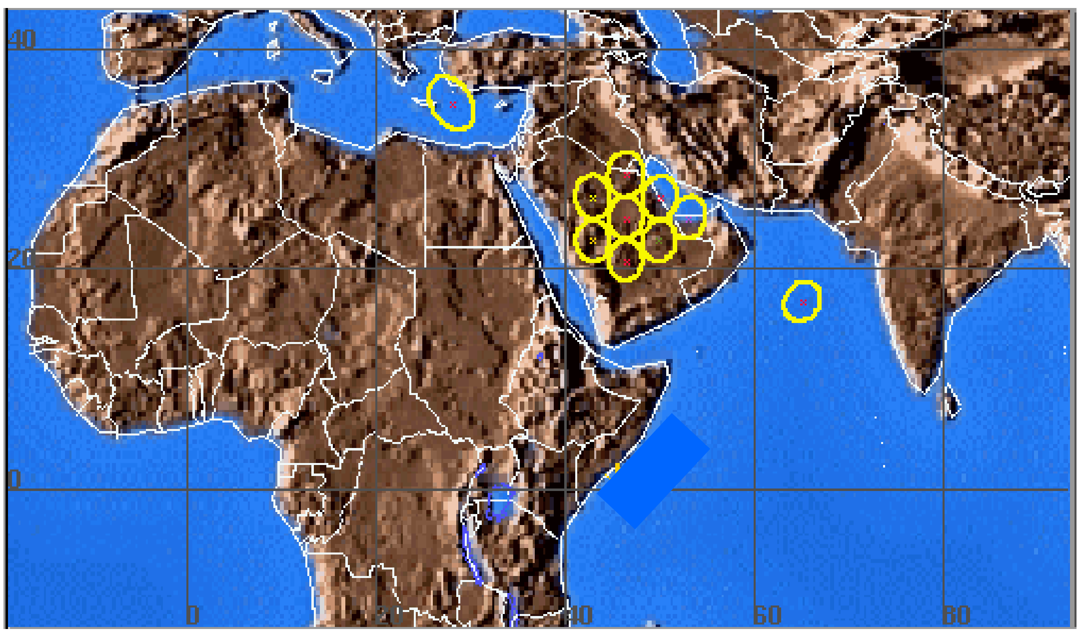

Figure 2.3. Coverage of 1-degree Spot Beams

However, there is a tradeoff between the size of the beam and the corresponding antenna gain, which directly affects the data rate that can be supported by the link. It can be shown that the satellite's antenna gain is inversely proportional to the square of the antenna beamwidth. Furthermore, we also note that the spot beam footprint is directly proportional to the antenna beamwidth. Thus, as the size of the spot beam's footprint increases, the antenna gain decreases at a faster rate, and this, in turn, decreases the data rates that can be supported on the uplink, as will be shown in section III.

In order to provide good coverage to AISR platforms distributed over large geographical areas at the data rates of interest, it is necessary to use several spot beams rather than a large area beam, such as an earth coverage beam. The individual spot beams provide the high gain needed to close the uplink at the high end data rates, and a collection of spot beams provides the desired large area coverage. This multiple spot beam spot capability can be achieved via a phased-array, or via several individual gimbaled dish antennas (GDAs). In both cases, the individual spot beams can be pointed independently at many ground locations for adequate coverage of the AISR platforms. In the case of phased-arrays, the beams are moved electronically. In the GDA case, the beams are moved by mechanical steering of the antennas. Multiple spot beams can also be implemented via a relatively large dish antenna with multiple feeds. Using combining circuits behind the feeds allows the generation of multiple spot beams of varying sizes (if desired). These are all more expensive designs when compared to a simple earth coverage horn antenna, or a single dish with a single feed. However, the multiple spot beam capability is necessary to be able to achieve both the high data rates and the wide area coverage.

Assuming that a multiple beam capability is available, it is still necessary to determine the required spot beam size. As stated previously, the smaller the spot beam size is, the higher the corresponding antenna gain is. Also, the higher the antenna gain, the higher the supportable data rate. On the other hand, the smaller the spot beam size, the larger the number of spot beams needed for adequate theater coverage. In addition, we note that the smaller the beam is, the larger the corresponding antenna is. As a result, many small spot beams require many large antennas on the satellite with the associated negative size, weight, and cost implications. Thus, the tradeoff involves finding a spot beam size that will provide adequate theater coverage when a reasonable number of beams is used, e.g., ten or less, even if the corresponding antenna gain (more precisely, the G/T) is not as high as desired. The link closure burden is then partially shifted to the terminal and to the waveform.

Figure 2.4 shows the relationship between antenna beamwidth and G/T, at Ka-band frequencies for typical satellite receiver noise figures and implementation losses of interest.

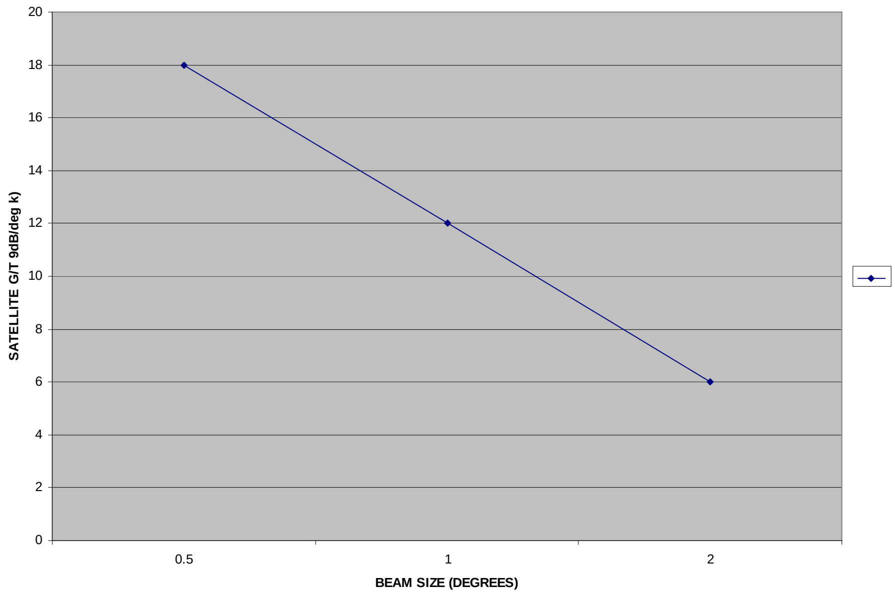

Figure 2.4. Satellite G/T vs. Beam Size (in degrees)

From this figure, we see that a 1-degree spot beam yields a G/T of approximately 12 dB/deg K. The G/T computations include implementation losses of 3 dB as well as additional losses of up to 2 dB to account for end of life degradations. Note that, when the geosynchronous satellite is directly overhead, a 1-degree spot beam has a circular footprint of approximately 665 kilometers across. Also, note that a 1-degree spot beam corresponds to a satellite dish antenna with a diameter of 30 inches.

This figure also shows that a 0.5 degree spot beam gives a G/T which is 6 dB higher than that of a 1-degree beam. However, the 0.5-degree beam requires a 5 ft antenna. In addition, to obtain the same total area coverage given by N 1-degree spot beams (where N is an integer), we would need more than 2xN 0.5-degree beams, and consequently more than 2 x N 5 ft-antennas on the satellite. As indicated previously, for adequate coverage of typical theaters, N is on the order of 10, or so. This makes the use of 0.5-degree beams rather prohibitive. On the other hand, using 2-degree spot beams would result in a much more economical design, but their associated G/T can be shown to be too low to sustain positive link margins at the data rates of interest. Because of all these reasons, we will henceforth assume that 1-degree spot beams with a G/T of 12 dB/deg K, as shown above, are used for Ka-band AISR communications.

III. Ka-band Link Analysis

In this section, we determine the signal-to-noise ratios (SNRs) that are typically available under the constraints imposed by the communications payload on the satellite as well as by the terminal equipment of interest. The SNR is given in terms of Eb/No (information bit-to-noise density ratio).

The classical link equation for the Ka-band uplink is given by:

$$Pr/No = EIRP - Ls - Lo - Lw - k + G/T,$$

where all the above terms are expressed in dBs and are defined as:

Pr/No = received (available) signal power-to-noise density ratio (dBHz)
EIRP = effective isotropic radiated power of the transmitting terminal (dBW)
Ls = total propagation losses (dB)
Lo = other losses, e.g., pointing, etc. (dB)
Lw = rain and atmospheric attenuation (dB)
k = Maxwell-Boltzmann constant (dB/deg K)
G/T = gain over temperature ratio of satellite antenna/receiver (dB/deg K)

Also, Pr/No is related to Eb/No via the baseband data rate, as follows:

$$Eb/No = Pr/No - Rb$$

where, Rb is the baseband data rate converted to dBHz.

Using the above equations, one can compute the available Eb/No at the satellite receiver as a function of desired baseband data rate. The results are shown in figure 3.1 for three types of airborne terminals of interest: (1) small, with a 1 ft antenna; (2) medium, with a 2 ft antenna; (3) large, with a 4 ft antenna. In all cases, it is assumed that the airborne terminals use a 250 W power amplifier. It is also assumed that all airborne ISR terminals fly above the weather, and therefore, there is no rain loss in the link.

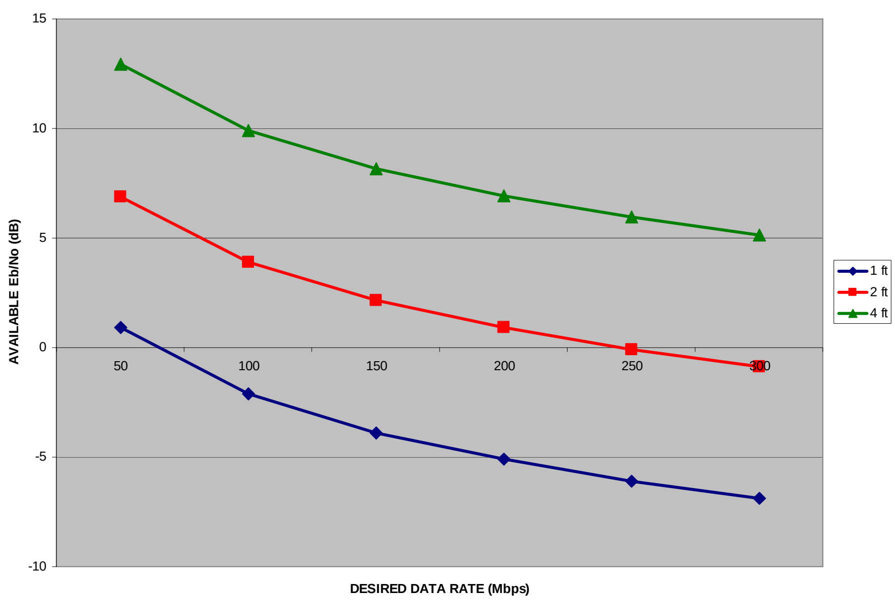

Figure 3.1. Available Eb/No at Satellite Receiver vs. Desired Data Rate

From figure 3.1, it can be seen that, depending on terminal antenna size, at the highest data rate of 300 Mbps, the available Eb/No at the satellite receiver varies from -7 dB to 5.2 dB, approximately. At the low end of 50 Mbps, the available Eb/No varies from 1 dB to 13 dB, approximately. These ranges of available Eb/No provide a design envelope for the waveform design, as seen next.

IV. Waveform Design

In order to close the link at the desired data rate, the available Eb/No at the satellite receiver has to match the required Eb/No with an additional excess margin of 1-2 dB. This additional margin is needed to cover relatively small but unpredictable variations/losses in the link.

Since one major goal is to be able to achieve the data rates at the high end, i.e., 300 Mbps, an extremely power efficient waveform is needed. However, we need to note that there is a limit to the amount of bandwidth that we can use for Ka-band AISR communications. The maximum available bandwidth in the military Ka-band is 1 GHz. Hence, a tradeoff of power vs. bandwidth efficiency is needed in the waveform design. In addition, the type of multiple access required also needs to be taken into consideration, since various types of terminals (large and small) need to be serviced at data rates in the range of 50 to 300 Mbps.

IV.1. Modulation and Error-Correction Coding

In order to obtain the best combination of data modulation and error-correction coding choices for the Ka-band AISR waveform, we need to recognize that there is a limit to the bandwidth and power efficiency that we can attain, and it is given by the Shannon bound [2], which is shown in Figure 4.1.

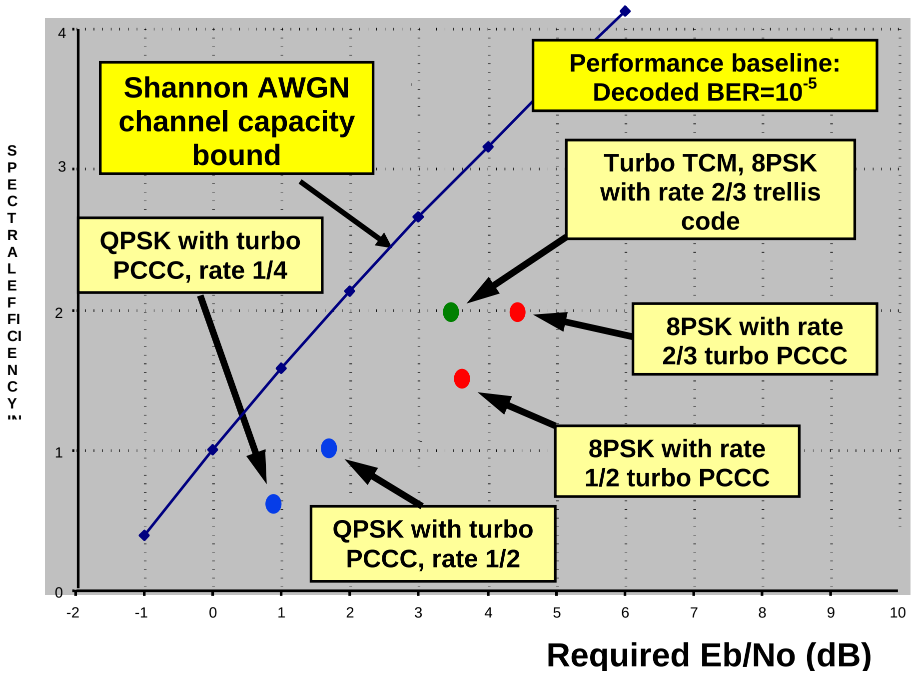

Figure 4.1. Bandwidth vs. Power Efficiency For Various Modulation/Coding Choices

Figure 4.1 also shows the spectral efficiency in terms of bits/sec/Hz (bits/sec per unit of bandwidth used) as a function of required Eb/No (in dB), for a BER = 10^{-5}, for various combinations of data modulation and error-correction coding. The forward error-correction codes in figure 4.1 are turbo parallel concatenated convolutional codes (turbo PCCC) with block lengths on the order of 1000-2000 bits.

From figure 3.1, we see that, at a baseband data rate of 300 Mbps, the available Eb/No at the satellite receiver is 5 dB, for an airborne terminal with a 4 ft antenna. As indicated previously, in order to close the link, the available Eb/No has to match the required Eb/No with an extra margin of 1-2 dB. Now, from figure 4.1 we see that the following three modulation/coding choices would allow link closure at this data rate with a decoded BER = 10^{-5}: (1) QPSK with a rate 1/4 turbo PCCC; (2) QPSK with a rate ½ turbo PCCC; (3) 8PSK with a rate ½ turbo PCCC; (4) Turbo TCM with a rate 2/3 trellis code

In terms of spectral efficiency, however, choice (1) has a spectral efficiency of only 0.5 bit/sec/Hz, and a 300 Mbps data rate would require the use of approximately 600 MHz of bandwidth, which is close to two thirds of the total available Ka-bandwidth on the uplink. Choice (2) has double the spectral efficiency of choice (1), and now 300 Mbps requires 300 MHz of bandwidth. For choice (3), which is based on 8PSK modulation, the spectral efficiency increases to 1.5 bits/sec/Hz, and 300 Mbps now require 200 MHz of bandwidth. However, choice (4), based on turbo TCM with 8PSK modulation, has the best spectral efficiency of all four modulation/coding combinations shown in figure 4.1, and now 300 Mbps require only 150 MHz. This is the best choice, since it meets the power efficiency needed, and it provides the best overall spectral efficiency.

From figure 3.1, we see that an airborne terminal with a 2 ft antenna yields an available Eb/No of -1 dB approximately, at a data rate of 300 Mbps. Because of this low Eb/No, it is clear that this terminal cannot achieve 300 Mbps for the modulation/coding choices shown in figure 4.1. However, from the Shannon bound in this figure, we note that at Eb/No = -1 dB, the best possible spectral efficiency is 0.3 bps/Hz. This theoretical performance could be approximated in practice with a combination of robust modulations and very powerful modern error-correction codes, e.g., turbo or low density parity-check codes, albeit at the expense of increased computational complexity. For example, use of 64-ary orthogonal modulation with coherent detection at the receiver along with forward error-correction provided by a turbo PCCC with a block length of about 5000 bits, requires an Eb/No of -1 dB approximately, for a BER = 10^{-5}. However, this combination of modulation/coding has a spectral efficiency of only 0.094 bps/Hz, since M-ary orthogonal modulations are power efficient but not bandwidth efficient. In this case, transmission at a rate of 300 Mbps would require 3.1915 GHz of bandwidth, which far exceeds the total Ka-bandwidth available on the uplink. The conclusion is that the waveform alone cannot provide this high data rate capability to airborne terminals with 2-ft antennas, for the baseline system parameters used in this paper.

In order to make possible for airborne terminals with antennas smaller than 4 ft to be able to close the link at the high end data rates, e.g., 300 Mbps, some of the terminal and system parameter would have to be changed, such as the terminal EIRP or the satellite beam G/T. However, increasing the terminal EIRP would require the power amplifier to be able to provide more than the baseline 250W. With the current state of technology, this is very difficult to implement at Ka-band frequencies because of size, weight, and cost constraints. With respect to the satellite G/T, the gain G would have to be increased by 6 dB in order for the available Eb/No to increase from -1 db to 5 dB, so that an airborne terminal with a 2 ft antenna can close the link at 300 Mbps, using the modulation/coding choices of figure 4.1. However, an increase of 6 dB in gain requires that the antenna be doubled in diameter. Furthermore, the doubling of antenna diameter reduces the beamwidth and beam footprint diameter by a factor of two. The result is that, in order to maintain the same theater coverage provided by N antennas with 1-degree spot beams, we would now need more than 2 x N antennas of essentially double the size (and weight) of the 1-degree beam antennas. This would be a serious impact to the satellite because of negative size, weight, volume, power, and cost implications, and it would probably be prohibitive in general. Hence, the general conclusion is that, for realistic system and terminal parameters, as assumed in this paper, small and medium airborne terminals have to be satisfied with data rates in the low and mid-range of the 50-300 Mbps total range.

IV.2. Multiple Access

In order to provide service to many terminals of different sizes at various data rates in the range of 50-300 Mbps, it is necessary to have a multiple access scheme that will make the best use of bandwidth, so that small and medium terminals transmitting at lower data rates do not use more bandwidth than it is really necessary. Since frequency-division multiple-access (FDMA) and time-division multiple-access (TDMA) have the same spectral efficiency, for simplicity we will use FDMA, and partition the uplink band into an appropriate set of sub channels, which could be grouped and used by the terminals to transmit at a desired data rate in a bandwidth-efficient manner.

It is now necessary to select the specific modulation/coding choices to be used by AISR terminals accessing the Ka-band service. Based on the discussion in section IV.1 above, we see that only choices (1), (2), and (4) are needed to cover the range of available Eb/No values of the various terminals, for data rates 50-300 Mbps. We will henceforth refer to these modulation/coding choices as communication modes 1, 2, and 4, respectively. One disadvantage with this selection is that modes 1 and 2 use forward error-correction, i.e., the encoding and data modulation are done separately, whereas mode 4 uses trellis-coded modulation, i.e., the 8PSK phases are encoded directly using set partitioning with a turbo code. As a result, the satellite receiver has to process these modes differently. When modes 1 and 2 are used, the uplink baseband signal is demodulated / detected first, and the output bits are then turbo decoded. When mode 4 is used (turbo TCM), the trellis-encoded phases of the 8PSK uplink baseband signal are demodulated using iterative techniques to obtain the information bits directly. As a result, the receiver complexity is increased because two different types of processing have to be implemented. Incidentally, it should be noted that the rate 1/2 turbo PCCC code in mode 2 could be derived from the rate ¼ code used in mode 1 by puncturing. Consequently, the same decoder could be used on board the satellite for both these modes.

Assuming that only communication modes 1, 2, and 4 are included in the baseline waveform design, we need to partition the uplink band into a number of sub channels that the terminals can access using these modes, as appropriate, to communicate at data rates 50-300 Mbps. For this, we partition the uplink 1 GHz band into 40 25-MHz sub channels, which can be accessed in groups consisting of one up to a maximum of 12 contiguous sub channels. For best spectral efficiency, the terminals are required to use the most spectral efficient mode that will allow link closure, based on the available Eb/No. We now give two examples of sub channel usage:

1. An airborne terminal with a 4 ft antenna that needs to transmit at 300 Mbps, would use mode 4 and would require six sub channels. As noted above, with mode 4, transmission at 300 Mbps requires 150 MHz of bandwidth, which is what six sub channels provide. If this terminal needed to transmit at 50 Mbps, it would still use mode 4, but now only one sub channel would be required.
2. Now, suppose that an airborne terminal with a 2 ft antenna needs to transmit at 100 Mbps. At this data rate, this terminal cannot use mode 4, because the link will not close. The most spectrally efficient mode than can now be used is mode 2, which has an efficiency of 1 bps/Hz. Hence, this terminal would need to use four sub channels, since 100 MHz are needed. If this terminal needed to transmit at 150 Mbps, it would have to switch to mode 1 in order to close the link. Since mode 1 has a spectral efficiency of 0.5 bps/Hz, 300 MHz of bandwidth would be needed, and so, 12 sub channels would be required for transmission at 300 Mbps.

The above examples illustrate the classical tradeoff of power efficiency vs. bandwidth efficiency in communication theory. Another note is that requests by the terminals for Ka-band sub channel resources along with actual sub channel assignments by the satellite have to be done by means of an order wire channel, which can operate as part of the Ka-band service. Hence, the Ka-band terminals need to also have receive capabilities.

V. Summary

We have presented a methodology for the design of waveforms for high data rate communications in the Ka- frequency band. Key design tradeoffs involving power and bandwidth efficiency were taken into consideration along with multiple access options, satellite communications payload constraints, and terminal limitations. It was shown that the data rate needs for airborne ISR communications can be met by a waveform design based on three communication modes. These modes use QPSK or 8PSK data modulation along with error-correction codes of various rates, or trellis-coded modulation of rate 2/3. A multiple access option, based on FDMA was also presented, and it was shown to meet the needs to service a mix of small, medium, and large terminals at various data rates in the range 50-300 Mbps, in a spectrally efficient manner.

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