Chapter 1

1.0 INTRODUCTION

1.1 OBJECTIVES

- To study and describe RF interference in Fixed Service (FS) Satellite Systems, from a link budget perspective.
- To consider two neighbouring satellite systems on the geostationary orbit and to determine the interference incurred by each system from the other.

1.2 OVERVIEW OF PROBLEMS OF GEOSYNCHRONOUS SATELLITE COMMUNICATIONS SYSTEMS

A geosynchronous or geostationary satellite orbits the Earth in a circular pattern at about 35,786 kilometres away from the earth surface if its elevation angle is orthogonal (90°) to the equator. In an ideal geosynchronous orbit a satellite moves around the earth in the equatorial plane so that the period of revolution of the satellite is exactly equal to the period of the rotation of the earth about its own axis (24 hours), and its velocity is 11,033 kilometres per hour. Hence to an observer on the earth, the satellite appears to be stationary in an apparent position relative to the earth. Geosynchronous satellites have the following advantages:

- Expensive tracking equipment is not required at the earth stations.
- Geosynchronous satellites are available to all earth stations within their shadow 100% of the time. (The shadow of a satellite includes all the earth stations that have a line-of-sight path to it and lie within the radiation pattern of the satellite’s antennas)
- There is no transmission breaks due to switching times (no need to switch from one geosynchronous satellite to another as they orbit overhead).
- The effects of Doppler shift are negligible.

However, geosynchronous satellite communications systems suffer from the following technical problems:
• Radio Frequency Interference
• Round-Trip Time Delay
• Free-space loss
• Noise
• Eclipse of satellite
• Sun Transit outage
• No coverage of polar region.

1.2.1 Radio Frequency Interference (RFI)
Geosynchronous satellite systems depend on the transmission of energy by way of electromagnetic waves between two antennas. The media traversed by the electromagnetic waves, the spectrum used and the geosynchronous orbit is shared. Therefore, any transmitter within the line of sight is a potential interferer. Geosynchronous satellites operate primarily in the 2GHz to 18GHz frequency spectrum. The most common carrier frequencies used for satellite communication are the 6/4GHz (C band) and 14/12GHz (Ku band). The first number is the uplink and the second number is the downlink frequency. Commercial geosynchronous satellites provide fixed satellite service (FSS) in the C and Ku bands of the radio spectrum. Unfortunately, the C-band is also used extensively for terrestrial microwave systems. This shared environment allows the following modes of radio frequency interference:

• **Intra-system**: interference arises from other users within the same satellite system
• **Inter-system**: interference is caused by an undesired signal received from a transmitter of a different system that uses the same transmission and/or reception frequencies.

Sources of inter-system interference may be other satellite communication systems, and/or terrestrial radio communication systems. Much about RF interference is dealt with in the preceding chapters.
1.2.2 Round-Trip Time Delay

In Geosynchronous Satellite Communications Systems, the signal has to travel a long distance from the transmit earth station to the receive earth station via satellite. Distances increases as the pointing angle to the satellite decreases (elevation angle). From the geometry of the geosynchronous satellite orbit, the time required for an RF signal to travel from earth station to satellite to another earth station- varies from 230 milliseconds (90º elevation) to 278 milliseconds (0º elevation). Hence round trip delay varies from 460ms to 556ms. This time delay does not pose any problem in data and broadcasting services, but it is quite perceptible in two-way telephone conversations. The resulting echo on telephone circuits influences certain data circuits in delay to reply for block or packet transmission systems and requires careful selection of telephone signaling systems; or call-setup time may become excessive. The International Telecommunications Union-Telecommunications Sector (ITU-T) specifies a delay of less than 400ms to prevent echo effects and delay variation of upto 3ms.

1.2.3 Free-space loss

Geostationary satellites encounter free-space losses as high as 196dB (for satellite operating on 4.2GHz), and 199 dB (for 6GHz operation). At 14GHz, the loss is about 207 dB. This presents no insurmountable problem for uplink; where comparatively high-power transmitters and very-high-gain antennas may be used. On the contrary, downlink power is limited for two reasons namely:

- in bands shared with terrestrial services such as the popular 4GHz band to ensure noninterference with those services
- in the satellite itself, which derives power only from solar cells.

It takes a great number of solar cells to produce the RF power necessary; thus the downlink is critical and received signal levels are low (as low as -150dBW). Geosynchronous satellites therefore require higher transmit powers and more sensitive receivers because of longer distances and greater path losses.
1.2.4 Noise

Noise is unwanted signal which limits the performance of the satellite communications link. Of the several different types of noise thermal noise ultimately determines link quality. Thermal noise has a flat power spectrum with frequency. Noise power density in given by

\[ N = kT_B B \]  \hspace{1cm} (1.1)
\[ N = k(T_{\text{earth}} + T_{\text{satellites}}) B \]  \hspace{1cm} (1.2)

where \( B \) = the frequency band of interest (measured in Hz)

\[ k = \text{Boltzmann's constant} \times 1.38 \times 10^{-23} \text{ J/K} \]

On the uplink the satellite transponder is looking at part of the earth's surface, which has a physical and noise temperature of about 300K. In many cases, satellite receivers operate with noise of about 1200K, of which 300K is due to the 'hot' earth.

The main noise components in the satellite system are:

- Uplink thermal noise
- Transponder intermodulation noise
- Downlink thermal noise

1.2.4.1 Uplink thermal noise

Uplink thermal noise is generated by the satellite's own receiving system. Both the earth station and the satellite have receiving antennas, low noise amplifiers (LNA) and gain-to-noise temperature (G/T) values. The G/T value, losses, power transmitted from the earth station and other parameters are used to calculate the ratio of the signal (or carrier) power to the thermal noise of the uplink system and is referred to as uplink \( C/T \). Figure 1.1 shows a model of uplink thermal noise in satellite communication.
1.2.4.2 Transponder intermodulation noise

The phenomenon of generating other signals from one or more signals is called \textit{intermodulation (IM)}. Intermodulation noise is generated by non-linear transfer characteristics of devices. The dominant source of nonlinearities in the RF link is the \textit{Traveling Wave Tube Amplifier} (TWTA) which acts as the backbone of the amplification sub-system in the satellite. Intersymbol interference caused by the Travelling Wave Tube Amplifier (TWTA) is a major consideration for accurate data detection at the receiver. Figure 1.2 shows the drive characteristic of an ideal TWT.
Figure 1.2 Dynamic characteristic of a TWT.

The input power level of a transponder may be pushed into the saturation region of the operational characteristic of the TWTA in order to boost the signal level of the satellite transponder (so that the received signal is above the general noise floor of the RF link). The amount of non-linearity is a function of the power level, and the operational point may have to be pushed back along the locus of the characteristic curve so that any instantaneous signal amplitude variations do not lie in the non-linear saturation region, thereby reducing the occurrence of intermodulation components, which may increase the effective bandwidth of the transmitted signal and interfere with neighboring channels.

The threshold of useful operation is determined by the Noise Figure of the tube. The dynamic range is that region between the threshold input level at which there is linear gain, until the point where the gain decreases by 6dB or reaches the saturation power level. If the input power is increased beyond this point, the output power will decrease. Proper back off at all stations is needed to keep IM within acceptable levels.
Towards the uplink the intermodulation noise is mainly generated because of High Power Amplifier (HPA) nonlinearity. If more than one carrier are transmitted by a single HPA, then amplification of these multiple carriers by the high-power amplifier, produces intermodulation products which are displaced from the carriers at multiples of the difference frequencies and in turn causes strong interference in other frequency. Figure 1.3 shows the generation of IM products.

![Input Spectrum](image)

**Figure 1.3 Generation of IM noise**

Even-order products, such as the second order product of \((f_1 + f_2)\), cannot appear in narrow band systems, unless the ratio of the highest frequency \((f_2)\) to the lowest \((f_1)\) is at least 2 to 1. Odd-order products, such as the third-order distortion products of \(2f_1-f_2\) or \(2f_2-f_1\), appear in the frequency band regardless of the frequency ratio. Third-order distortion may be defined as the ratio of the level of the undistorted two-tone output power of the primary fundamental signals, which are \(f_1\) and \(f_2\), to the output power of the first or closest pair of side band intermodulation products, which are \(2f_1-f_2\) and \(2f_2-f_1\). The power level of these intermodulation products is dependent on the relative power level of the carrier and the amplifier linearity. Figure 1.4 illustrates the variation of carrier and IM products power level as drive power changes if two balanced carriers are transmitted.
From Figure 1.4, the following deductions can be made:

- In a multicarrier operation, the saturated power will not be the same as that we can achieve for a single carrier.
- The IM distortion is significantly reduced in the small signal region of the RF drive range, because this region is more linear. Communication power amplifiers are operated 2 to 10 dB below their saturation power level to minimize the IM effects.

### 1.2.4.3 Downlink thermal noise

The downlink thermal noise is defined as the ratio of the power in the carrier that is being received to the noise added to the system by the downlink, and again is designated C/T. Downlink thermal noise is dominated by the G/T of the satellite earth station. Figure 1.5 shows the downlink thermal noise model. The frequency represents the downlink frequency band. For C-band systems this value can be considered to be 4 GHz, and for Ku-band systems the typical value is approximately 12 GHz.
Fig. 1.5 Downlink thermal noise model

where $T_a =$ antenna temperature (K)

$T_r =$ receiver temperature (K)

$f_{IF} =$ Intermediate frequency

TWTA = Traveling Wave Tube Amplifier

1.2.5 Eclipse of Satellite

A Satellite is said to be in eclipse when the positions of the Earth, the Sun and the Satellite are such that the earth prevents sun light from reaching the satellite (i.e. when the satellite is in the shadow of the earth). For geosynchronous satellites, eclipses occur for 46 days around equinox (March 21 and September 23). During full eclipse, a satellite does not receive any power from solar array and it must operate entirely from batteries. In case the power available from battery is not enough, some of the transponders may be required to be shut down during the eclipse period. The satellite passes through severe thermal stress during its passage into and out of the earth’s shadow. The solar power also fluctuates sharply at the beginning and end of an eclipse. For these reasons the probability of failure of satellite is more during eclipse than at any other time.
1.2.6 Sun Transit Outage
Sun transit outage takes place when the sun passes through the beam of an earth station. During vernal and autumnal equinox, the sun approaches toward a geosynchronous satellite as seen from an earth station and this increases the receiver noise level of the earth station very significantly and prevent normal operations. This effect is predictable and can cause outage for as much as 10 min. a day for several days. The sun transit outage is about 0.02 percent in an average year. A receiving earth station cannot do anything about it except wait for the sun to move out of the main lobe.

1.2.7 No Coverage of polar Regions
The geosynchronous satellite from its location of 35,786-km altitude above equator is not suitable for communications beyond the latitude of 81 degrees. Thus the polar region of the earth cannot be properly covered by geosynchronous satellites.
Chapter 2

2.0 RADIO FREQUENCY INTERFERENCE IN FIXED SERVICE SATELLITE SYSTEMS

The quality of signals received by the satellite transponder and that retransmitted and received by the receiving earth station is important if successful information transfer via the satellite is to be achieved. RF interference has the effect of adding to the overall noise on the link, thereby increasing the receiving system noise temperature and degrading the quality of the received signal. The solution to this is to study potential sources, types and levels of RFI and their effect on system performance. Intersystem interference can be minimized by adjusting the antenna discrimination and receiver selectivity, and choosing proper frequency plans. The control of external interference partly depends on coordination, control, and sometimes compromising on the radio channel through direct negotiation.

Earth stations must comply with carefully considered performance criteria in order to ensure that the various users of a satellite system can share the satellite resources without unduly affecting each other’s service quality. The design, installation quality and performance of an earth station determines both the sensitivity of transmissions to interference from other services and the potential for the transmissions to interfere with other services.

The common types of RF interference in FS satellite systems are:

- Adjacent Satellite Interference (ASI).
- Co-Channel Interference (CCI).
- Cross-Polarization Interference (XPI).

2.1 ADJACENT SATELLITE INTERFERENCE

Radio-frequency spectrum and the geosynchronous orbit are natural resources; therefore geosynchronous satellites must share limited space and frequency spectrum within a given arc of a geostationary orbit. Each communication satellite is assigned a longitude in the geostationary arc approximately 35786km above the equator.
The position in the slot depends on the communications frequency band used. Satellites operating at or near the same frequency must be separated in space to avoid mutual interference. Generally, spatial separation of 1° to 4° is required depending on the following variables: [1]

- Beamwidth and side lobe radiation of both the earth station and satellite antennas.
- RF carrier frequency
- Encoding or modulation technique used
- Acceptable limits of interference
- Transmit carrier power

A transmit earth station can inadvertently direct a proportion of its radiated power towards satellites that are operating at orbital positions adjacent to that of the wanted satellite. This can occur because the transmit antenna is badly pointed towards the wanted satellite, or because the earth station antenna beam is not sufficiently concentrated in the direction of the wanted satellite. This unintended radiation can interfere with services that use the same or similar frequencies on the adjacent satellites.

Similarly, a receive earth station can inadvertently receive transmissions from adjacent satellite systems which then interfere with the wanted signal. This happens because the receive antenna, although being very sensitive to signals coming from the direction of the wanted satellite, is also sensitive to transmissions coming from other directions. Figure 2.1 shows two neighbouring geosynchronous satellites and interferences due to each other.
Figure 2.1 Two neighbouring geosynchronous satellites and interferences due to each other.

KEY:
- - - - -  Uplink unwanted (interfering) signal
- - - - - -  Downlink interfering signal
E/S = Earth Station

ASI depends on the antenna pattern and on the satellite spacing. If a transmitting earth station (earth station 1) radiates a small percentage of its EIRP toward another satellite (satellite B), this interfering signal appears as noise in the information bandwidth. The noise signal in a frequency translating transponder is amplified and re-radiated to the receiving earth station 3. As a result, the re-radiated interfering downlink and the wanted downlink signal combine and appear as noise in the receiving earth station 3. Similarly, if satellite B radiates some interfering signal to earth station 2, then this interfering signal combines with a wanted downlink signal from satellite A.
Although antennas used in satellite communications use a highly focused beam, exactly how focused the main beam is, or the reduction in transmitted (or received) power at any angle off the main beam, is determined by equipment design or, more specifically, by a particular antenna discrimination pattern. [10]

2.1.1 ANTENNA CONSIDERATION
A transmitting antenna does not radiate uniformly in all angular directions. This directional directivity of an antenna is characterized in terms of its radiation pattern. Antenna radiation pattern may be defined as a plot of relative strength of radiated field, amplitude and phase, as a function of angular parameters, \( \theta \) and \( \phi \), of spherical co-ordinate system for a constant radius \( r \). [4]

Figure 2.2 shows antenna power pattern in polar coordinates.

![Figure 2.2](image-url)
Most of the power radiated by an antenna is contained in the **main lobe**. However, a certain amount of power can be transmitted, (or received), in off-axis directions. Often the interference generated by an earth station comes from its antenna **side lobes**. [2]

Side lobes are an intrinsic property of antenna radiation and cannot be completely eliminated. However, side lobes are also due to antenna defects that can be minimized with proper design. The International Telecommunications Union-Radio (ITU-R) Record 580-1, Module 1, defines the desired side lobe envelope for different types of antennas. They are:

- Antennas installed after 1988 and with a ratio of $D/\varphi > 150$ must meet the following characteristics:

  \[
  G = 29 - 25 \log_{10} \theta \text{ dBi}
  \]  
  where $\theta = \text{degrees from boresight and } 1^\circ \leq \theta \leq 20^\circ$

  \[
  D = \text{the antenna diameter (meters)}
  \]

  \[
  \varphi = \text{the wavelength for the operation frequency (meters)}
  \]

- For smaller antennas with $D/\varphi$ between 35 to 100, (1.75m to 5m for C-band and 0.75m to 2.1 m for Ku-band):

  \[
  G = 52 - 10 \log D/\varphi - 25 \log \theta \text{ dBi},
  \]  
  (for the angular region $100 \varphi/D^\circ \leq \theta \leq D/5 \varphi$) [2]

Figure 2.3 shows a radiation pattern for a paraboloidal antenna and the recommended side lobe characteristics to permit closer spacing of satellites.
A practical antenna has side lobes of finite levels. An antenna with side lobes around the main beam, better than -35dB down from the boresight peak gain is considered a high performance antenna. Regulatory agencies provide some guidance on permissible side lobes envelope level relative to a unity isotropic gain (1 or 0 dB). For example, the Federal Communications Commission (FCC) specifies the following as permissible side lobe envelope levels.

\[
\begin{align*}
    (29 - 25 \log_{10} \theta) \text{ dBi} & \quad 1^\circ \leq \theta \leq 7^\circ \\
    +6 \text{ dBi} & \quad 7^\circ \leq \theta \leq 9.2^\circ \\
    (32 - 25 \log_{10} \theta) \text{ dBi} & \quad 9.2^\circ \leq \theta \leq 48^\circ \\
    -10 \text{ dBi} & \quad 48^\circ \leq \theta \leq 180^\circ
\end{align*}
\]  

where \( \theta \) is the antenna off-axis angle in degrees. [4]

For example, at 6.2° the side lobe envelope level must not exceed 9.2dB above the isotropic (0 dB) level. Figure 2.4(a) and Figure 2.4(b) shows reference radiation diagrams generated by The International Radio Consultative Committee (CCIR) to the ITU. [2]

\( X\)-axis \( \Rightarrow \) Angle between the axis of main beam and the direction considered (degrees)
\( Y\)-axis \( \Rightarrow \) Gain relative to an isotropic antenna (dB)
**Figure 2.4(a)** CCIR reference radiation diagram from \( G(\theta) = (32 - 25 \log_{10} \theta) \) dB

*X-axis* ⇒ *Angle between the axis of main beam and the direction considered (degrees)*

*Y-axis* ⇒ *Gain relative to an isotropic antenna (dB)*

**Figure 2.4(b)** CCIR reference radiation diagram from \( G(\theta) = (29 - 25 \log_{10} \theta) \) dB
2.1.2 ANGULAR SEPARATION

The angular separation between satellites, as seen by the earth stations, influences the level of interference generated or received from the side lobe of the earth station antenna into or from an adjacent satellite. Side lobe characteristic is one of the main factors in determining the minimum spacing between satellites and, therefore, the orbit/spectrum efficiency. [1]

Figure 2.5 shows a satellite broadcast receiver with an antenna front-end that receives the wanted signal from satellite 1 with interferers on adjacent satellites 2 and 3 due to insufficient angular separation.

If the angular separation between two geostationary satellites is 3.45°, and a station-keeping accuracy of ±0.5° is assumed, then the worst case viewing angle is 2.95°, which corresponds to the antenna off-axis a of approximately 3°. Hence, using (2.3), the earth station antenna side lobes' envelope level must not exceed 17.1 dB above the isotropic (0-dB) level. Using equation (2.5), the worst case interference from satellites placed on either sides of the wanted satellite can be estimated. . [9]

Figure 2.5 shows two unwanted or interfering satellites spaced at 3° interval on each side of the wanted satellite.
If all the five satellites radiate with the same EIRPs toward the earth station, at the same frequency, then expected level of interference with respect to the wanted signal can be calculated. For example, if the wanted signal is at 4GHz and if the earth station antenna diameter is 10 metres then the following can be calculated:

(First note that equation (2.5) is independent of the diameter of the earth station antenna as long as the diameter is over 50\(\lambda\)).

At 4GHz, \(\lambda\approx7.5\) cm, \(50\lambda\approx3.75\) m which is less than the antenna diameter (10m). Hence equation (2.5) is valid for a 10-m antenna. The boresight gain \(G_b\), of a 10-m antenna at 4GHz (assuming efficiency factor, \(\eta=0.7\)) can be estimated using the equation

\[
G_b = \frac{4\pi A_{\text{eff}}}{\lambda^2} \eta = \frac{4\pi A_{\text{eff}}}{\lambda^2}
\]

where \(A_{\text{eff}}\) = effective area of the antenna

\(\eta\) = efficiency factor (normally between 0.4 to 0.85)

**Figure 2.6** Adjacent satellite interference
Therefore,

\[ G(0^\circ) = \left( \frac{\pi \times 10 \times 10^2}{7.5} \right)^2 \times 0.7 \]

\[ = 122,822 = 50.9 \text{ dBi} \]

Then at \( \theta = 3^\circ, \)

\[ G(3^\circ) = (32 - 25 \log_{10} 3) = 20.1 \text{ dBi} \]

And at \( 6^\circ, \)

\[ G(6^\circ) = (32 - 25 \log_{10} 6) = 12.5 \text{ dBi} \]

Since there are two interfering satellites, one on each side equally spaced,

\[ \frac{G(0^\circ)}{2 \times G(3^\circ)} = 50.9 \times (20.1 + 3) = 27.8 \text{ dB} \]

and

\[ \frac{G(0^\circ)}{2 \times G(6^\circ)} = 50.9 \times (12.1 + 3) = 35.4 \text{ dB} \]

If the 4GHz received signal level is normalized to 1W (0 dBW) for the wanted satellite, the interference is -27.8 dBW and -35.4 dBW, respectively, or \( 1.66 \times 10^{-3} \) W and \( 2.88 \times 10^{-4} \) W, respectively.

The sum of all interfering signals gives a level = \( 1.66 \times 10^{-3} + 2.88 \times 10^{-4} \) W

\[ = 1.948 \times 10^{-3} \text{ W} \]

\[ = -27.1 \text{ dBW} \]

Thus the carrier-to-interference \((C/I)\) ratio is 27.1 dB. In practice, a \((C/I)\) ratio of 27dB is considered acceptable. . \[8\]

This example shows that the **two immediate adjacent satellites** contribute almost all of the interference if the satellite EIRPs are all the same. If the EIRPs of the adjacent satellites are higher than the EIRP of the wanted satellite, the \((C/I)\) deteriorate further by the amount equal to the difference between the wanted and unwanted EIRPs. Normally, a single-entry \((C/I)\) of worse than 18 dB is considered undesirable, since the link is further degraded at the same time by thermal noise contributions.
Interference into adjacent satellite systems is controlled to an acceptable level by ensuring that the transmit earth station antenna is accurately pointed towards the satellite and that its performance (radiation pattern) is sufficient to suppress radiation towards the adjacent satellites. In general, a larger uplink antenna has less potential for causing adjacent satellite interference, but is generally more expensive and may require a satellite tracking system.

2.2 CO-CHANNEL INTERFERENCE

Co-channel interference occurs if external interference from other transmitters (e.g., terrestrial microwave transmitters) is at the same frequency as the signal of interest. Interference that is near the frequency of the signal is called adjacent channel interference. Co-channel interference may be caused by either of the following:

- harmonics from a different type of system
- unintentional radiators
- signals from a similar system that are some distance away (frequency reuse).

In each case, the interference is received within the operating bandwidth of the receiver. Unlike thermal noise, co-channel interference cannot be reduced by simply increasing carrier power because increasing the carrier power at one nominal bandwidth increases the likelihood of interference with the carriers that are adjacent in frequency to the wanted carrier. \[5\]

Satellites in geosynchronous orbits are co-located using orthogonal polarization to place more number of satellites to meet the demand. But while co-locating satellites operating in the same frequency band, careful system analysis and optimization is required to deal with co-channel interference. Since co-channel interference enters the receiver at or near the centre of its bandwidth, the receiver filter does not attenuate it. Adjacent channel interference can be a problem depending upon the spectral properties of the receiver filter. Adjacent channel interference enters the receiver at a nearby frequency and therefore is attenuated by the receiver filter with a sharper roll-off.

If the filter roll-offs are not sufficiently attenuated, the interference can cause undesired operation. Figure 2.7 shows receiver filter response with co-channel and adjacent interference.
Figure 2.7 Receiver filter response with co-channel and adjacent channel interference

Ideally, the power of a carrier transmitted by an earth station is entirely contained within a fixed range of frequencies, or bandwidth (e.g. 6000 MHz ± 500 kHz), and is zero outside of this range. This permits carriers from different earth stations to be placed side by side in frequency with no interference between them, so long as their bandwidths do not overlap. However, in practice some carrier power is radiated outside of the nominal bandwidth of the carrier and this can interfere with the carriers that are adjacent in frequency to the wanted carrier. The principal factor that governs the amount of interference that is generated in this way is the output back-off of the earth station’s high power amplifier (HPA). The larger the back-off, the lower the potential for causing adjacent channel interference.

Figure 2.8 shows co-channel interference in the desired satellite link due to the unwanted emissions from the uplink earth station, (E/S2) of the other co-located satellite.
2.3 CROSS-POLARIZATION INTERFERENCE

Most satellite systems employ opposite polarization states to make most efficient use of the frequencies that are available for transmission and reception. This means that two signals may share the same frequency within a satellite system, so long as they employ opposite polarization states (e.g. horizontal linear polarization and vertical linear polarization). Theoretically, each signal can be received without interference from the co-frequency signal on the opposite polarization. However, being practical devices, the earth station and satellite antennas and their feeds are not able to perfectly separate the two polarization states, which results in a small proportion of the unwanted “cross-polar” signal being transmitted or received along with the wanted signal, causing cross-polarization interference. Since the polarization performance of the satellite antennas is fixed, cross-polarization interference is maintained at an acceptable level by ensuring that the earth station antenna has adequate cross-polar performance (cross-polar discrimination, XPD). \[\text{[4]}\]

If the XPD level of an uplink antenna is less than 30dB, antenna transmits both vertical and horizontal polarizations. Polarization discrimination between co-polar and cross-polar signals is important in a dual polarization frequency re-use satellite communication system. Figure 2.9 illustrates polarization discrimination in an antenna radiation pattern.
In the case of linear polarization, it is also very important to ensure that the antenna feed is properly aligned with the linear polarization plane of the satellite antennas (by rotating the feed), otherwise the cross-polar discrimination of the antenna will be poor and this may lead to unacceptable levels of cross-polarization interference. The optimum isolation is received when both the transmitting (causing interference) and the receiving (victim) antennas have a similar cross-polarized response. A typical isolation requirement is about 27 dB for circular polarization and 33 dB for linear polarization. Low side-lobes and cross-polarization are necessary to prevent excessive interference among beams. [5]
3.0 INTERFERENCE BETWEEN TWO NEIGHBOURING SATELLITE SYSTEMS IN GEOSTATIONARY ORBIT

Two neighbouring satellite systems in space may cause unacceptable levels of interference to each other. This may occur due to either of the following:

- Inadequate angular separation between the two transponders
- Bad antenna pointing
- Antenna beams not sufficiently concentrated in the direction of the wanted satellite

3.1 UPLINK INTERFERENCE

The satellite uplink comprises transmitting uplink station, and a satellite transponder which receives the signal. The uplink signal transmitted to the satellite transponder is called the ‘wanted signal’ and the satellite transponder is called the ‘wanted satellite’. [4]

There are however, a number of other satellite transponders either co-located or in the vicinity of the wanted one, each of which is receiving its own signals. These unwanted signals may enter the receiver of the wanted satellite transponder causing interference to the wanted signal. This phenomenon is illustrated in Figure 3.1. Satellite B is supposed to receive a signal from Earth station 2, but it is also receiving an interfering signal from unwanted Earth station 1.
Figure 3.1 Uplink interference

3.1.1 Uplink Carrier-to-Interference Ratio

Uplink Carrier-to-Interference power spectral density ratio is expressed as

\[
\frac{C}{I_{\text{total}}} = \left[ \frac{C}{I_{0\text{adj}}} + \frac{C}{I_{0\text{co}}} \right]^{-2} \text{ dB}
\]  

In the bandwidth of interest, the uplink Carrier-to-Interference ratio (C/I), is the ratio expressed in dB, between a desired uplink carrier power and an interfering signal power received by the "victim" receiver. The C/I ratio is used to determine whether an interference case is acceptable or not.

Mathematically,

\[
\frac{C}{I} = \frac{P_{C}}{P_{I}}
\]  

where

\[
P_{I} = P_{F}D_{F} \times A_{i} \times G_{r} \theta_{i}
\]  

\[
P_{F} = \frac{P_{G}G_{d} \theta_{2}/4\pi d_{u}^{2}}{}
\]

\[d_{u} = \text{distance from interfering earth station to satellite}
\]

\[A_{i} = \text{the effective area of the antenna}\]
If different types of interference are present in the uplink (e.g. adjacent satellite interference and co-channel interference), then the total uplink $C/I$ is expressed as

$$
(C/I)_{\text{Total U/L}} = \left( (C/I)_{\text{adj}}^{-1} + (C/I)_{\text{cc}}^{-1} \right)^{-1} \text{ dHz}
$$

(3.5)

Figure 3.2 shows how Carrier-to-Interference ratio results.

![Figure 3.2 Uplink Carrier-to-Interference ratio](image)

3.1.2 Uplink Carrier-to-Noise plus Interference ratio

The carrier signal (C) can be compared with the noise signal (N) and any interference (I) present in the satellite receiver. Figure 3.3 shows the ratio of the wanted signal to noise plus interference expressed both as a linear ratio and also in the more normal logarithmic ratio in decibels.
Figure 3.3 Signal to noise plus interference

Wanted signal power = $C$ watts in bandwidth $B$ Hz

$N_o$ = noise power spectral density measured in watts/Hz

Unwanted interfering signal power = $I_o$ watts

= $I$ watts in bandwidth $B$ Hz (given by overlap)

The ratio of carrier power to noise power spectral density plus interference signal power in the uplink is given by the expression

$$\left(\frac{C}{N_o + I_o}\right)_{U/L} = \left[\left(\frac{C}{N_o}\right)^{-1}_{U/L} + \left(\frac{C}{I}\right)^{-1}_{Total\ U/L}\right]^{-1}$$ dB \hspace{1cm} (3.6)

In bandwidth $B$ Hz, unwanted noise power is given by $N = N_o B$. Hence uplink carrier-to-noise plus interference ratio is expressed as

$$\left(\frac{C}{N_0 + I}\right)_{U/L} = \left[\left(\frac{C}{N_0}\right)^{-1}_{U/L} + \left(\frac{I}{I}\right)^{-1}_{Total\ U/L}\right]^{-1}$$ dBHz \hspace{1cm} (3.7)

3.1.3 Uplink Energy of Bit-to-Noise Density plus Interference Ratio

Energy of Bit-to-Noise Density Ratio is inversely related to bit error rate (BER). Hence higher energy of bit-to-noise density ratio means better quality. Interference reduces this ratio.
where $f_b$ = bit rate (Mbps)

$E_b$ = energy of a single bit (joules per bit)

$N_0$ = noise density (dB)

$I_0$ = unwanted interfering signal power (dB)

3.2 DOWNLINK INTERFERENCE

The satellite antenna cannot be pointing directly at all the earth stations to which it is transmitting. There is a resultant angular difference between the boresight of the satellite antenna and the direction of the receiving earth station given by $\theta_2$ in Figure 3.4 [4]

![Diagram of satellite antenna and earth station](image)

Figure 3.4 Composite view of downlink

$$P_t = PFD_w \times A \times G_p(\theta) = \frac{P_t G_d(\theta) AG_r(\theta)}{4\pi d_r^2}$$
\[ P_I = PFD_I \times A \times G_r(\theta_E) = \frac{P_I G_{NI}(\theta_E) AG_T(\theta_E)}{4\pi d_{u,w}^2} \]  

(3.10)

where \( d_{w} \) = range to wanted satellite from receiving earth station

\( d_{u,w} \) = range to unwanted satellite from receiving earth station

\( G_r \) = receiver gain temperature

Each earth station receiving signal from the satellite has its own angular offset from the satellite transmit boresight which can introduce losses of up to 5dB from the maximum signal power available.

### 3.2.1 Downlink Carrier-to-Interference ratio

If both adjacent satellite interference and co-channel interference are present in the downlink, then

\[ \left( \frac{c}{i} \right)_{Total \text{ D/L}} = \left[ \left( \frac{c}{i} \right)_{adj, f}^{-1} + \left( \frac{c}{i} \right)_{cc}^{-1} \right]^{-1} \text{ dB} \]  

(3.11)

In the bandwidth of interest, downlink carrier-to-interference ratio is given by

\[ \left( \frac{c}{i} \right)_{Total \text{ D/L}} = \left[ \left( \frac{c}{i} \right)_{adj, f}^{-1} + \left( \frac{c}{i} \right)_{cc}^{-1} \right]^{-2} \text{ dHz} \]  

(3.12)

### 3.2.2 Downlink Carrier-to-Noise plus Interference ratio

The ratio of carrier power to noise power spectral density plus interference signal power in the downlink is given by the expression

\[ \left( \frac{c}{N_0 + i} \right)_{D/L} = \left[ \left( \frac{c}{N_0} \right)_{D/L}^{-1} + \left( \frac{c}{i} \right)_{Total \text{ D/L}}^{-1} \right]^{-1} \text{ dB} \]  

(3.13)

In the bandwidth of interest,
\[
\left( \frac{c}{N + I} \right)_{D/L} = \left[ \left( \frac{c}{N_0} \right)_{D/L}^{-1} + \left( \frac{c}{I} \right)_{Total D/L}^{-1} \right]^{-1} \text{ dBHz}
\]  
(3.14)

### 3.2.3 Downlink Energy of Bit-to-Noise Density Ratio

It is given by the expression

\[
\left( \frac{E_b}{N_0 + I_0} \right)_{D/L} = \left( \frac{c}{N_0} \right)_{D/L}^{-1} - 10 \log_{10} f_0
\]  
(3.15)

### 3.3 THE OVERALL LINK PERFORMANCE

The signal-to-noise plus interference ratio for the overall link is calculated by combining the separate uplink and downlink contributions. For interference-free transmission and reception, the signal-to-noise density ratio for the overall link may be expressed as

\[
\left( \frac{c}{N_0} \right)_{Overall} = \left[ \left( \frac{c}{N_0} \right)_{U/L}^{-1} + \left( \frac{c}{N_0} \right)_{D/L}^{-1} \right]^{-1}
\]  
(3.16)

But for a system affected by interference, the overall signal-to-noise density plus interference ratio is expressed as

\[
\left( \frac{c}{N_0 + I_0} \right)_{Overall} = \left[ \left( \frac{c}{N_0 + I_0} \right)_{U/L}^{-1} + \left( \frac{c}{N_0 + I_0} \right)_{D/L}^{-1} \right]^{-1}
\]  
(3.17)

And in the bandwidth of interest, signal-to-noise plus interference ratio is given by

\[
\left( \frac{c}{N + I} \right)_{Overall} = \left[ \left( \frac{c}{N + I} \right)_{U/L}^{-1} + \left( \frac{c}{N + I} \right)_{U/L}^{-1} \right]^{-1} \text{ dBHz}
\]  
(3.18)

Figure 3.5 illustrates combination of up and down links in presence of an interfering signal with power \( I \) watts in bandwidth \( B \) Hz
Figure 3.5 Combination of up and down links

Overall Energy of Bit-to-Noise Density Ratio is a standard product over the sum relationship and is expressed mathematically as

$$\left( \frac{E_b}{N_0+I_0} \right)_{\text{Overall}} = \left( \frac{E_b}{N_0+I_0} \right)_{U/L} \times \left( \frac{E_b}{N_0+I_0} \right)_{D/L}$$  \hspace{1cm} (3.19)$$

where all $\left( \frac{E_b}{N_0+I_0} \right)$ ratios are in absolute values.
Chapter 4

4.0 SATELLITE LINK BUDGET

The design of satellite communication system is a complex process requiring compromises between many factors to achieve the best performance at an acceptable cost. GEO satellites carry the vast majority of the world’s satellite traffic, therefore it becomes utmost for the link designer to design with optimum utilization of space segment as well as transponder downlink EIRP.

The Link budget plays a vital role in the deployment of any radio frequency network:

- It defines the amount of power available in the communication link for transmission and reception.
- It compares the received signal power available via the uplink station, satellite and downlink station with the combination of noise and interference which arises in the link.

During the link budget analysis, tradeoffs can be made to achieve a balance between cost and performance. Mismanagement of the link budget calculation leads to vital problems such as interference, cross polarization of the antenna and rising of the noise floor of a transponder.

All communication links should be designed to meet certain performance objectives, usually a bit error rate (BER) in a digital link or a signal to noise ratio (S/N) in an analog link, measured in the baseband channel. The baseband channel is where an information carrying signal is generated or received. The baseband channel BER or S/N ratio is determined by the carrier to noise ratio (C/N) at the input to the demodulator in the receiver. C/N ratio is calculated at the input of the receiver, at the output terminals (or port) of the receiving antenna.

RF interference received along with the signal and noise generated by the receiver are combined into an equivalent noise power at the input of the receiver. The overall C/N at the earth station receiver depends on both uplink and downlink, and both therefore must achieve the required performance for a specified percentage of time. Path attenuation in the earth’s atmosphere may become excessive in heavy rain, causing the C/N ratio to fall below the minimum permitted value, leading to link outage.

Additional constrains may be imposed to a satellite system by the need to conserve RF bandwidth and to avoid interference with other users.
4.1 IMPORTANT ELEMENTS OF A LINK BUDGET.

The following is a detailed description of important elements which are required for the calculation of Link budget of a particular satellite system.

4.1.1 Transmit Power and Bit Energy

To operate as efficiently as possible, a power amplifier is operated as close as possible to saturation. The saturated output power is designated $P_{o_{s\alpha}}$ or simply $P_{s}$ and is generally expressed in dBW (decibels in respect to 1 watt). Consequently, a parameter more meaningful than carrier power is energy per bit $E_{b}$.

$$E_{b} = P_{s}T_{b} = \frac{P_{s}}{f_{b}}$$

where $E_{b}$ = energy of a single bit (joules per bit)

$P_{s}$ = total saturated output power (watts or joules per second)

$T_{b} = \frac{1}{f_{b}}$, where $f_{b}$ is the bit rate in bits per second,

4.1.2 Back-Off loss

High-power amplifiers used in earth station transmitters and the travelling-wave tubes used in satellite transponders are nonlinear devices; their gain (output power versus input power) is independent on input signal level. To reduce the amount of intermodulation distortion caused by the nonlinear amplification of HPA, the input power is reduced (backed-off) by several dB. This allows the HPA to operate in a more linear region. The amount the output level is backed off from rated levels is equivalent to a loss and is approximately called back-off loss $L_{b\alpha}$.

a) Input back off (IBO)

Power Flux Density (PFD) for saturation minus total PFD at satellite; $\delta_{total}$ means all contributions to satellite, values in dB.
b) **Output back off (OBO)**

Saturated satellite EIRP minus actual satellite EIRP (values in dB). Actual EIRP can be calculated from the input power back off in conjunction with the input/output power transfer curve for a satellite transponder. This is illustrated in figure 4.1

![Figure 4.1 Input-Output characteristic of a satellite transponder](image)

**4.2.3 Antenna Gain**

The power density at a distance $d$ from antenna is $\frac{P_e}{4\pi d^2}$ $W/m^2$. If the transmitting antenna has some directivity in a particular direction, the power density in that direction is increased by a factor called **the antenna gain**, $G_T$. Hence the power density at a distance $d$ is $\frac{P_e G_T}{4\pi d^2}$ $W/m^2$. A receiving antenna pointed in the direction of the radiated power gathers a portion of the power that is proportional to its cross-sectional area. Hence, the received power extracted by the antenna may be expressed as

$$P_r = \frac{P_e G_T A_r}{4\pi d^2}$$  \hspace{1cm} (4.2)

where $A_r$ is the effective area of the antenna and is expressed as
where \( \lambda = c/f \) is the wavelength of the transmitted signal, \( c \) is the speed of light \( \left(3 \times 10^8 \text{ m/s}\right)\), and \( f \) is the frequency of the transmitted signal.

\( G_r = \) gain of receiving antenna.

Therefore, received power is given by *Frii’s free space equation* [11]

\[
P_r = \frac{P_t G_t G_r}{(4\pi d/\lambda)^2}
\]  

(4.4)

The factor \( L_s = \left(\frac{4\pi d}{\lambda}\right)^2 \) is called the free-space loss. If other losses, such as atmospheric losses, are encountered in the transmission of the signal, they may be accounted for by introducing an additional loss factor, say \( L_\alpha \). Therefore, the received power may be written in general as

\[
P_r = P_t G_t G_r (1/L_s)L_\alpha
\]  

(4.5)

A parabolic antenna of diameter \( D \) has an effective area:

\[
A_r = \frac{1}{4} \pi D^2 \eta
\]  

(4.6)

where \( 1/4 \pi D^2 \) is the physical area and \( \eta \) is the illumination efficiency factor, which falls in the range \( 0.5 \leq \eta \leq 0.6 \). Hence, the antenna gain for a parabolic antenna of diameter \( D \) is

\[
G_r = \eta \left(\frac{\pi D}{\lambda}\right)^2
\]  

(4.7)

or

\[
G_r(dB) = 10 \log \eta \left(\frac{\pi D}{\lambda}\right)^2
\]  

(4.8)

Figure 4.2 shows a plot of antenna gain as a function of antenna diameters while using frequency and efficiency parameters.
4.2.4 Uplink free-space path loss

Free-space path loss is the largest signal energy attenuation as a function of the distance travelled. For line of sight links, this loss is a function of the square of the distance between isotropic antennas. For an uplink signal, the free-space path loss is the largest of all other types of losses, and is given by

\[ L_s = \left( \frac{4\pi d_u}{\lambda_u} \right)^2 \text{ or } 20\log \left( \frac{4\pi d_u}{\lambda_u} \right) \text{ dB} \] (4.9)

where \( \lambda_u = \) wavelength of uplink signal (m), typically 0.021 at 14GHz

\( d_u = \) earth station to satellite range on uplink (m); typically 35786km for a geostationary satellite.
4.2.5 Downlink free-space path loss

\[ L_s = \left( \frac{4\pi d_d}{\lambda_d} \right)^2 = 20\log \left( \frac{4\pi d_d}{\lambda_d} \right) \text{dB} \] (4.10)

where \( \lambda_d \) = wavelength of downlink signal (m)

\( d_d \) = satellite to earth station range on downlink (m)

For an elevation angle of 90 and distance of 35 786 kilometres above the earth surface, Figure 4.3 shows free space path loss (dB) determined from equation

\[ L_p = 183.5 + 20\log_{10} f_{(GHz)} \] (4.11)

**X-axis ⇒ Frequency (GHz)**

**Y-axis ⇒ Free space path loss (dB)**

![Free-space path loss graph](image)

**Figure 4.3** Free-space path loss

4.2.6 Atmospheric Loss

Residual atmospheric loss under clear sky conditions due to water vapour and oxygen absorption is 0.2dB through a typical earth station/satellite at 14GHz.
4.2.7 Effective Isotropic Radiated Power

Effective Isotropic Radiated Power (EIRP) is basically the radiated power relative to an isotropic antenna for $G_z = 1$. The gain of a directive antenna results in a more economic use of the RF power supplied by the source. Effective isotropic radiated power may be defined as an equivalent transmit power. It is expressed as a function of the antenna transmit gain $G_z$ and the transmitted power $P_{in}$ fed to the antenna and expressed mathematically as

$$EIRP = P_{in}G_z \text{ (watts)}$$

(4.12)

where $P_{in} = \text{antenna input power (watts)}$

$G_z = \text{transmit antenna gain (unitless ratio)}$

Expressed as a log,

$$EIRP_{dBW} = P_{in}(dBW) + G_z(dB)$$

(4.13)

And in respect to the transmitter output,

$$P_{in} = P_t - L_{bo} - L_{bf}$$

(4.14)

Thus,

$$EIRP = P_t - L_{bo} - L_{bf} + G_z$$

(4.15)

where $P_{in} = \text{antenna input power (dBW)}$

$L_{bo} = \text{back-off losses of HPA (decibels)}$

$L_{bf} = \text{total branching and feeder loss (decibels)}$

$G_z = \text{transmit antenna gain (decibels)}$

$P_t = \text{saturated amplifier output power (dBW)}$

The EIRP must be accurately controlled, because an **excessive EIRP causes interference** to adjacent and co-channel carriers, while a **low EIRP results in poor quality performance** of the service. [1]
a) **Earth station EIRP**

\[ EIRP = P_e + G_e \quad \text{Watts or} \quad 10\log P_e G_e \quad dBW \]  

(4.16)

where \( P_e \) = earth station amplifier transmit power

\( G_e \) = earth station antenna gain

b) **Satellite EIRP**

The EIRP of the wanted signal is that fraction of the total output power according to the relative power contributions of the input signals to the amplifier. Saturated satellite EIRP is the maximum downlink power available from satellite in a given pointing direction.

### 4.2.8 Antenna Noise Temperature

The atmosphere and the Earth surrounding a receiving ground station antenna generate some noise. If the main lobe of an antenna can be brought down to illuminate the ground, the system noise temperature would increase by approximately 290°K. However, synchronous satellites require vertical angles of elevation of 5° or more. If the directivity of the antenna is such that the ground absorbs 5 percent of its radiated energy illuminates, then the same antenna used for reception would contribute 5/100 x 290°K, i.e., 14.5°K of noise. The antenna noise temperature is a complex function of antenna gain pattern, background noise, temperature of the sky, equivalent atmospheric noise temperature, and noise temperature of the Sun.

Figure 4.4 shows antenna noise temperature as a result of other noise sources
Figure 4.4 Antenna noise temperature as a result of other noise sources

A typical curve variation of the antenna noise temperature with the antenna elevation angle is shown in Figure 4.5. It is usually a minimum at zenith, typically 15°K to 20°K for a low loss antenna with low side lobes. It increases considerably as the elevation angle falls below 10°.

Fig.4.5 Noise Temperature of an Antenna (K) as a Function of Elevation Angle (degrees)
4.2.9 Receiver Equivalent Noise Temperature

In satellite communications systems, equivalent noise temperature \( T_e \) is often used rather than noise figure because it is a more accurate method of expressing the noise contributed by a device or a receiver when evaluating its performance. Equivalent noise temperature is a hypothetical value that can be calculated but cannot be measured.

\[
T_e = T(F - 1) \tag{4.17}
\]

where \( T_e \) = equivalent noise temperature (Kelvin)

\( F \) = noise factor (unitless)

\( T \) = temperature of environment (Kelvin)

Typically, equivalent noise temperatures of the receivers used in satellite transponders are about 1000K. For earth station receivers, \( T_e \) values are between 20K and 1000K. Equivalent noise temperature is generally more useful when expressed logarithmically referenced to 1K with the unit of dBK, as

\[
T_{e(dB)} = 10 \log_{10} T_e \tag{4.18}
\]

Essentially, equivalent noise temperature represents the noise power present at the input to a device plus the noise added internally by the device. This allows analysis of noise characteristics of a device by simply evaluating an equivalent input noise temperature.

4.2.10 System Noise Temperature

The system noise temperature of an Earth station consists of the receiver noise temperature, the noise temperature of the antenna, including the feed and waveguides, and the sky noise picked up by the antenna.

\[
T_{system} = \frac{T_{ant}}{L + \left(1 + \frac{1}{L}ight) T_e + T_s} \tag{4.19}
\]

where \( L \) = feed loss in numerical value

\( T_e \) = receiver equivalent noise temperature
$T_0$ = standard temperature of 290°K

$T_{ant}$ = antenna equivalent noise temperature (K)

The interference threshold $\Delta T/T$ is a measure of the amount of interference that can be tolerated by the satellite system. $\Delta T/T$ is related to the increase in system noise temperature. $\Delta T/T$ corresponds to the interference-to-noise ratio, I/N (e.g. for $\Delta T/T=5\%$, $10\log(0.05) = -13.01$ dB). Coordination is required for a $\Delta T/T$ greater or equal to 6%.

4.2.11 Gain-to-Equivalent Noise Temperature Ratio, $G/T_a$

Gain-to-equivalent noise temperature ratio is a figure of merit used to represent the quality of a satellite or earth station receiver. It is a ratio of the receive antenna gain ($G$) to the equivalent system noise temperature ($T_0$) of the receiver.

$$\frac{G}{T_0} = G - 10\log(T_0)$$  \hspace{1cm} (4.20)

where $G$ = receive antenna gain (dB)

$T_0$ = operating or system temperature (Kelvin)

($T_0 = T_a + T_r$, where $T_a$ is the antenna temperature (Kelvin) and $T_r$ is the receiver effective input noise temperature (Kelvin))

4.2.12 Satellite $G/T$

Satellite $G/T = \frac{G_r}{T_{sat}} K^{-1}$ or $10\log\left(\frac{G_r}{T_{sat}}\right)$ dB/K \hspace{1cm} (4.21)

where $G_r$ = gain of satellite receive antenna

$T_{sat}$ = system noise temperature of satellite receiver.

4.2.13 Earth station receiver $G/T$

Receiver $G/T = \frac{G_e}{T_{es}} K^{-1}$ or $10\log\left(\frac{G_e}{T_{es}}\right)$ dB/K \hspace{1cm} (4.22)
where \( G_a \) = gain of earth station receive antenna

\[
T_{es} = G_a = \text{earth station system noise temperature.}
\]

\[
T_{es} = T_{ma} + L_f T_{amb} + (1 - L_f) T_{amb} + (1 - L_t) L_f T_{amb} \quad (K)
\]

(4.23)

where

\[
T_{ma} = T_{ma}^l + \frac{T_{2nd \, stage}}{G_{ma}} + \frac{T_{3rd \, stage}}{G_{ma} G_{2nd \, stage}} + \ldots
\]

(4.24)

(the first term dominates because of \( G_{ma} \) and \( G_{2nd \, stage} \))

\( T_{ma}^l \) = noise temperature of low noise amplifier in isolation

\( T_{2nd \, stage} \) = noise temperature of second stage

\( G_{2nd \, stage} \) = gain of the second stage

\( G_{ma} \) = gain of low noise amplifier, when \( G_{ma} \) is large, then \( T_{ma} = T_{ma}^l \)

\( T_{amb} \) = antenna noise temperature arising from antenna inefficiencies

\( T_{amb} \) = ambient temperature (say 290 K)

\( L_f \) = feed loss between receive antenna and low noise amplifier expressed as a fraction

4.2.14 Noise Density \((N_0)\)

Noise density is the noise power normalized to a 1-Hz bandwidth, or the noise power in a 1-Hz bandwidth. It is expressed mathematically as

\[
N_0 = \frac{N}{B} = \frac{kT_a B}{B} = kT_a
\]

(4.25)

where \( N_0 \) = noise density (watts/per hertz). (\( N_0 \) is generally expressed as simply watts; the per hertz is implied in the definition of \( N_0 \))
\( N = \) total noise power (watts)

\( B = \) bandwidth (hertz)

\( K = \) Boltzmann\'s constant (joules/per Kelvin)

\( T_e = \) equivalent noise temperature (Kelvin)

Expressed as log with 1 W/Hz as reference,

\[
N_o(dB/Wz) = 10 \log N - 10 \log B
\]  
(4.26)

\[
N_o(dB/Wz) = 10 \log k - 10 \log T_e
\]  
(4.27)

4.2.15 Power Flux Density for saturation (PFD)

The power flux density at the satellite causes maximum (saturated) power output from the satellite on the downlink and varies according to earth station position in the satellite receive beam. PFD is a function of the satellite, its antenna and its transponder gain settings.

4.2.16 PFD at satellite

This is given by the expression

\[
PFD = \frac{E_{IRP}}{4\pi d_w^2} \ W/m^2 \text{ or } 10 \log \left( \frac{E_{IRP}}{4\pi d_w^2} \right) \ dBW/m^2
\]  
(4.28)

4.2.17 Carrier-to-Noise Density Ratio \((C/N_0)\)

Carrier-to-noise density ratio is the average wideband carrier power-to-noise density ratio. The wideband carrier power is the combined power of the carrier and its associated sidebands. \(C/N_0\) may also be written as a function of noise temperature;

\[
\frac{C}{N_0} = \frac{C}{kT_e}
\]  
(4.29)

Expressed as a log,

\[
\frac{C}{N_0}(dB) = C_{(dBW)} - N_o(dBW)
\]  
(4.30)
4.2.18 Uplink Carrier power-to-Noise density ratio

Uplink \[ \frac{C}{N_0} = \frac{E_{IRP} \Pi (\text{loss contributions}) G_r}{kT_{FAC}} \text{ Hz} \] (4.31)

\[ = 10 \log (E_{IRP}) + \sum 10 \log (\text{loss contributions}) + 10 \log (G_r/T_{sat}) - 10 \log (k) \text{ dBHz} \]

where \( k = 1.38 \times 10^{-23} \text{ J/K} \) or -228.6 dBJ/K (Boltzmann\& constant)

\[ \frac{C}{N_0} = (E_{IRP} - \text{uplink path loss} - \text{atm. loss} - \text{excess attenuation} + \text{sat}.G/T + 228.6) \text{ dBHz} \] (4.32)

4.2.19 Downlink \( \frac{C}{N_0} \)

Downlink \[ \frac{C}{N_0} = \frac{E_{IRP} \Pi (\text{loss contributions}) G_r}{kT_{FAC}} \text{ Hz} \] (4.33)

\[ = 10 \log (E_{IRP}) + \sum 10 \log (\text{loss contributions}) + 10 \log (G_r/T_{sat}) - 10 \log (k) \text{ dBHz} \]

\[ \frac{C}{N_0} = (\text{sat}.E_{IRP} - \text{downlink path loss} - \text{atm. loss} - \text{excess attenuation} + \text{ES}.G/T + 228.6) \text{ dBHz} \] (4.34)

4.2.20 Carrier-to-Noise Ratio in encoded signal Bandwidth, C/N

C/N is the carrier to noise ratio and is given by

\[ \frac{C}{N} = \frac{E_B}{N_0} \times \frac{\text{bit rate}}{\text{bandwidth}} \] (4.35)
\[
\frac{E_b}{N_0} = 10 \log \left( \frac{\text{bandwidth}}{\text{bit rate}} \right) \text{ dB} \tag{4.36}
\]

**4.2.21 Energy of Bit-to-Noise Density Ratio** (\(E_b/N_0\))

Energy of bit-to-noise density ratio is a convenient term used to compare digital systems that use different transmission rates, modulation schemes, or encoding techniques. In practice, it is more convenient to measure the wideband carrier power-to-noise density ratio and convert it to \(E_b/N_0\). The \(E_b/N_0\) ratio is the product of the carrier-to-noise ratio (\(C/N\)) and the noise bandwidth-to-bit rate ratio (\(B/f_b\)).

Expressed as a log,

\[
\frac{E_b}{N_0} (dB) = \frac{C}{N} (dB) + \frac{B}{f_b} (dB) \tag{4.37}
\]

The energy bit (\(E_b\)) remains constant as long as the total wideband carrier power (\(C\)) and the transmission rate (bps) remains unchanged. The noise density (\(N_0\)) also remains constant as long as the noise temperature remains constant. Therefore, for a given carrier power, bit rate, and noise temperature, the \(E_b/N_0\) ratio remains constant regardless of the encoding technique, modulation scheme, or bandwidth. \[1\]

**4.2.22 Excess attenuation**

Signal strength can be reduced by the presence of water vapour and oxygen in the atmosphere. Water droplets arising from heavy rain can also be particularly damaging to the link as they can absorb, scatter, reflect and de-polarise the incident signal. These effects manifests themselves on both the uplink and downlink as fades in signal strength. Under clear sky conditions, excess attenuation is 0dB. Excess attenuation due to rainfall is given by

\[
\alpha = a(f) R^b(f) \times \text{slant path through raincell} \tag{4.38}
\]

where \(\alpha = \text{attenuation due to rainfall in dB/km}\)
\( \alpha(f) \) = frequency dependent multiplier

\( R = \text{rainfall rate (mm/h) for a particular climatic zone} \)

\( b(f) = \text{frequency dependent exponent} \)

### 4.2.23 Implementation margin

Implementation margin accounts for any variation relative to theoretical arising from practical equipment which exhibit certain fluctuations (level, frequency, phase) and noise perturbations which degrades the received signal. This margin could also include an allowance for mispointing. Typical values lie from 0.5 to 3dB. \([4]\)

### 4.2.24 Bit error rate (BER)

The BER, as a measure of the signal quality, is an important figure of merits in all link budgets. It is related to the ratio of energy per transmit bit-to-noise power density by the equation

\[
\text{BER} = \frac{1}{2} \operatorname{erfc} \left( \sqrt{ \frac{2}{N_0} \log_2 m } \right)
\]

(4.39)

for \( m = 2 \) (BPSK), \( m = 4 \) (QPSK), \( m = 8 \) (8-PSK)

where \( \operatorname{erfc} \) is the complementary error function for \( m = 2 \) (BPSK), \( m = 4 \) (QPSK), \( m = 8 \) (8-PSK). For a QPSK signal in an additive white Gaussian noise channel, equation (4.39) when plotted on a log-log scale has a classic waterfall shape. BER is inversely related to \( \frac{E_b}{N_0} \). Higher \( \frac{E_b}{N_0} \) means better quality. \([4]\)

### 4.2.25 Modulation scheme

Most modern satellite systems use either phase-shift keying (PSK) or quadrature amplitude modulation (QAM) rather than conventional frequency modulation (FM). With PSK and QAM, the input baseband is generally a PCB-encoded, time-division-multiplexed signal that is digital in nature. Also, with PSK and QAM, several bits may be encoded in a single transmit signaling element.
4.2 SATELLITE SYSTEM PERFORMANCE WITH RF INTERFERENCE

A communication system must meet certain minimum performance standards. This section makes use of carrier-to-noise plus interference ratio $C/(N+I)$ as a measure of the system performance. A satellite system which uses 16-PSK modulation scheme and has minimum required $C/(N+I)$ of 13.50 dB is considered and a link budget is made to analyse its performance in the presence of some adjacent interference from a neighbouring satellite system. A raised cosine of $\alpha$ equal to zero assumed. All the parameters in section 4.1 are held constant and interference of different levels are introduced at a time to evaluate the effect on the overall system performance. The performance of the system with the presence of co-channel interference of (-179 dB uplink, -190 dB downlink) and adjacent interference of (-207 dB uplink, -240 dB downlink) is illustrated by Table 4.1

Table 4.1 Satellite Link Budget

<table>
<thead>
<tr>
<th><strong>Uplink parameters</strong></th>
<th><strong>Value</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth station transmitter output power at saturation (W)</td>
<td>12000</td>
</tr>
<tr>
<td>Earth station backoff loss (dB)</td>
<td>4.00</td>
</tr>
<tr>
<td>Earth station branching and feeder losses (dB)</td>
<td>2.00</td>
</tr>
<tr>
<td>Earth station transmit antenna gain (dB)</td>
<td>64.00</td>
</tr>
<tr>
<td>Additional uplink atmospheric losses (dB)</td>
<td>0.80</td>
</tr>
<tr>
<td>Free-space path loss (dB)</td>
<td>206.50</td>
</tr>
<tr>
<td>Satellite receive antenna gain (dB)</td>
<td>26.54</td>
</tr>
<tr>
<td>Satellite equivalent noise temperature (K)</td>
<td>900</td>
</tr>
<tr>
<td>Satellite G/Te (dB/K)</td>
<td>-3.00</td>
</tr>
<tr>
<td>Satellite branching and feeder losses (dB)</td>
<td>0.00</td>
</tr>
<tr>
<td>Bit rate (Mbps)</td>
<td>100</td>
</tr>
<tr>
<td>Modulation scheme</td>
<td>16 PSK</td>
</tr>
<tr>
<td>Earth station antenna diameter (m)</td>
<td>15</td>
</tr>
<tr>
<td>Uplink frequency (GHz)</td>
<td>14</td>
</tr>
<tr>
<td>Co-channel interference, $I_o(cc)$ (dB)</td>
<td>-179.00</td>
</tr>
<tr>
<td>Adjacent interference, $I_o(adj)$ (dB)</td>
<td>-207.00</td>
</tr>
<tr>
<td>Path distance to satellite (km)</td>
<td>36000</td>
</tr>
</tbody>
</table>
### Downlink parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite transmitter output power at saturation (W)</td>
<td>10</td>
</tr>
<tr>
<td>Satellite backoff loss (dB)</td>
<td>0.80</td>
</tr>
<tr>
<td>Satellite branching and feeder losses (dB)</td>
<td>0.50</td>
</tr>
<tr>
<td>Satellite transmit antenna gain (dB)</td>
<td>33.00</td>
</tr>
<tr>
<td>Additional downlink atmospheric losses (dB)</td>
<td>0.60</td>
</tr>
<tr>
<td>Free-space path loss (dB)</td>
<td>205.60</td>
</tr>
<tr>
<td>Earth station receive antenna gain (dB)</td>
<td>62.00</td>
</tr>
<tr>
<td>Earth station branching and feeder losses (dB)</td>
<td>0.00</td>
</tr>
<tr>
<td>Earth station equivalent noise temperature (K)</td>
<td>300</td>
</tr>
<tr>
<td>Earth station G/Te (dB)</td>
<td>37.23</td>
</tr>
<tr>
<td>Bit rate (Mbps)</td>
<td>100</td>
</tr>
<tr>
<td>Modulation scheme</td>
<td>16 PSK</td>
</tr>
<tr>
<td>Earth station antenna diameter(m)</td>
<td>0.5</td>
</tr>
<tr>
<td>Downlink frequency (GHz)</td>
<td>12</td>
</tr>
<tr>
<td>Co-channel interference, Io(cc) (dB)</td>
<td>-190.00</td>
</tr>
<tr>
<td>Adjacent interference, Io(adj) (dB)</td>
<td>-240.00</td>
</tr>
<tr>
<td>Path distance to satellite (km)</td>
<td>36000</td>
</tr>
</tbody>
</table>

### Additional information

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Boltzmann's constant (J/K)</td>
<td>1.38E-23</td>
</tr>
<tr>
<td>Occupied Bandwidth (MHz)</td>
<td>25</td>
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</table>

### Uplink calculation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth station EIRP (dBW)</td>
<td>98.79</td>
</tr>
<tr>
<td>Carrier power density at satellite antenna (dBW)</td>
<td>-108.51</td>
</tr>
<tr>
<td>(C/No) uplink (without interference) (dB)</td>
<td>5.11752E+11</td>
</tr>
<tr>
<td>(Eb/No) uplink (dB)</td>
<td>5117.521197</td>
</tr>
<tr>
<td>(C/N) uplink (dB)</td>
<td>20470.08479</td>
</tr>
<tr>
<td>(C/Io) adj (dB)</td>
<td>3.18553E+12</td>
</tr>
<tr>
<td>(C/Io)cc (dB)</td>
<td>5048719541</td>
</tr>
<tr>
<td>(C/Io) total uplink (dB)</td>
<td>5040730521</td>
</tr>
<tr>
<td>C/(No+Io) uplink (dB)</td>
<td>4991563889</td>
</tr>
<tr>
<td>(C/I) adj (dB)</td>
<td>127421.067</td>
</tr>
<tr>
<td>(C/I) cc (dB)</td>
<td>201.9487816</td>
</tr>
<tr>
<td>(C/I) total uplink (dB)</td>
<td>201.6292208</td>
</tr>
<tr>
<td>C/(N+I) uplink (dB)</td>
<td>199.6625555</td>
</tr>
<tr>
<td>Eb/(No+Io) uplink (dB)</td>
<td>49.91563889</td>
</tr>
</tbody>
</table>
### Downlink calculation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite transponder EIRP (dBW)</td>
<td>41.70</td>
</tr>
<tr>
<td>Carrier power density at earth station antenna (dBW)</td>
<td>-164.50</td>
</tr>
<tr>
<td>(C/No) downlink (dB)</td>
<td>13583123797</td>
</tr>
<tr>
<td>(Eb/No) downlink (dB)</td>
<td>135.831238</td>
</tr>
<tr>
<td>(C/N) downlink (dB)</td>
<td>543.3249519</td>
</tr>
<tr>
<td>(C/Io) adj (dB)</td>
<td>5.62341E+13</td>
</tr>
<tr>
<td>(C/Io)cc (dB)</td>
<td>562341325.2</td>
</tr>
<tr>
<td>(C/Io) total downlink (dB)</td>
<td>562335701.8</td>
</tr>
<tr>
<td>C/(No+Io) downlink (dB)</td>
<td>539980723.4</td>
</tr>
<tr>
<td>(C/I) adj (dB)</td>
<td>2249365.301</td>
</tr>
<tr>
<td>(C/I) cc (dB)</td>
<td>22.49365301</td>
</tr>
<tr>
<td>(C/I) total downlink (dB)</td>
<td>22.49342807</td>
</tr>
<tr>
<td>C/(N+I) downlink (dB)</td>
<td>21.59922894</td>
</tr>
<tr>
<td>Eb/(No+Io) downlink (dB)</td>
<td>5.399807234</td>
</tr>
</tbody>
</table>

### Overall Link Performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C/No) overall (without interference) (dB)</td>
<td>101.22</td>
</tr>
<tr>
<td>C/(No+Io) overall (dB)</td>
<td>86.88</td>
</tr>
<tr>
<td>(C/N) overall (without interference) (dB)</td>
<td>27.24</td>
</tr>
<tr>
<td>C/(N+I) overall (dB)</td>
<td>12.90</td>
</tr>
<tr>
<td>(Eb/No) overall (without interference) (dB)</td>
<td>21.22</td>
</tr>
<tr>
<td>Eb/(No+Io) overall (dB)</td>
<td>6.88</td>
</tr>
<tr>
<td>C/(N+I) (Required) (dB)</td>
<td>13.50</td>
</tr>
<tr>
<td>Margin (dB)</td>
<td>-0.60</td>
</tr>
</tbody>
</table>
Chapter 5
5.0 RESULTS AND ANALYSIS

For different levels of interference introduced into the system, the link budget results were tabulated in Table 5.1

Table 5.1 Satellite system performances with different levels of adjacent and co-channel interference

<table>
<thead>
<tr>
<th>U/L Io cc (dB)</th>
<th>U/L Io adj (dB)</th>
<th>D/L Io cc (dB)</th>
<th>D/L Io adj (dB)</th>
<th>Overall C/(N+Io) (dB)</th>
<th>Overall C/(N+I) (dB)</th>
<th>Overall Eb/(No+Io) (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-205</td>
<td>-225</td>
<td>-210</td>
<td>-255</td>
<td>100.28</td>
<td>26.3</td>
<td>20.28</td>
</tr>
<tr>
<td>-200</td>
<td>-220</td>
<td>-205</td>
<td>-250</td>
<td>98.75</td>
<td>24.77</td>
<td>18.75</td>
</tr>
<tr>
<td>-190</td>
<td>-215</td>
<td>-200</td>
<td>-246</td>
<td>95.7</td>
<td>21.72</td>
<td>15.7</td>
</tr>
<tr>
<td>-182</td>
<td>-210</td>
<td>-194</td>
<td>-242</td>
<td>90.54</td>
<td>16.56</td>
<td>10.54</td>
</tr>
<tr>
<td>-180</td>
<td>-209</td>
<td>-192</td>
<td>-241</td>
<td>88.68</td>
<td>14.7</td>
<td>8.68</td>
</tr>
<tr>
<td>-179</td>
<td>-207</td>
<td>-190</td>
<td>-240</td>
<td>86.88</td>
<td>12.9</td>
<td>6.88</td>
</tr>
<tr>
<td>-178</td>
<td>-206</td>
<td>-189</td>
<td>-239</td>
<td>85.91</td>
<td>11.93</td>
<td>5.91</td>
</tr>
<tr>
<td>-177</td>
<td>-205</td>
<td>-188</td>
<td>-238</td>
<td>84.94</td>
<td>10.96</td>
<td>4.94</td>
</tr>
<tr>
<td>-176</td>
<td>-204</td>
<td>-186</td>
<td>-237</td>
<td>83.06</td>
<td>9.08</td>
<td>3.06</td>
</tr>
<tr>
<td>-175</td>
<td>-203</td>
<td>-185</td>
<td>-235</td>
<td>82.08</td>
<td>8.1</td>
<td>2.08</td>
</tr>
<tr>
<td>-174</td>
<td>-202</td>
<td>-184</td>
<td>-234</td>
<td>81.09</td>
<td>7.11</td>
<td>1.09</td>
</tr>
<tr>
<td>-173</td>
<td>-201</td>
<td>-182</td>
<td>-233</td>
<td>79.18</td>
<td>5.2</td>
<td>-0.82</td>
</tr>
</tbody>
</table>

The considered satellite system in Table 4.1 resulted to $C/(N+I) = 12.90\text{dB}$. This value is below the minimum value of $C/(N+I)$ that can be tolerated by the satellite system (13.50dB), hence successful communication is not possible (margin is negative). From Table 5.1, the values of interference in the Rows highlighted in Blue are acceptable to this system since they gave values of $C/(N+I)$ greater than the minimum required (13.50dB). On the other hand, the values of interference in the Rows highlighted in Red are unacceptable to this system since they gave values of $C/(N+I)$ lower than 13.50dB. Table 5.1 also shows that higher levels of interferences result to lower values of $\frac{E_b}{N_0+Io}$. This implies higher bit error rates. For a system to operate successfully, it must have a positive margin.
Chapter 6

6.0 CONCLUSION & RECOMMENDATION

Sources of Radio Frequency interference, types of RF interference, factors affecting RF interference and determination of an acceptable level of RF interference were discussed. The thorough study and description of RF interference in Fixed Service Satellite Systems showed that RF interference from Adjacent satellites in the Geosynchronous Earth Orbits contribute significantly to signal degradation. Two neighbouring satellite systems were considered. A Satellite Link Budget was successfully used to analyse system performance \((C/(N+I))\) specified at the receiving site. Link Budget method of analysis using \((C/(N+I))\) therefore may be used to monitor the satellite system performance at some Earth station. If the interference situation is one in which another party's antenna can be changed to resolve an interference case, such changes may be accomplished through negotiate with that party. These changes will normally have to be funded by the party planning the new system unless the other party is using antennas that do not meet the minimum Federal Communications Commission (FCC) requirements for radiation patterns.

RECOMMENDATION

Other Link Budget parameters to be varied to analyse satellite system performance in presence of different levels of RF interference. Energy bit-to-noise density ratio to be used as to analyse system performance.

REFERENCES


**Internet sources**

[10] [http://www.rfk.co.uk](http://www.rfk.co.uk)


[12] [http://www.complexoreal.com](http://www.complexoreal.com)