KA BAND SATELLITE COMMUNICATIONS DESIGN ANALYSIS AND OPTIMISATION

LEONG See Chuan, SUN Ru-Tian, YIP Peng Hon

ABSTRACT

Ka band satellite communications (SATCOM) frequencies provide new opportunities to meet high bandwidth demands, especially for small aerial, maritime and mobile land platforms supporting beyond line of sight requirements for network-centric operations. This is possible due to the availability of 3.5GHz of bandwidth, and also because Ka ground segment components are typically smaller in dimension compared to those of Ku band. However, Ka band links experience much higher rain fades in tropical regions as compared to Ku band and C band. In this article, various factors in the link budget are explored to determine their impact on overall signal strength. These factors can be traded off and optimised to enable the realisation of a Ka band solution for SATCOM.

Keywords: Ka band, satellite communications, link budget, trade-off analysis, mitigation technique

INTRODUCTION

Various types of satellites, including Geosynchronous Earth Orbit (GEO), Medium Earth Orbit and Low Earth Orbit support beyond line of sight communications. The link budget analysis in this article is based on GEO satellites. A GEO satellite orbits at a fixed longitudinal location at an altitude of about 36,000km above the equator. The transponders on the satellite provide a signal boost and frequency translation of signals for the ground terminals. The antennas on the satellite are designed to provide the required communications coverage to the terminals on the ground. The ground segment comprises the hub and remote terminals of different sizes and transmission powers. The remote terminals can be hosted on different static or mobile platforms.

Operating in the Ka band offers some significant advantages over conventional satellite networks operating in the Ku band and lower frequencies. Not only is more bandwidth available at the higher Ka band frequencies, Ka band antennas have higher gain than antennas of comparable size operating at lower frequencies. However, the disadvantage of using the Ka band is that adverse weather conditions impact the Ka band much more than at lower frequencies. It is therefore important that there is appropriate planning for the implementation of well-designed ground systems, network links reliability and resources so as to mitigate these adverse weather effects (Petranovichl, 2012) (Abayomi Isiaka Yussuff, & Nor Hisham Khamis, 2012) (Brunnenmeyer, Milis & Kung, 2012).

This article presents a design approach and analysis of key satellite communications (SATCOM) network parameters for a Ka band network. Various trade-offs and optimisation between operational parameters (e.g. link availability), ground segment (e.g. power amplifier ratings and antenna sizes) and space segment (e.g. transponder power and bandwidth) will be considered. In addition, mitigation techniques such as hub site diversity, adaptive coding and modulation (ACM) and uplink power control are explored to mitigate the increased rain fades at Ka band and improve the overall link availability. This analysis demonstrates that it is feasible to use the Ka band to support mission critical SATCOM operations in our region.

KA BAND DRIVERS

The Ka band is attractive as a SATCOM solution due to a few reasons.

Availability of Spectrum and Higher Throughput

Substantially more spectrum bandwidth is available at the Ka band than at the Ku band and other lower frequencies. For example, Ku band allocation is around 2GHz for uplink and 1.3GHz for downlink with actual contiguous bandwidth allocation of less than 0.5GHz per satellite. In comparison, the Ka band SATCOM has a bandwidth of 3.5GHz for both uplink and downlink. Table 1 illustrates the military and civilian frequency allocation. With the wider spectrum availability at the Ka band, higher traffic throughput can be supported. Full motion video for example, has been identified as a key driver in the demand for bandwidth that can be realised by Ka band satellites (Northern Sky Research [NSR], 2012). In addition, as the Ka band has commercial and military bands adjacent to each other, commercial services can also complement the military band's capacity.

Band	Receive (GHz)	Transmit (GHz)
Military	20.2 - 21.2	30.0 - 31.0
Civilian	17.7 - 20.2	27.5 - 30.0

Table 1. Frequency allocation within the Ka band

Greater Cost Efficiency

Ka band satellites feature narrow spot beams (0.5° to 1.5° at 3dB beam width) which support greater frequency reuse in geographically isolated spots. With larger allocation and frequency reuse capabilities, using the Ka band translates to at least a 1 to 2 order magnitude increase in transponder throughput, therefore reducing leasing cost per unit bandwidth.

Smaller Terminals

At higher frequencies, wavelengths are smaller, allowing proportionally smaller, lighter weight and probably less expensive terminals to be realised. The reduction of physical dimensions therefore allows Ka band SATCOM to be made available for new markets such as manpacks and mobile platforms. The use of more focused and narrow Ka band spot beams provides higher equivalent isotropic radiated power (EIRP), signal gain (G/T) and therefore better signal link quality or higher data rates for these smaller terminals. Comparing the Ka band to the Ku band, the improvement in overall link quality with the use of narrow spot beams is in the range of 6dB to 10dB.

Greater Resiliency to Interference

With wider Ka band bandwidth, better inherent anti-interference properties can be achieved (e.g. frequency hopping or direct sequence spread spectrum). With Ka band transponder sizes of 125MHz or more over 54MHz at Ku band, the additional interference margin with twice the spreading can be improved by at least 3dB.

KA BAND CHALLENGES

With the introduction of smaller mobile terminals for Ka band SATCOM, more stringent link requirements will need to be met. The design challenges are as follows:

Meeting Adjacent Satellite Interference Regulations

The regulatory bodies governing satellite communications include the International Telecommunication Union (ITU) and the Federal Communications Commission. With the high density of satellites in orbit and many more Ka band satellites planned for launch, adjacent satellite interference (ASI) will be a key concern. Satellite terminals that wish to transmit must meet the emission regulations. ASI is more challenging for small terminals where the antenna side lobe powers are large with respect to their main lobes, thereby limiting the maximum power they are allowed to transmit. When these terminals are on the move, allowable emissions are constrained further as the mechanical antenna pointing accuracy experienced during shock and vibration needs to be accounted for during movement through land, various sea states or air turbulence.

Large Rain Attenuation

The SATCOM link that passes through the atmosphere is degraded by rain, fog, cloud, ice, snow and hail. The biggest challenge in using the Ka band is the high rain attenuation compared with the Ku band and higher rainfall rates in the tropics. Since the electromagnetic wave absorption component is increased at Ka band, the amount of attenuation per unit length is also increased (see Figure 1). Additional margin is needed to ensure high system availability or trade-off in link availability. However, adding an additional margin may be impractical for remote terminals with small antenna and low power amplifier that operates in high rainfall regions. For example, collected rain statistics in Singapore generated by Leong and Foo (2007) show a higher rain rate than ITU specifications (International Telecommunications Union – Radiocommunications Sector [ITU-R], 2012). This results in a downlink rain loss of 12dB at the Ka band versus 2.6dB at the Ku band to achieve 99% link availability. In addition to higher attenuation, the rain fade rate at the Ka band will be very much higher than at the Ku band. The high rain fade rate will impact the operation of mitigation measures such as ACM algorithms built into the satellite modem.

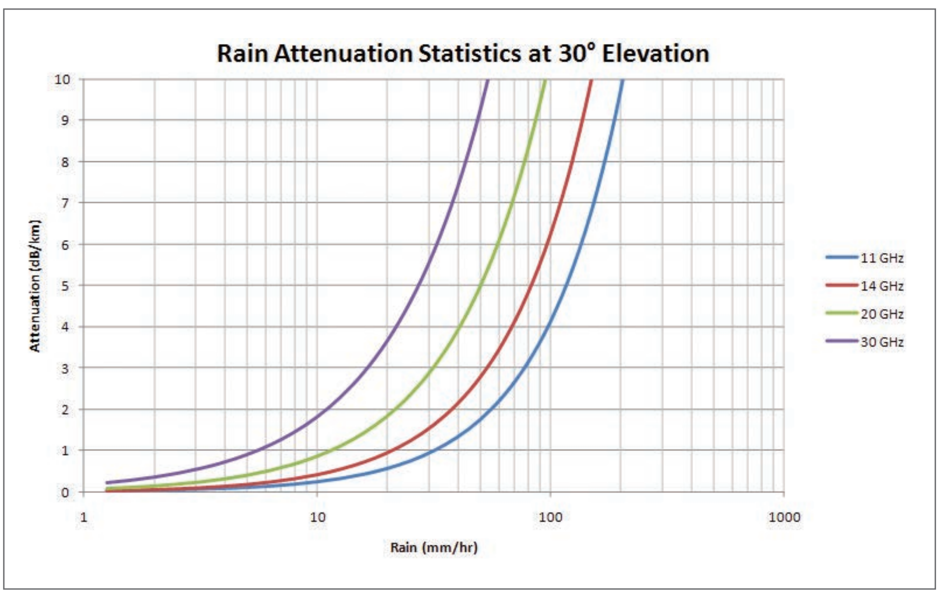

Figure 1. Rain attenuation statistics at 30 degrees elevation

MITIGATION TECHNIQUES

The large rain attenuation at the Ka band may not be compensated fully by the improvement in Ka band narrow spot beams and better interference environment. Degradations in link quality can be further mitigated by employing three main techniques.

Hub Site Diversity

Site diversity is a fade mitigation measure that involves two or more hub terminals set up to transmit or receive the signal in real time by using an algorithm to choose the least amount of link degradation among all the hub sites at any one instance. When one hub experiences rain and detects that the link may be cut, the algorithm calls for a switchover to the other hub where there are clear skies (see Figure 2).

For site diversity to be useful, there are two main considerations. First, hub sites must be sufficiently separated to achieve the required diversity gain or diversity improvement factor. It is shown that diversity gain improves with distance but the gain tapers off at distances more than 11km as it can be treated as a single site fade event (Leong, Loh, Chen, Yip, & Koh, 2012). Table 2 shows that the diversity gain is not just a function of distance but also the orientation of the line connecting the two sites. The diversity gain for Sentosa-Woodlands (South-North direction) is almost equivalent to the Tuas-Changi (West-East) site combination although the distance between each pair of sites is quite different. Second, when a site diversity decision is made, the downtime incurred from the hub switchover and the predicted duration of rain outage must both be taken into account. Due to the complexity of site diversity and the resulting cost of implementation, it will be more cost effective to use Ka band satellite networks.

The hub diversity concept can similarly be extended to remote terminals. In a bent pipe link, when the transmitter and receivers are located at a distance apart, the two sites may not experience the same amount of rainfall but the rainfall at the sites may be correlated. Therefore, in a typical link budget planning, the dual rain fade conditions for both the uplink and downlink are considered when the distance between the transmitter and receiver is less than 3km. For distances greater than 50km, a single rain fade condition, usually on the uplink side, is considered. In these two planning methods, the range of rain attenuation at 99% total link availability at the Ka band varies from 12dB to 39dB. Due to this large attenuation range, it is therefore important to plan the attenuation value accurately so as to meet the end user service level agreement while optimising the entire ground and space resources (Leong, 2012).

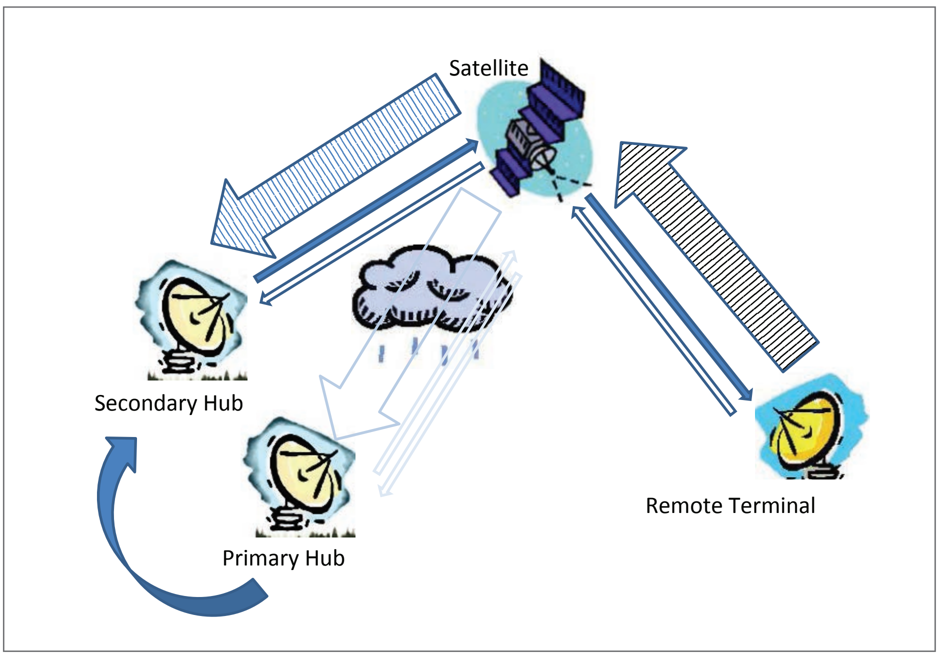

Figure 2. Illustration of hub site diversity

Selection Combination	**Div Gain / dB**	**Dist / km**
Tuas-Sentosa	11.2	22.72
Tuas-Woodlands	10.1	24.40
Sentosa-Woodlands	13.9	23.62
Sentosa-Changi	8.8	23.13
Woodlands-Changi	12.0	27.49
Tuas-Changi	14.8	42.44

Table 2. Diversity gain improvement over a single site

Adaptive Coding and Modulation

In ACM, the modulation and coding (MODCOD) of the carrier is altered within the modem in step sizes to increase the survivability of the transmission link. By decreasing the data rate, the signal to noise ratio required for a lower MODCOD is reduced and therefore the carrier becomes more resilient to rain fade. To support a varying data rate transmission during dynamic rain conditions, the video codec running in the application layer should allow a seamless reduction in video quality or resolution to ensure that the recipient is able to receive it. In other words, by adjusting the MODCOD, it is possible to optimise the trade-off between performance and survivability. Applications therefore need to be designed and tested accordingly to take full advantage of the ACM capability. ACM typically provides 15dB of margin across the full range of MODCODs.

Automatic Uplink Power Control

Automatic Uplink Power Control (AUPC) is implemented by increasing carrier power at the transmit end to ensure link survivability. When a rain fade event is encountered, more power is drawn from the high power amplifier (HPA) to maintain the carrier to noise ratio. Due to the need for additional equipment, AUPC is usually employed only at larger hub stations since the smaller remote terminals' HPA may already be operating with negligible backoff during clear sky. AUPC at hub stations typically provide 15dB of power control margin.

DESIGN ANALYSIS AND OPTIMISATION

Taking into consideration space segment parameters; ground segment mitigation techniques that improve the link quality; environment factors that decrease the link quality significantly; and the increased use of high bandwidth demand video application, a more stringent design analysis approach for link budget calculations is required. The approach will also require a sensitivity analysis, where various trade-offs between operational parameters (e.g. desired link availability for control and mission links), ground segment (e.g. power amplifier ratings and antenna sizes) and space segment (e.g. transponder power and bandwidth) can be analysed and optimised. Through these trade-off analyses, the feasibility of using the Ka band to support mission critical military aeronautical, maritime and land SATCOM operations can be determined.

There are many parameters to consider in the link budget. The primary parameters are as shown in Figure 3.

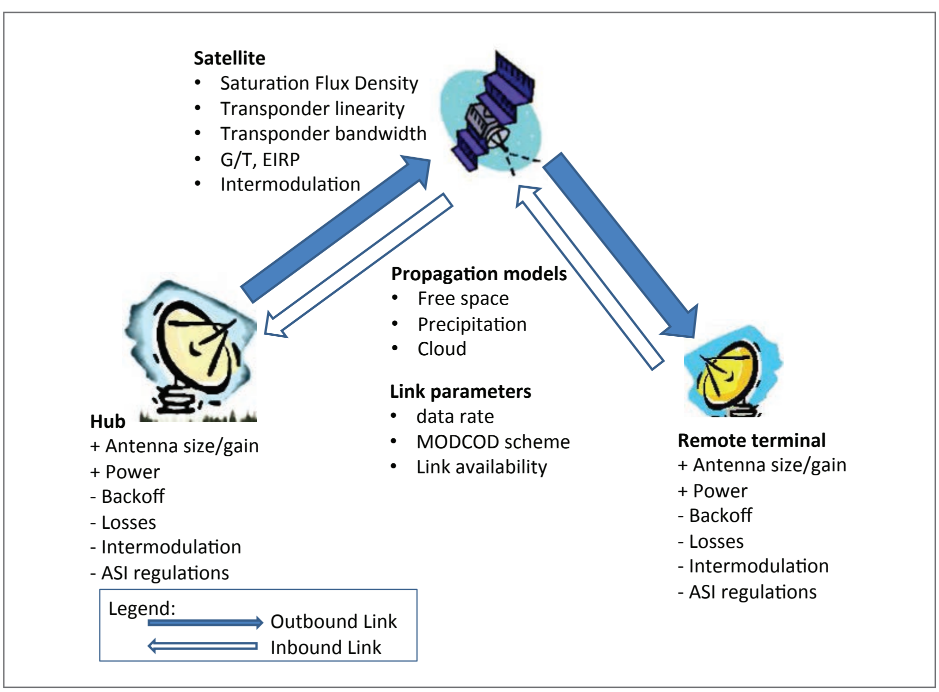

Figure 3. Major link parameters used in link budget analysis

It is recommended to start the satellite network design by first identifying the design boundaries – which are the most constraining factor(s) and which are the parameters that are within and outside of the designers' control. The typical constraints are as follows:

Satellites

Usually, the area of operations will define the choice of satellites. If two or more satellites are able to provide the required coverage, then parameters such as the available power and bandwidth on the transponder, receiver G/T, saturation points of the receivers and saturation flux density (SFD) can be used for the trade-off analysis. The linearity of the transponders is also an indicator of their performance. The more linear they are, the lower the intermodulation noise relative to the carrier will be produced, and therefore the better the output signal which can be achieved.

Remote Terminals and Hub

Constraints for remote terminals include the infrastructure or platform they will be hosted in. If the terminals are to be used on the move, the platform will very likely limit the antenna size/weight, position, minimum/maximum elevation angles and/or power amplifier size. If the hub has been implemented, its fixed infrastructure such as antenna size and power amplifier size may be constraining factors. Transmit power back-off (reduction in the transmit power level) and intermodulation noise should be catered for if multiple frequency carriers are transmitted from a common power amplifier. Losses due to cables and interconnectors as well as inaccuracies in antenna pointing should also be taken into account.

Besides these technical parameters, the satellite network designer should also take market availability of the products into consideration.

Communication Links

a) Outbound Link - The outbound link is the overall communications link from the hub to the terminal. It consists of the hub uplink and the terminal downlink. The outbound link is generally engineered so that the terminal downlink dominates performance. Since the hub services many terminals, it is generally cost effective to make the hub antenna large enough to provide extra transmit power margin on the hub uplink.

b) Inbound Link - The inbound link is the overall communications link from the terminal to the hub. It consists of the terminal uplink and the hub downlink. The inbound link is also generally engineered so that the terminal uplink dominates performance, since the large hub antenna provides extra receive gain on the hub downlink.

c) MODCOD Scheme - The choice of MODCOD is related to the signal to noise ratio required by the modem to demodulate the signal successfully as well as the carrier bandwidth required. These parameters are usually referenced from the modem specifications. The available transmit power or the receiver sensitivity may limit the choice of MODCOD scheme.

Operational Inputs

The operational inputs consist of the information exchange requirements, data rates and link availability required for the mission. Depending on the application and mission, the end user may have minimum data rate and link availability requirements. These would then be set as design targets and inputs to the link budget analysis. They impact the satellite transponder resources directly such as power and bandwidth required to support the link.

CASE STUDY: SATCOM ON THE MOVE

A remote terminal antenna size of 0.45m or 0.6m, power amplifier of up to 20W and an inbound link of up to 5Mbps are used as the input parameters in this case study. If the choice of satellite is still open, the designer should look for one with high G/T and high linearity transponder in order to meet the desired link availability for the mission and minimise the resources required.

Sensitivity Analysis

With numerous link budget parameters, sensitivity analysis is needed to determine the critical trade-offs between size, power, bandwidth and link availability. The key findings are highlighted as follows:

a) Increasing remote terminal antenna size from 0.45m to 0.60m allows a reduction in the required transponder power equivalent bandwidth (PEB) by 20% to 40% per 64Kbps link, leading to long-term savings in operating expenses. At the same time, it allows the required power on the hub to be reduced by 30% to 40%. Both directly contribute to an increase in the number of remote terminals that can be supported.

b) It is estimated that a single transponder can support about 9 x 5Mbps or 16 x 3Mbps mission links. For the mission link, satellite SFD – a parameter controlled by the satellite service provider – and the EIRP contour in which the hub is located, are the major factors influencing the number of links which can be supported per satellite transponder. Increasing the SFD sensitivity level by 6dBW/m^2 reduces the transponder PEB required by 60% to 70%, leading to significant savings in operating expenses. It is therefore important to choose, negotiate and establish a service level with the satellite service provider which meet user requirements.

c) For a mission link with high data rate (3Mbps to 5Mbps) but small antenna (0.45m to 0.6m) and limited power (up to 20W), the maximum link availability is only 96% to 97%. With lower data rates (below 1Mbps), a higher link availability of at least 98% can be achieved.

Application of Mitigation Techniques

Hub Site Diversity

Hub site diversity provides a means to overcome rain fade on the path between the hub and the satellite. Consequently, when there is no rain attenuation, the number of links that can be supported per transponder/hub increases. In essence, this increases the total capacity of the satellite network in terms of increasing the number of remote terminals that can be supported per satellite transponder. For remote terminals equipped with 0.45m antenna and up to 20W power, hub site diversity can increase the number of remote terminals supported per transponder by up to 18%.

Adaptive Coding and Modulation

The mission link availability will be improved if ACM is applied. During rain events when the link functions in degraded mode, for example at a lower data rate, videos are transmitted at a lower resolution. By decreasing the data rate from 1Mbps to 512Kbps or 256Kbps, the link availability is increased from 98% to 98.5%. This translates to a reduction in downtime of 43.8 hours per year. Commercial-off-the-shelf satellite modems are usually equipped with ACM that enable the link to be sustained as link conditions deteriorate.

Operational Considerations

Besides designing a network with the required link availability, data rates and power, it is necessary to address operational concerns and plan for contingencies.

Impact of Loss of Mission Link and Mitigation

A link of 64Kbps could be lost in rain exceeding approximately 20mm/hr. The impact to the mission depends on factors such as the period of link outage and latency requirements of the data. Mitigating measures for link outage can include a store-and-forward method whereby the data is stored on board the platform until a communications link is re-established.

Link Resiliency

The links should be designed to be robust against intentional or unintentional interferences. The communications security and transmission security features of the SATCOM link depend to a large extent on the modem capabilities and waveform. The accuracy of tracking and pointing as well as the design of the SATCOM antennas, especially on side lobe emissions, also play a part in reducing interferences in the network.

CONCLUSION

The use of the Ka band in SATCOM has allowed for new and smaller mobile terminals that utilise high throughput applications as compared to the Ku band to be feasible options in operations. However, with significantly larger rain attenuation to overcome, the Ka band link budget design analysis is more complex than in lower frequency bands to achieve comparable link availability. The use of sensitivity and trade-off analysis in the illustrated SATCOM on the move case study demonstrates the feasibility of Ka band SATCOM in our region. Other Ka band operational considerations – such as the possibility of fallback to lower frequency band during severe fade conditions and change in transmission plans required when crossing over multiple spot beams to cover the area of operation – may also be included as part of the design analysis upon future exploration.

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BIOGRAPHY

LEONG See Chuan is a Development Manager (C4I Development). He has designed, developed and managed complex software based command and control systems including satellite communications (SATCOM). He has published numerous academic publications, some of which are related to SATCOM, with a best paper presentation award in an IEEE conference. A recipient of the Public Service Commission Scholarship, See Chuan graduated with a Bachelor of Engineering (Electrical Engineering) degree from the National University of Singapore (NUS) in 1999. He further obtained a Master of Engineering (Electrical Engineering) degree from NUS in 2002.

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