Airborne Satellite COTM

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Introduction

Successful communication network design, whether terrestrial, satellite, static or communications-on-the-move (COTM), is successful only when user applications and requirements are fully understood. Designing a satellite airborne COTM infrastructure for the military is challenging. The end-user applications range from routine data and email through flash override Voice over IP (VoIP), to high-definition Intelligence, Surveillance and Reconnaissance (ISR) video. These demanding, end-user applications require high bandwidths that must be supported on a fast-moving aircraft using a very small antenna, while providing global coverage under stringent Communications Security (COMSEC) and Transmission Security (TRANSEC) requirements. This paper presents the challenges and the current state of technology enabling a global airborne COTM network for Ministries of Defense (MoD).

Traditional Data Applications

There are two primary sets of applications for airborne COTM. The first is what are considered traditional data applications, such as email, video conferencing and VoIP. The second is ISR video backhaul and dissemination. The military's unique demands on the transmission of these data types can greatly impact network design.

Whether traditional data applications are encrypted or not, it is important to understand how IP data is transported in a satellite network. Transmission Control Protocol (TCP) acceleration is used to ensure link efficiency when transmitting over a high latency media, such as geostationary satellite. With unencrypted data, the TCP acceleration occurs transparently in the satellite router. When the end user encrypts the data prior to transmission, the TCP headers are not available for TCP acceleration. Therefore, the acceleration has to occur prior to encryption. Introducing TCP or Wide Area Network (WAN) accelerators to a network can dramatically change the architecture, IP addressing and cost of deployment.

Prioritizing both voice and data traffic is imperative to the military. In the case of Multilevel Precedence and Preemption (MLPP) VoIP, multiple levels of prioritization with strict priority queuing must be supported. This exceeds the quality of service capabilities of most commercial-grade satellite products on the market today, making military grade networks necessary.

TCP, WAN and MLPP capabilities are now being deployed on military aircraft executing data transfers. While the bandwidth requirements of a given mission will vary, typical data applications being utilized on an aircraft is usually on the order of a T-1 (1.544 Mb/s). Such data rates are easily obtainable in the Ku-Band using a 30cm to 45cm parabolic antenna or the equivalent aperture flat panel, using a Time Divisional Multiple Access (TDMA) return channel.

Airborne COTM frequency band and return-channel architecture are particularly important to ensure secure data transmission. Due to the proximity of adjacent satellites and the need for such small diameter antennas on aircraft, the Ku-Band often necessitates using spread-spectrum technology to lower the power spectral density of the waveform.

ISR Design Considerations

The second application driving the airborne COTM market is ISR video backhaul and dissemination. High-definition video transmission from an aircraft is a daunting challenge because it requires a great deal of bandwidth. Using the appropriate Coder/Decoder (CODEC), high-definition video can be transmitted in as little as 2 Mb/s on an in-route carrier. With aircraft challenged by adjacent satellite interference and power-limited transponder transmission rates, while using very small aperture antennas, this data rate begins to push the transmission limit of an aircraft utilizing TDMA in the Ku-Band.

ISR Requirements

There are network design decisions that can improve ISR video data rates. 14 Mb/s and greater data rates off an aircraft are possible with the right combination of technologies. Frequency band is important because the proximity of the next satellite transmitting in your frequency band determines the need for spread spectrum. While most Ku-Band satellites have another satellite in the next orbital slot, usually spaced 2 degrees, X-Band satellites are spaced at 3 degrees, allowing higher transmit power without Adjacent Satellite Interference (ASI). While it is not always practical, either, X- or Ka-Band can allow for greater data throughputs.

Another important design choice when building an ISR airborne COTM network is network topology. TDMA is a very bandwidth efficient technology, but only when transporting intermittent, packetized data. A better choice for ISR transmission off an aircraft is a Single Channel Per Carrier (SCPC) link. Video links are effectively always on, so there is no statistical sharing to leverage in TDMA. With their simplicity, SCPC carriers have much lower Layer 2 overhead and more efficient spectral efficiencies. In addition, because SCPC channels are not as dynamic as in TDMA, the demodulators often have 1 to 1.5 dB better C/N characteristics. An SCPC modem is often the simple solution for a network which supports only one ISR platform.

Most networks need to support multiple platforms simultaneously. That, coupled with the fact that ISR data transmission is very asymmetric, with most of the data being transmitted off the aircraft, mean a shared out-route with SCPC return channels is the optimal network configuration.

Antenna Limitations

One of the greatest airborne COTM challenges is the requirement for extremely small, equivalent aperture antennas. The practical limit for an antenna on an aircraft is between 30cm and 45cm. There are notable exceptions of course, including the 1.2m Ku antenna mounted in a Global Hawk. However, in this paper, we will describe the requirements and limitations of approximately 45 cm equivalent aperture antennas. Antennas of this dimension severely limit the achievable link budgets of a COTM network. In addition, the pointing error and focus of such antennas often require using Spread Spectrum technology to mitigate ASI.

Spread Spectrum

Spread Spectrum is a technology used to lower the Power Spectral Density (PSD) of a given waveform. While lowering the PSD of a waveform lowers the interference with other satellites adjacent to the target satellite transmitting in the same, it comes with a price. To lower the PSD of a waveform, a Pseudo-Noise (PN) Code of the appropriate chip rate must be XORed with the transmitted data. The net result is a transmitted waveform at the same data rate that occupies a greater amount of transponder bandwidth.

The large bandwidth required for an airborne network is detrimental to the proliferation of World Wide Airborne Networks (WWANs). All Spread Spectrum implementations on satellite routers are not alike. Spread Spectrum for satellite systems can be implemented in two broad ways. One way to implement Spread Spectrum for satellite systems is Code Division Multiple Access (CDMA). In CDMA, the network uses multiple, orthogonal PN codes to differentiate remotes in the network. The main disadvantage of using CDMA to mitigate ASI is that the power transmitted by multiple remotes on the same frequency effectively stacks. This means the chip rate required to stay below the PSD required is based on the combination of link budget, satellite band, proximity to nearest satellite transmitting in the same beam, antenna off-axis characteristics and the number of remotes in the network.

For an airborne network of any size, this would lead to an unacceptably high use of satellite bandwidth. A more cost-effective approach is using a TDMA-based direct sequence Spread Spectrum. In a TDMA-based network only one remote at a time will transmit. Therefore, the chip rate needed and the occupied bandwidth required will be independent of the number of aircraft in the network.

Two of the factors determining if Spread Spectrum is required are the satellite band being utilized and the proximity to the nearest satellite utilizing the same band. As stated earlier, Ku-Band satellites are closely packed in the orbital slots, virtually guaranteeing Spread Spectrum us for Airborne COTM networks utilizing this band. This is contrasted to X-Band. There are fewer X-Band satellites in orbit so their spacing is much greater. In most cases, an airborne network operating on X-Band will not need to implement Spread Spectrum. The use of Spread Spectrum exacts a toll beyond the extra bandwidth it occupies. All satellite modems have a maximum transmission rate, known as the symbol rate. Since Spread Spectrum requires more occupied bandwidth for a given data rate, a satellite modem using spread spectrum may be limited by its maximum symbol rate.

Doppler Effect

The Doppler Effect has been a consideration of satellite modem manufacturers for some time. The Doppler Effect is the change in frequency of a wave, as perceived by a receiving station, as either the transmitter or the receiver moves. Historically, the Doppler Effect in satellite transmission has been a secondary consideration arising from the satellite's motion in its station-keeping box. With high-speed COTM vehicles such as aircraft, the Doppler Effect has a great impact on the effectiveness of demodulators. The amount of Doppler Effect observed from a moving vehicle is dependent on the geometry of motion. For example, whether the aircraft is moving toward or away from the satellite (+/-), as well as the angle (θ), the velocity, and the acceleration of the vehicle, all impact the Doppler Effect. These formulas quantify frequency shift based on the pertinent variables.

UNIFORM VELOCITY

$$\text{Time Drift} = \frac{\pm v \cdot \cos(\theta\ E1) \cdot 10^9}{c} \ (\text{ns/s})$$

$$\text{Frequency Shift} = \frac{\pm V \cdot f_{carrier} \cdot \cos(\theta\ E1)}{c} \ (\text{Hz})$$

$$\text{Frequency Drift} = 0$$

UNIFORM ACCELERATION

$$\text{Time Drift} = \frac{\pm (v \cdot at) \cdot \cos(\theta\ E1) \cdot 10^9}{C} \ (\text{ns/s})$$

$$\text{Frequency Shift} = \frac{a \cdot t \cdot f_{carrier} \cdot \cos(\theta\ E1)}{c} \ (\text{Hz})$$

$$\text{Frequency Drift} = \frac{a \cdot f_{carrier} \cdot \cos(\theta\ E1)}{c} \ (\text{Hz/s})$$

Terrestrial and maritime vehicles travel relatively slow so the Doppler Effect does not come into play. It is, however, a major factor on airborne platforms. For comparative purposes, at Ku-Band, an aircraft travelling at 1,188 Km/h, and experiencing 1.7 G acceleration with a zero degree look angle, will have an uplink frequency shift of 15,950 Hz. Such large frequency shifts must be compensated for. For the in-bound, in the iDirect® system, such frequency shifts have been accommodated through advances in demodulator code, primarily by adopting a multiple correlator structure.

Antenna Skew

Flat-panel antennas can cause skew angle issues. This off-axis Effective Isotropic Radiated Power (EIRP) problem must be addressed.

Some antennas, particularly vehicle mounted antennas, have apertures that are not round. As a consequence, the beams coming from these antennas have a peculiar shape – they are elongated, with the large width of the beam along the narrow width of the antenna. Because these antennas are mounted on the tops of vehicles, the beam leaving the aircraft is wide in the vertical direction and narrow in the horizontal direction, as seen from the aircraft. For a mobile terminal, this presents some particular challenges. Antennas with wider beams hit the adjacent satellites with more power, for a given bore site power. For antennas with beams that are not round, the adjacent satellite interference will depend on the location of the antenna on the earth.

As illustrated in Figure 1, the satellite is due north of the antenna's longitude, and the wide angle of the beam is perpendicular to the geosynchronous arc. The ASI is low for a given bore site power. However, if the antenna moves to a location west of the satellite, as shown in Figure 2, then the wide part of the beam is exactly along the geosynchronous arc, and the adjacent satellites see a significant amount of radiation from the terminal. The angle between the short axis of the beam and the geosynchronous arc is the skew angle. Figure 1 illustrates 0 degrees skew, which is the best case, while Figure 2 illustrates 90 degrees skew, which is the worst case. The challenge is having an adaptive system respect the ASI limits in the bad skew case, while taking advantage of the better spectral efficiency in the good skew case.

Figure 1. Flat Panel Antenna - Favorable (low) Skew

Figure 2.   Flat Panel Antenna - Unfavorable (high) Skew

The beam width of a terminal, combined with the appropriate regulatory ASI limits, limit the spectral power density that the terminal can radiate on the bore site. This, in turn, affects the allowable C/N and the spectral efficiency achievable.

Figure 3 illustrates how a given antenna is characterized. The X axis is the skew angle, with 0 on the left and 90 degrees on the right. The vertical axis is the allowable spectral power density allowed for a given regulatory regime. This curve can be computed for a given antenna pattern and regulatory regime by looking at the beam pattern as sliced along different skew angles, and comparing them to the regulatory limits.

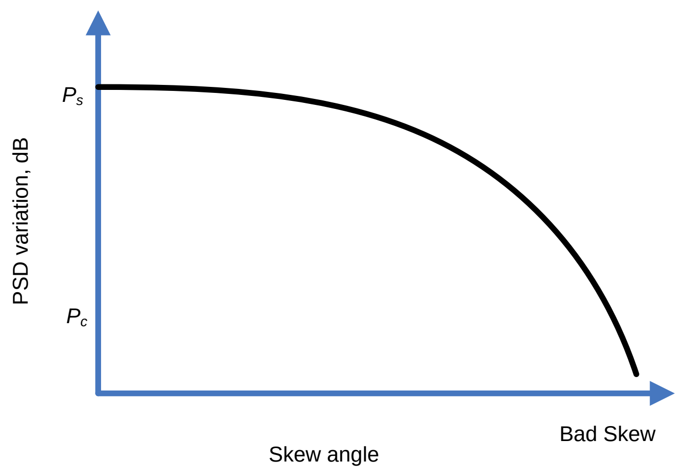

Figure 3. Maximum Allowable PSD as a Function of Skew Angle

If the vehicle tilts, the skew angle is affected. For example, if the aircraft in Figure 1 banks by 45 degrees, and is flying due south, then the skew angle will be 45 degrees. Sometimes local tilt will make the skew angle worse, and sometimes better, depending on the direction of tilt. So, given an antenna with an elongated beam, how can we maximize the spectral efficiency while guaranteeing that the off-axis regulatory requirements are met?

Terminal and Network Configurations

Terminal Configuration

The iDirect Government Technologies (iGT) system allows a terminal to be configured with a maximum operational C/N. This is controlled by a combination of an accurate uplink power control, and only assigning TDMA bursts to a remote on carriers with a low enough C/N to respect this limit. To determine the C/N, the customer must do a link budget to translate the allowable uplink power spectral density into a C/N. This approach allows the transmitted spectral power density to be increased above the clear sky regulatory limit in the event of rain fade. This is consistent with existing regulatory standards, which assume adjacent satellites see the same rain fade as the targeted satellite.

However, the maximum C/N can change based on two factors:

1. For a given PSD, the C/N will depend on the satellite G/T for a particular spot on the earth. Hence, in spots with higher G/T values the maximum allowable C/N can be increased.
2. For different skew angles, the allowable PSD can be increased, which allows for higher C/N values.

The first case is catered to by using a map of the G/T contours, which is stored on the remote for avionic terminals.

The second factor is discussed in this paper. Ultimately the terminal will determine how much it can increase its C/N from the map and the skew considerations, and report these to the hub. The hub will then use this information to assign slots on carriers which will respect the maximum C/N. The map that is created should be done with only the G/T contours, and without any skew angle considerations.

Determining the maximum PSD as a function of skew angle under the regulatory regime of interest should be completed first. This is usually done by the antenna manufacturer or terminal integrator. Next, a completed link budget determines the lowest C/N carrier needed to support the worst-case skew angle you wish to support. Depending on the satellite parameters, it may be possible to support skew angles to the maximum of 90 degrees. However, the carrier required may be so inefficient as to not make business sense. In this case, a smaller maximum skew can be chosen. The link budget will give an operational C/N for the worst case skew and G/T. Carriers must be included in the in-route group which will support this worst case condition. Once the worst case (or "cut off") skew angle is determined, the maximum local tilt must be configured. A local tilt maximum value will allow the remote to stay in network during more extreme maneuvers, but force the remote to use a less efficient carrier. This is explained in more detail in the next section.

Once the parameters have been determined, the relative C/N as a function of skew angle is entered in the Network Management System (NMS) for the antenna. In addition, the maximum local tilt is configured for the remote. Adaptive inroute groups with appropriate carriers for the different conditions are configured including low C/N carriers for the high skew cases, and higher C/N (and more efficient) carriers for the low skew cases.

Once the parameters above have been configured, then the system operates as follows:

1. When the terminal acquires, it only sends burst invitations on carriers for which the | regulatory limit is met under the worst case skew and G/T for the beam. The terminal sends the maximum configured skew angle to the antenna control unit (ACU) using OpenAMIP (Antenna Modem Interface Protocol). By utilizing OpenAMIP, any antenna could be integrated to any vendor modem.

2. If at any time the ACU determines the skew exceeds that specified in the OpenAMIP command, it ceases transmission and signals this to the remote. This is treated as a blockage.

3. Once the remote has acquired, it determines its "level flight skew" based on its geo-location and the satellite position. It adds the local tilt to this value, and computes a new current maximum skew. With this maximum skew, it does two things. First, it signals this value to the ACU over OpenAMIP. Next, it uses the configured C/N versus skew curve to compute the C/N adjustment over the worst-case skew which is allowed, and signals this to the hub. This is illustrated in Figure 4. Aa is the level flight skew, and Ae is the skew with the maximum local tilt. The increase in C/N is Ps-Pc in the diagram.
   The remote also reads the increase in C/N from the local map, and signals this to the hub as well.

4. The hub takes the total allowable increase in C/N, and uses this to allow more spectrally-efficient carriers to be used by the terminal.

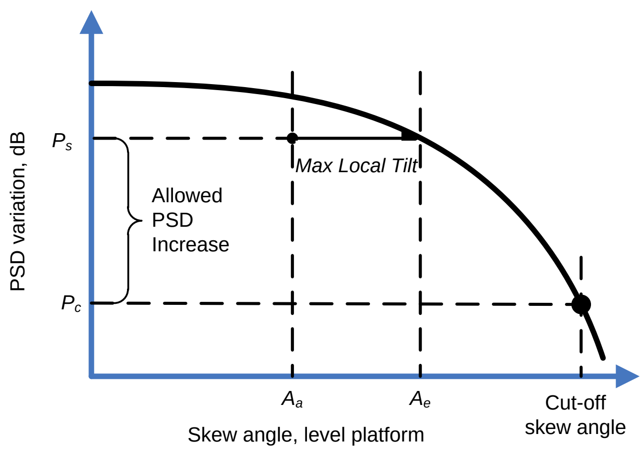

Figure 4. Picking Operational Parameters

Automatic Beam Switching

The antenna systems used on airborne platforms have become remarkably sophisticated. The strides made in improving the performance and effective aperture of flat panel antennas are very impressive. Whether the designer chooses a parabolic or flat panel antenna, the integration of the antenna with both the aircraft flight systems and the satellite router requires a great deal of development. To understand why such a level of integration is required, all the steps necessary to seamlessly hand off an aircraft from one satellite beam to the next must be considered.

Let us consider an aircraft leaving the east coast of the United States heading for a location in Western Europe. While the aircraft is in the U.S., the antenna is locked on a particular DVB-S2 out-route carrier from a satellite and landed at a teleport on the east coast of the U.S. The satellite router's IP network is a part of a system and all IP traffic destined for the aircraft router is being sent to the east coast teleport upstream router. As the aircraft travels east, at some point over the Atlantic, the current satellite coverage ends and the transition to another, hopefully overlapping satellite beam needs to take place. The question is, where and when is the right place to make the switch and how would either the remote satellite router or the antenna control unit know when to make the switch?

The only feasible solution is to provide the satellite router and antenna control unit system with the EIRP contour maps of the available satellites. The iDirect Global Network Management System (NMS) includes global mapping which has the EIRP contour maps for most geosynchronous satellites in orbit. The challenge now becomes one of communications. The aircraft IRU has the current geographic location of the aircraft and the satellite router is in communication with the hub and can receive the appropriate EIRP maps. Utilizing the OpenAMIP protocol, different devices in the network can communicate with each other. Therefore, the IRU can provide the geo coordinates to the remote, and the remote can command the antenna ACU. Internet Protocol networking requirements present the next set of challenges faced by anyone designing a World Wide Airborne network.

Global Network Management

Fast moving and long distance airborne terminals will need to be handed from one beam to another and from one teleport to another. This mobility poses a number of challenges for IP networks and network management systems. Basic IP network design assumes core network devices like routers and switches will remain at a fixed location even if host devices come in and out of the network. Dynamic routing protocols like OSPF, RIP v2, ISIS, BGP and others are designed to accommodate subnets being added to and deleted from a network and for interconnecting links to come in and out based on backhoes and power outages.

The new mobility in the satellite market allows for IP routers, built into remote terminals, to move from beam to beam and roam from teleport to teleport and from continent to continent. COTM requires a new approach to the design and management of mobile networks. To address this challenge iDirect has developed a global NMS, within which a single COTM remote may have multiple instances in teleports around the globe. The flexibility of iDirect's global NMS allows IP addresses to remain fixed while allowing for configuration differences across beams, including varying out-route and in-route sizes, as well as different QoS profiles.

Security

COTM and itinerant terminals pose new challenges from a security perspective. The need for advanced encryption over the satellite link is obvious. As a remote moves from location to location and beam to beam, one never knows who may be listening to the link. Satellite service providers will need to offer strong encryption, such as 256-bit keyed AES. For government users, FIPS 140-2 certified encryption will be required.

TRANSEC

iDirect has developed Transmission Security (TRANSEC) for TDMA-based COTM systems to meet very high security requirements. TRANSEC has a number of components, including the ability to obfuscate any traffic volume or remote terminal activity information, which may allow an adversary to infer useful information based on activity levels.

It is doubtful any commercial applications will require the level of security TRANSEC provides. There is one aspect of TRANSEC, however, that may prove beneficial in a commercial network. The more mobile and dynamic a network is, the more vulnerable it becomes to rogue remote terminals gaining access to the network. Most satellite NMS systems authenticate a remote terminal by verifying a physical hardware address in the remote terminal, similar to a MAC address in Ethernet. It is theoretically possible for an adversary to change the hardware address of a remote. Once a remote's hardware address has been changed, it could be acquired into a restricted network.

There is a component of TRANSEC for TDMA VSAT systems known as X.509 certificates which could be employed in both commercial and military networks to stop such intrusions. X.509 certificates are a standard RFC 2459, and are simply a digital certificate issued by a Certificate Authority (CA). The X.509 certificate uses the Public Key Infrastructure and leverages RSA public key encryption. In this way, a remote can be authenticated to a teleport and a teleport to a remote. By employing X.509 certificates, a network operator can be assured all remotes acquiring into the network are authorized and that remotes in the field will not acquire into an adversary's network. The iDirect NMS has the capability to accept third party certificates or to generate its own.

The advent of airborne COTM technology will be very beneficial for MoD operations, if implemented correctly. However, COTM presents a number of physics, operations and security challenges. A holistic approach to COTM network design is needed, taking into account satellite frequency bands, antenna sizes, integration of a satellite remote with a global key distribution for seamless beam switching between secure networks and an antenna control unit for uninterrupted communication.