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BISANTE

Broadband Integrated Satellite Network Traffic Evaluations

Deliverable 2.2

GEO Satellite Network Characteristics

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Abstract: This deliverable identifies the GEO satellite network characteristics which have an impact on the application. The idea is to model the GEO satellite network using a layered block diagram and characterising individual blocks. This will simplify simulation by just using different modules for different scenarios.
Therefore the characteristics of each functional block are described and the parameters which are used to determine the loss and delay values are provided. Furthermore two GEO satellite network scenarios are described and parameter values for these scenarios are given.

The BISANTE Consortium consists of :

Thomson-CSF Communications	Partner	France
Netway	Partner	Austria
Solinet	Partner	Germany
University of Vienna	Associated Partner	Austria
University of Surrey	Associated Partner	United Kingdom
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1. EXECUTIVE SUMMARY

This deliverable provides information about the GEO satellite network characteristics and the parameters which have to be taken into account in WP3 when the simulation models are implemented.

First the Terrestrial Network Termination Module (TNTM) characteristics are described. The emphasis is in delays introduced by protocol conversion/tunnelling. Furthermore the bandwidth efficiency of modulation schemes and the trade-off between coding gain and error correction code overhead is explained. Techniques to make ATM transmission, which requires low Bit Error Rate, over satellite more robust are described. Then Section 3 describes the GEO satellite uplink characteristics. The fixed multiple access schemes are described. Equations for mean packet (or message) delays introduced by the access schemes are provided. This is followed by an in depth description of the propagation impairments which are applicable for both uplink and downlink. Section 4 provides the characteristics and protocol stack for repeater and on-board switching satellites. Section 5 outlines the differences between uplink and downlink characteristics and Section 6 describes the Satellite Network Termination Module (SNTM) characteristics. The relation of the Sections in the deliverable is shown in Figure 1-1.

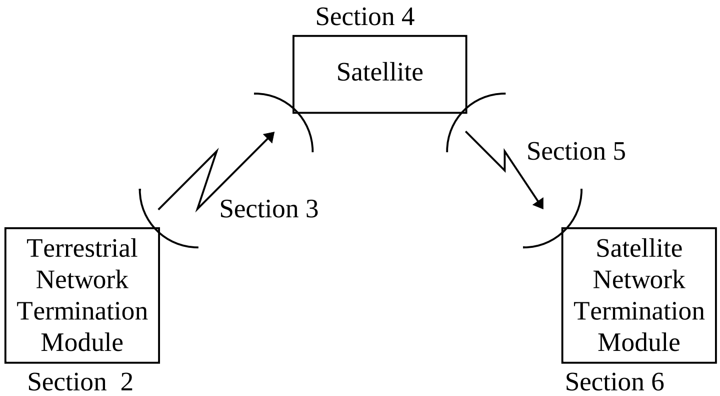


Figure 1-1 The relation of the Sections for the deliverable

2. TERRESTRIAL NETWORK TERMINATION MODULE CHARACTERISTICS

2.1. PROTOCOL MAPPING/TUNELLING

This module carries out mapping/tunelling of the terrestrial network protocol to the satellite protocol. Two protocols have been selected to be used for transmission over satellite, namely IP and ATM. First the modules required for ATM transmission are explained and this is followed by the modules required for IP transmission over satellite.

2.1.1. THE LAN ATM CONVERTER MODULE

The LAN ATM Converter (LAC) module converts the FDDI and Ethernet packets into ATM cells, then passes the cells to the ATM Adaptation Module (ATM-AM). A large buffer may be required. During the CATALYST project a 4 Mbyte buffer was used [SUN98].

2.1.2. THE ATM ADAPTER MODULE (ATM-AM)

The ATM-AM is an ATM Adapter. It multiplexes the ATM cell streams from the input ports into one ATM cell stream. For example for the CATALYST project [SUN98] this module had buffers of 154 cells for port 0 and 77 cells for port 1. The output rate of the ATM-AM module is dependent on the maximum possible uplink rate of the satellite. It is anticipated that the satellite uplink bandwidth will not be sufficient to support the terrestrial ATM rates hence some buffering on the ground terminal is required. During the CATALYST the output rate was 34.368 Mbit/s. This bit rate comes from draft Rec. G 751 [ITUT88] on ATM cell mapping, where 537 bytes are available every 125 microseconds. 530 bytes are allocated to the payload (10 cells) and 7 bytes to various overhead functions (see Figure 2-1). This module provides an interface between the terrestrial network and the satellite ground-station.

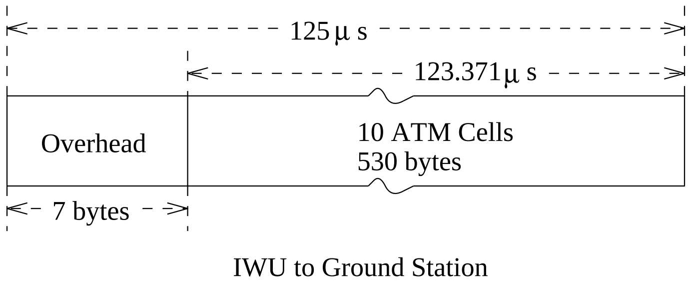


Figure 2-1 Frame Structure for 34.368 Mbit/s cell mapping.

2.1.3. THE IP ADAPTER MODULE (IP-AM)

The IP adaptor module multiplexes the IP packet streams from the input ports into one IP packet stream. Similar to the ATM-AM the output rate of the IP-AM module is dependent on the maximum possible uplink rate of the satellite which might not be sufficient to support the aggregate input traffic. Hence some buffering on the ground terminal is required. Furthermore mapping to protocols such as Synchronous Digital Hierarchy (SDH) may be required. This module provides an interface (similar to ATM-AM) between the terrestrial network and the satellite ground-station.

2.1.4. MODULATION TECHNIQUES

The relationship between C/N and the bit error rate of the channel is a measure of performance for a digital link. This is computed from the Carrier-to-Noise Density ratio., C/N_0 ratio, for a particular modulation scheme by:

$$\frac{E_b}{N_0} = \begin{cases} C/N_0 - 10\log_{10}(DataRate) \\ C/N - 10\log_{10}(DataRate/Bandwidth) \end{cases} \tag{2.1}$$

The data rate over bandwidth ratio, R/B, is called the spectrum or bandwidth efficiency of the modulation. Because of the limited bandwidth, the ideal is to have this value as large as possible. To improve the bandwidth efficiency, modulation has become more complex. The simplest modulation scheme, BPSK, is composed of a binary alphabet. The higher the modulation order the larger the alphabet order. QPSK, for example, uses a two-bit alphabet.

The error relationships allows to use error functions to compute the symbol error rates using the equations given below. Depending on the alphabet level, the symbol error rate is different than the bit error rate. To compare modulation methods, convert the symbol error rates computed to bit error rates. For a simple gray coded M level modulation, the bit error rate p_e is related to the symbol error rate P_s by :

$$p_e = \frac{P_s}{\log_2(M)} \tag{2.2}$$

It is possible to chose from several modulation methods and some of these methods have different names. Table 2-1 shows the common alternate names for each modulation.

The Q function used in the Table 2-1 is a variation of the *erfc* function and is quite often used in the literature instead of the *erfc* function. Q is related to *erfc* by :

$$Q(x) = \frac{1}{2} erfc(\frac{x}{\sqrt{2}}) \tag{2.3}$$

Modulation	P_E(symbol)
Coherent Binary Signalling Techniques	
ASK (Amplitude Shift Keying)	$Q(\sqrt{E_b/N_0})$
QAM, **M-ary QAM** (Quadrature Amplitude Modulation) **APK** (Amplitude Shift Keying)	$2Q(z)(1-0.5Q(Z))$ for M = 4 $z=\sqrt{2(E_b/N_0)}$ for M = 4 $3Q(Z)(1-0.75Q(Z))$ for M = 16 $z=\sqrt{(2E_b/9.75N_0)}$ for M = 16

	$3.5Q(Z)(1-49/56Q(Z))$ for M = 16 $z=\sqrt{(2E_b/41.93N_0)}$ ....for M = 16
FSK (Frequency Shift Keying)	$1/2erfc(\sqrt{E_b/N_0}$
M-ary FSK (M-ary Frequency Shift Keying)	$M/2erfc(\sqrt{E_b/N_0}$
CPFSK (Continuos Phase Shift Keying) **MSK** (Minimum Shift Keying) **Fast FSK**	$erfc(\sqrt{E_b/N_0})-1/4erfc^2(\sqrt{E_b/N_0})$
PSK (Phase Shift Keying)	$1/2erfc(\sqrt{E_b/N_0})$
M-ary PSK	$2Q(\sqrt{2E_b/N_0}\sin(\pi/M))$
QPSK (Quaternary Phase Shift Keying) **OQPSK** (Offset QPSK) **SQPSK** (staggered QPSK)	$erfc(\sqrt{E_b/N_0})$
Noncoherent Signalling Techniques	
ASK (Amplitude Shift Keying) **FSK** (Frequency Shift Keying) **DPSK** (Differential Phase Shift Keying) (noncoherent PSK)	$1/2erfc(-E_b/N_0)$

Table 2-1 Modulation Methods

2.1.5. ERROR CORRECTING CODES

Channel coding is required to achieve low Bit Error Rate (BER) over the satellite link. When coding is used, the transmitted data rate increases because redundant bits are added to the baseband bit stream. If *R* is the information rate, the new coded data rate R_c, as defined for an (n,k) block code, where *n* bits are sent for *k* information bits is:

$$R_c=R\cdot n/k \tag{2.4}$$

First convolutional and block code coding gains are shown and then the enhancement techniques required for broadband and wideband ATM are explained.

The uncoded bit error rate for both BPSK and QPSK is:

$$P_e=\tfrac{1}{2}erfc\sqrt{\frac{E_b}{N_o}} \tag{2.5}$$

From this relationship the required Eb/No for a given Bit Error Rate of the channel, can be defined.

Hence to improve the link quality in bad atmospheric conditions, error correcting codes can be added. These codes, at the expense of larger required bandwidth and larger overhead (reduced throughput), provide a coding gain that boosts up the available E_b/N_o to maintain the desired link quality.

ID	n bits	k bits	t Error	Gain
Convolutional Code1	3	1	1	6.2
Convolutional Code2	2	1	1	5.8
Convolutional Code3	3	2	2	5.2
Convolutional Code4	4	3	3	4.8
Reed Solomon Code1	63	57	3	6.1
Reed Solomon Code2	63	53	5	6.5
Reed Solomon Code3	63	49	7	6.7
Reed Solomon Code4	63	45	8	6.8
Reed Solomon Code5	63	41	11	6.8
Reed Solomon Code6	63	37	13	6.6
Reed Solomon Code7	63	33	15	6.5

Table 2-2 Coding Options

Two basic types of codes are used: Convolutional and Block codes, both with error detecting and correction capabilities. Some of the coding options and the relevant coding gain are shown in Table 2-2.

2.1.6. ENHANCEMENT TECHNIQUES FOR SATELLITE ATM

ATM was designed for transmission on a physical medium with excellent error characteristics, such as optical fibre. Therefore, many of the features included in older protocols that cope with an unreliable channel are no longer part of ATM. While this results in considerable advantages (less overhead, increased throughput) in an optical network, it also causes severe problems when ATM is transmitted over an error-prone channel, such as the satellite link.

A geostationary satellite channel is often modelled as an Additive White Gaussian Noise (AWGN) channel. While the AWGN, which produces *random single bit errors*, is only an approximation, it is widely used and fairly accurate in many situations.

Satellite systems are usually power or bandwidth limited and in order to achieve reliable transmission Forward Error Correction (FEC) codes are often used in satellite modems. With such codes (typically convolutional codes), the incoming data stream is no longer reconstructed on a symbol by symbol basis. Rather some redundancy in the data stream, which generally increases the bandwidth, is used.

On average, coding reduces the bit error rate or alternatively decreases the transmission power needed to achieve a certain QoS for a given S/N ratio, at the expense of coding overhead. However, when a decision is made for a wrong data sequence, in general a large number of bits is affected, resulting in *burst errors*. Because ATM was designed to be robust with respect to random single bit errors, burst errors considerably degrade the performance of ATM.

Hence some enhancement techniques have to be used to make the transmission of ATM cells over the satellite link more robust. Different methods have been proposed which are applicable for two scenarios. The performance of these scheme is directly related to the code rate (bandwidth efficiency) and/or the coding gain (power efficiency), provided the delay involved is acceptable to any ATM-based application.

2.1.6.1. ENHANCEMENT TECHNIQUES FOR BROADBAND SATELLITE ATM

Most recent research had focused on a scenario for large earth stations operating at data rates higher than 2 Mbit/s. The underlying poor performance of ATM on satellite links is that an undesired concatenation of the convolutional channel code (FEC, inner code) and the ATM HEC code (outer code) takes place. Since the outer HEC code is only capable of correcting single bit errors, the errors at the output of the inner code should be dispersed by using an interleaver.

By interleaving the ATM cell headers (not the payload) of several cells the performance of ATM in a random single bit error channel (e.g. AWGN channel) can be achieved [CHIT94]. Note that interleaving merely re-shuffles the bits on the channel (to spread the bit errors among ATM cell headers) and does not produce additional overhead which might decrease the overall bit rate. However, interleaving requires memory at the transmitter and the receiver, and it introduces additional delay. Assuming an average number of 30 bit errors in an error burst [KALT95], interleaving over 100 cell headers seems to be sufficient. This requires a memory of only about 10 kbytes and introduces a delay of 840 µs at 50 Mbit/s and a delay of 21 ms at 2Mbit/s. The performance improvement achieved by interleaving has been confirmed in several studies [AGNE93, KALT95, FAIR97]. Since the above interleaving scheme requires a continuos data stream, there are problems using it for portable terminals where single ATM cells may be transmitted.

Another way of correcting the burst errors due to FEC techniques applied to satellite links are Reed-Solomon (RS) codes. This type of block codes, which are based on symbols, have been identified as performing particularly well in concatenation with convolutional FEC codes, because of their ability to correct bursts of errors [AGNE96].

Moreover, error bursts longer than what the RS code can correct should be spread over several blocks to take advantage of the error correction capabilities of the block code. This can be done by interleaving between the two codes.

2.1.6.2. ENHANCEMENT TECHNIQUES FOR WIDEBAND SATELLITE ATM

For users to whom economical, rapid deployment and relocation is an important requirement, it is only practical to use smaller earth stations such as portable terminals. There is no clear definition of wideband, but we will define it as bit rates of 2.048 Mbit/s and below.

Since inter-cell interleaving is not feasible because only few cells may be transmitted from the terminal, mechanisms which protect single cell have to be found. Interleaving within an entire ATM cell (not only the header), so-called intra-cell interleaving, leads to a performance gain which is too small to be effective.

A better improvement can be achieved by using additional coding to protect the ATM cells. Note that this introduces additional overheads and therefore reduces the useful data bit rate. There are several reasons why FEC or concatenated FEC may not be suitable for enhancing ATM performance over wideband satellite links. First, if only FEC coding is used, than symbol interleaving is usually used to spread the burst errors over several ATM cell headers. The resulting interleaving delay (which is inversely proportional to the data rate) may be too large at a low rate for certain applications. Second if RS codes are used to correct burst of errors in concatonation with FEC either additional bandwidth has to be provided or the data rate has to be reduced.

The latest proposal for improvement of ATM performance for wideband satellite links is the construction of enhancing equipment which optimises the ATM protocols over a satellite link. This allows the data link layer to be optimised using a combination of protocol conversions and error control techniques. This approach allows commercial off-the-shelf ATM equipment to be used. At the transmitter standard ATM cells are modified to suit the satellite link. At the receiver, error recovery techniques are performed and the modified ATM cells (S-ATM cells) are converted into standard ATM cells.

The main aim of modifying standard ATM cell is to minimise the rather large ATM header overhead which is 5 bytes per 48 byte payload. Of the ATM header information, the address field (which is divided into the VPI and VCI) occupies 24 bits. This allows up to 16 million VC to be set up. Considering that in particular Constant Bit Rate (CBR) connection cells all carry the same address information in the header, there may be methods not to duplicate the same information. Furthermore, wideband satellite links cannot support 16 million virtual connections and the use of 24 bits for address space may be considered a waste of bandwidth for this scenario.

One method to protect the ATM cell header when interleaving is not possible is the compression of the 24 bits address space to 8 bits and to store the duplicate header information (except the HEC field) of the previous cell [FAIR97]. The HEC is still computed over the first 4 bytes of the header and inserted into the fifth byte of the header. Therefore if a cell header contains errors, the receiver can store the payload in a buffer and recover the header information from the next cell provided that its header does not also contain errors. This method is only effective if the cell containing errors in the cell header has no errors in the payload. Simulations [FAIR97] show that this method provides considerable improvements in CLR compared to standard ATM transmission and even compared to interleaving.

Another alternative is to use a 3 byte HEC instead of a 1 byte HEC, which is inadequate for the satellite environment. For the mentioned (56,32) error correction scheme, candidate codes include a shortened form of the four-bit-error correcting (63,39) binary BCH code and a shortened form of the three-symbol-error correcting (15,9) RS code (with 4-bit symbols).

3. GEO SATELLITE UPLINK MODULE CHARACTERISTICS

3.1. MEDIUM ACCESS CONTROL (MAC) LAYER CHARACTERISATION

This section examines the techniques which are available for allowing a number of users to communicate via a common satellite transponder. This is broadly termed ‘multiple access’, where the transponder’s available power and bandwidth are shared between a number of different channels and earth stations, which may themselves have quite different transmit powers and signal characteristics. Efficient use of these resources is important, while meeting the need of the user’s traffic demands.

There are three principal forms of fixed multiple access:

- Frequency Division Multiple Access (FDMA)
- Time Division Multiple Access (TDMA)
- Code Division Multiple Access (CDMA)

Each has its advantages and disadvantages, and all of the above are in current use, together with hybrid schemes.

3.1.1.1.FREQUENCY DIVISION MULTIPLE ACCESS (FDMA)

FDMA is a traditional and popular technique, whereby several earth stations transmit simultaneously, but on different preassigned frequencies into a transponder.

Preassigned FDMA was attractive because of its simplicity and cheapness. Single Channel Per Carrier (SCPC) FDMA was commonly used for very thin-route telephony, VSAT systems and mobile services, but it is inflexible for bursty applications which have varying bandwidth requirements. In order to use bandwidth efficiently ‘demand assignment’ is commonly used (demand-assigned FDMA).

Access by multiple carriers, as in FDMA, can give significant problems with Inter-Modulation-Products (IMPs), and hence a few dBs of back-off from saturation is required. The resultant reduction in downlink EIRP may represent a penalty, especially when working to small terminals.

The traffic delay is defined as the time between the arrival of a message in a buffer at the ground terminal and completion of the departure. The average message delay for an FDMA channel is [HA86]:

$$T_{FDMA} = \frac{1}{\mu} + \frac{\lambda(\frac{1}{\mu^2 + \sigma^2})}{2(1-\rho)} \text{ (s)} \qquad (3.1)$$

where σ is the variance in the service time, λ is the average number of the message (or packets) arriving per second and μ (carrier transmission rate/the length of a packet) is the average service rate. ρ=λ/μ is the traffic intensity.

When the service time (or packet length) is exponentially distributed, then $\sigma^2 = 1/\mu^2$ and

$$T_{FDMA} = \frac{1}{\mu - \lambda} \text{ (s)} \tag{3.2}$$

When the service time (or packet length) is constant, then σ = 0 and

$$T_{FDMA} = \frac{2 - \frac{\lambda}{\mu}}{2(\mu - \lambda)} \text{ (s)} \tag{3.3}$$

3.1.1.2.TIME DIVISION MULTIPLE ACCESS (TDMA)

In TDMA, each user is allocated a time slot in which information can be transmitted. The information burst of each user, together with reference bursts which provide synchronisation information, make up a TDMA frame. The simplest system has fixed assignment of slots (fixed-TDMA), although demand-assignment schemes can be very flexible, with allocation of burst length as required.

Only one TDMA carrier accesses the satellite transponder at a given time, and the full downlink power is available for that access. TDMA can achieve efficiencies in power utilisation of 90 percent or more and similar efficiencies in bandwidth utilisation because the guard time loss in efficiency can be kept small by accurate timing techniques. The high bandwidth utilisation of TDMA is the reason why it is widely used.

Clearly TDMA bursts transmitted by ground terminals must not interfere one with another. Therefore each earth station must be capable of first locating and then controlling its transmit burst time phase. Each burst must arrive at the satellite transponder at a prescribed time relative to the reference burst. This ensures that no two bursts overlap and that the guard time between any two bursts is small enough to guarantee a high transmission efficiency

Synchronisation is the process of providing timing information at all stations and controlling the TDMA bursts so that they remain within their prescribed slots. All this must operate even though each Earth station is at a different distance from the satellite for instance, and considering the motion of the satellite with respect to the Earth.

GEO satellites are located at a nominal longitude and typically specified to remain within a “window” with sides of 0.1 degree as seen from the centre of the Earth. Moreover, the satellite altitude varies as a result of a residual orbit eccentricity of about 0.001. The satellite can thus be anywhere within a volume of space which is typically 75 km · 75 km · 85 km.

The tidal movement of the satellite causes an altitude variation of about 85 km, resulting in around trip delay variation of about 500 μs and a frequency change of signals due to the Doppler effect.

One can easily understand that the TDMA co-ordination is all the more complex as the satellite is not fixed in the sky (LEO or MEO satellites), which means that the propagation delay varies. As a consequence, TDMA is harder to implement for LEO satellites than for GEO satellites.

TDMA Buffers and Timing Control

Since the bit streams entering the ground terminal are continuous while the output of the TDMA modulator is bursts according to a time plan, the TDMA modem must contain a data buffer. This buffer stores the data bits received from one frame until the next. The total storage required is M bits for N input bit streams of bit rate f_{di} and frame period τ_f where

$$M = \sum_{i=1}^{N} f_{di} \tau_f \tag{3.4}$$

TDMA timing at a ground terminal can be slaved either to an actual clock on-board the satellite or to an earth terminal clock at a terminal designated as the master.

TDMA Frame Rates and Formats

The format of a TDMA frame can have different formats. A superframe of *N* frames can be used to allow for some very low data-rate users desiring to transmit at a rate below the frame rate. The frame rate, for example might be 84 frames/sec, and a user terminal *i* who desires to transmit at 32 kbit/s would transmit on the average 384 bits (ATM cell payload) per frame. On the other hand if a user terminal wants to transmit at an average of 8 kbit/s it would transmit 384 bits per 4 frames. However, most users transmit one data burst per frame plus perhaps a timing burst for synchronisation.

Traditional TDMA bursts were subdivided into a preamble for receiver synchronisation, data bits addressed to various receive terminals and postambles that identify the end of the burst (to resolve carrier phase and frequency ambiguities). Currently preambleless modems are available that do not require pre- and postambles, minimising the burst overhead [CELA97]. Guard times (T_g) are required at the beginning of each burst, to prevent overlap of adjacent bursts from different ground terminals. This guard time (typically from 30nsec-300nsec) must be sufficient to account for system timing inaccuracies and tails from adjacent bursts caused by finite filter-response times.

If a TDMA frame is divided into *N* subframes of length b[bits], the time for one frame is :

$$T_f = \frac{N_b}{R} \tag{3.5}$$

where R is the bit rate. The average service rate, μ, is then :

$$\mu = \frac{1}{T_F} = \frac{R}{N_b} \tag{3.6}$$

The traffic intensity is described as,

$$\rho = \frac{\lambda}{\mu} \tag{3.7}$$

where λ is the average number of the message (or packets) arriving per second.

If, for a TDMA channel, we assume a Poisson-distributed message arrival (or packet size), the average TDMA delay is [HA86]:

$$T_{TDMA} = \frac{1}{\mu - \lambda} - \frac{1}{2\mu} + \frac{1}{N\mu} \text{ (s)} \tag{3.8}$$

For constant packet size the average delay is:

$$T_{TDMA} = \frac{2 - \frac{\lambda}{\mu}}{2(\mu - \lambda)} - \frac{1}{2\mu} + \frac{1}{N\mu} \text{ (s)} \tag{3.9}$$

which is shorter than FDMA delay. Shorter delays can be achieved with random access methods (ALOHA and slotted ALOHA), however with a limit on the throughput.

A demand assigned access system, DAMA, is essentially a TDMA with dynamically variable frame assignment when the traffic increases. This allows larger frames to some users and effectively allows the available capacity to be shard by more users than the static capacity allocation..

TDMA System Efficiency

The efficiency of the satellite transponder with TDMA inputs and hard limiting depends on the guard times between the transmissions T_{gi} of each terminal, the preamble and postamble times and the addressing time required for each transmit/receive terminal pair T_{aij}, the time utilised for timing-ranging function T_R, and the frame duration T_f. The maximum efficiency for all terminals occupying the frame is

$$\eta_{\max} = \frac{T_f - \left[T_R + \sum_i T_{gi} + \sum_j T_{aij} \right]}{T_f} \tag{3.10}$$

where i is summed over all N terminals in the network and j is summed over all N-1 which can be addressed by the terminal. If all guard times and address times are identical, then the maximum efficiency is

$$\eta_{\max} = \frac{T_f - \left[T_R + NT_g + N(N-1)T_a \right]}{T_f} \tag{3.11}$$

where it is assumed that all terminals are communicating with all the other terminals and the frame is fully utilised. The inefficiencies of the data channels due to channel coding are not considered in this calculations.

3.1.1.3.CODE DIVISION MULTIPLE ACCESS (CDMA)

CDMA is an access technique employing spread spectrum modulation, where each channel is modulated with a unique spreading function. The resulting wide-band signals from all users may be overlaid in a common RF bandwidth, and employ the same carrier frequency simultaneously. It is also known as Spread Spectrum Multiple Access (SSMA). A feature of spread spectrum is that operation is possible in the presence of high levels of uncorrelated interference, and this property of spread spectrum has important antijamming applications in military communications.

Each CDMA user combines his data signal of a few kHz bandwidth with a very wide-band spreading function. This has a bandwidth of typically several MHz and is derived from a pseudo-random code sequence, and the resulting transmitted signal then occupies a similar wide bandwidth. At the receiver, the input signal is correlated with the same spreading function, suitably synchronised, to reproduce the originating data. At the receiver output, the small residual correlation products from unwanted user signals amount to additive noise, known as self-interference. As the number of users in the system increases, the total noise level will increase and degrade the bit-error-rate performance. This will give a limit to the maximum number of simultaneous channels which can be accommodated within the same overall frequency allocation, and it can be shown that, theoretically, CDMA is inferior to FDMA or TDMA in terms of capacity for a given power and bandwidth. In practice the performance can be superior to FDMA allowing for the latter’s limitation of guard bands and TWTA back-off. There is no need for network timing references as in TDMA, and speech duty cycles may be readily exploited. The overall merits or otherwise of CDMA are very scenario dependant, and the subject of considerable debate.

3.2. UPLINK PROPAGATION IMPAIRMENTS

The major consideration in planning an overall satellite link is the quality in the baseband. This is measured in terms of S/N for an analogue system and in terms of Bit Error Rate (BER) for a digital system. In both cases the quality of the link is proportional to the carrier to total noise (C/N_T) at the input of the receiver demodulator. The link budget is a calculation of the (C/N) power ratio at the receiving side of a transmission link, taking into consideration the transmission medium and the transmitter/receiver characteristics.

The received power by the satellite P_r is given by:

$$P_r = G_t P_t G_r / L_{FS} \text{ where } L_{FS} = \left(\frac{4\pi R}{\lambda}\right)^2 \qquad (3.12)$$

where λ is the wavelength, G_t the gain of the transmitting antenna in the receiver direction, G_r the gain of the receiving antenna, and R the distance between the satellite and the ground terminal. This means that the received power is inversely proportional to R^2.

The principal role of the satellite receiver is to amplify the received signal to a usable level. Receiver noise, external background noise and interference from others transmitters corrupt this amplified signal. The received noise power spectral density is given by:

$$N_0 = Kt \qquad (3.13)$$

where T is the equivalent noise temperature of the receiving equipment (satellite). k the Boltzmann constant = $1.397 \cdot 10^{-23}$ W/Hz/K

Denoting the received carrier power level by C, the uplink carrier power-to-noise power spectral density ratio is expressed at:

$$\left(C / N_0\right)_U = EIRP_U \left(\frac{1}{L}\right)_U \left(\frac{G_r}{T_r}\right) \frac{1}{k} \qquad (3.14)$$

where

$(EIRP)_U = P_t G_t$ is the effective isotropically radiated power on the uplink

T_r the equivalent noise temperature of the receiving equipment (satellite)

$L = L_{FS} + L_a$ the total loss: L_{FS} the free space loss, and L_a the additional losses, where L_a depends on:

- gaseous atmospheric absorption
- rain attenuation
- antenna pointing and fade losses
- fading and scintillation losses

3.2.1. CLEAR SKY FREE-SPACE LOSS

Clear sky free-space loss is due to directional spreading of the beam as it travels through space. It is defined as :

$$L_u = 20 \log_{10} \left(4\pi \frac{d}{\lambda} \right) [\text{dB}] \qquad (3.15)$$

where d is the distance between the transmitter and the receiver, and λ is the wavelength.

In addition to the free-space loss, which is larger than all the other losses, other losses can also play important part in adding up another several dBs. At frequencies of 10 GHz and above, losses due to atmospheric absorption and rain can be significant. At these frequencies, electromagnetic waves interact and resonate with molecules of atmospheric gases to cause signal attenuation. The most important resonant attenuation occurs at 22.235 GHz due to water vapour and between 53 to 65 GHz due to oxygen. Loss at other frequencies are usually small (less than 1 dB). These atmospheric losses can be calculated and included in the link equation to determined its impact of the overall quality.

At lower frequencies, less than 1 GHz, losses due to multipath fading and scintillation are predominant. Faraday Rotation due to the total electron count in the atmosphere becomes significant, but, using proper polarization, these losses can be controlled in high-gain communications.

3.2.2. GASEOUS ABSORPTION ATTENUATION

The International Telecommunication Union (ITU) proposes an approximate method for calculating the gaseous absorption attenuation [IPPO89]. The input parameters for this are :

- f = frequency in GHz
- θ = path angle or elevation
- h_s = height above sea level in kilometers
- ρ_w = water vapour density at the surface of location of interest in g/m^3

If the water vapour density is not available, it is possible to use mean values to obtain a range of attenuation.

Attenuation due to dry air is defined as follows for f < 57 GHz :

$$\gamma_o = \left[7.19 \times 10^{-3} + \frac{6.09}{f^2 + 0.227} + \frac{4.3}{(f-57)^2 + 1.5} \right] 10^{-3} f^2 \quad \text{[dB/km]} \quad (3.16)$$

Attenuation, λ_w [dB/km], due to water vapour ρ_w is defined as follows :

$$\gamma_w = \left[0.067 + \frac{3}{(f-22.3)^2 + 7.3} + \frac{9}{(f-183.3)^2 + 6} + \frac{4.3}{(f-323.8)^2 + 10} \right] 10^{-4} f^2 \rho_w$$

Local temperature corrections for the preceding equations are given as follows :

$$\gamma_o = \gamma_o [1 - 0.01(T_o - 15)]$$

$$\gamma_w = \gamma_w [1 - 0.01(T_o - 15)]$$

Equivalent heights for oxygen (h_o) and the water vapour (h_w) are determined by :

h_0 = 6 km for f < 57 GHz

$$h_w = \left[2.2 + \frac{3}{(f-22.3)^2+3} + \frac{1}{(f-183.3)^2+1} + \frac{1}{(f-323.8)^2+1} \right]$$

The total slant path gaseous attenuation through the atmosphere, A_g , is found by :

$$A_g = \begin{cases} \dfrac{\gamma_o h_o e^{\frac{-h_s}{h_o}} + \gamma_w h_w}{\sin e\theta} & \text{for } \theta \geq 10 \text{ degrees} \\ \dfrac{\gamma_0 h_o}{g(h_o)} + \dfrac{\gamma_w h_w}{g(h_w)} & \text{for } \theta < 10 \text{ degrees} \end{cases} \quad (3.17)$$

where

$$g(h) = 0.661x + 0.339 \sqrt{x^2 + \frac{h}{1545.5}} \quad (3.18)$$

$$x = \sqrt{\sin^2\theta + \frac{h_s}{4250}} \quad (3.19)$$

where h_s is replaced by h_0 and h_w.

3.2.3. RAIN ATTENUATION

Rain is the dominant cause of attenuation in satellite links above 10 GHz. Most rain attenuation models are based on statistical data of rain rate. Typical satellite link design allows for rain fades for a certain small percentage of times. To allow capability to communicate in various rain rates, attenuation factors can be empirically calculated based on several models that are available. The commonly used rain model are :

- Crane Global Rain Attenuation Model
- Modified CCIR/SAM (Simplified Attenuation Model) Rain Model
- Climate Zone CCIR Model

3.2.3.1.CRANE GLOBAL RAIN MODEL

Steps to create a Crane Global Rain Attenuation Model

1. Obtain annual rain rate distribution, R_p, for several values of p, the probability of exceeding a specified rain rate for the year (see Figure 3-1and Table 3-1).

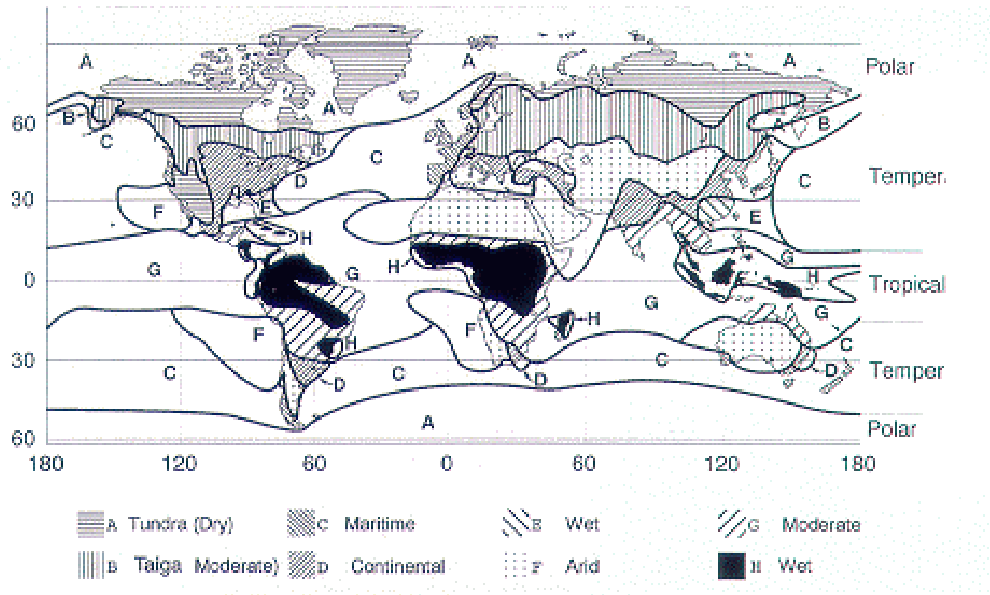


Figure 3-1 Global Rain Climate Regions

% of year	A	B1	B	B2	C	D1	D2	D3	E	F	G	H
0.001	28.5	45.0	57.5	70.0	78	90.0	108	126	165	66	185.0	253.0
0.002	21.0	34.0	44.0	54.0	62	72.0	89.9	106	144	51	157.0	220.5
0.005	13.5	22.0	28.5	35.0	41	50.0	64.5	80.5	118	34	120.5	178.0
0.01	10.0	15.5	19.5	23.5	28	35.5	49.0	63.0	98.0	23	94.0	147.0
0.02	7.0	11.0	13.5	16.0	18	24.0	35.0	48.0	78.0	15	72.0	119.0
0.05	4.0	6.4	8.0	9.5	11	14.5	22.0	32.0	52.0	8.3	47.0	86.5
0.1	2.5	4.2	5.2	6.1	7.2	9.8	14.5	22.0	35.0	5.2	32.0	64.0
0.2	1.5	2.8	3.4	4.0	4.8	6.4	9.5	14.5	21.0	3.1	21.8	43.5
0.5	0.7	1.5	1.9	2.3	2.7	3.6	5.2	7.8	10.6	1.4	12.2	22.5
1.0	0.4	1.0	1.3	1.5	1.8	2.2	3.0	4.7	6.0	0.7	8.0	12.0
2.0	0.1	0.5	0.	0.8	1.1	1.2	1.5	1.9	2.9	0.2	5.0	5.2
5.0	0.0	0.2	0.3	0.3	0.5	0.0	0.0	0.0	0.5	0.0	1.8	1.2

Table 3-1 Rain Climate Region

2. Determine 0° C isotherm H(p) for each percent of the average year p from the relationship shown in Table 3-2.

p%	Latitude < 25 degrees	Latitude ≥ 25 degrees
1.0	4.6	-4.6 (lat - 70)/45
0.1	4.8	-(4.8 - 0.8)(lat - 70)/45 + 0.8
0.01	5.2	-(5.22 - 1.5)(lat - 70)/45 + 1.5
0.001	5.4	-(5.4 - 2.4)(lat- 70)/45 + 2.4

Table 3-2 Isotherm Height *H(p)* [km]

3. Calculate the projected surface path length *D* for each *p* percent of the year desired, from

$$D = \frac{H(p) - h_s}{\tan\theta} \qquad \text{for } \theta > 10 \text{ degrees} \qquad (3.20)$$

where H(p) are the 0°isotherm heights (freezing height) obtained in step 2, h_s is the ground level above mean sea level, and θ is the elevation angle to satellite.

At elevation angle < 10 degrees, the curvature of the earth must be accounted for, giving a surface path length :

$$D = (R_e + h_s)\sin^{-1}\left\{\frac{\cos\theta}{R_e + H(p)} \cdot \left[\sqrt{(R_e + h_s)^2\sin^2\theta + 2R_e(H(p) - h_s) + H^2(p) - h_s^2} - (R_e + h_s)\sin\theta\right]\right\}$$

where R_e = 8500 km, is the effective radius of the earth.

4. Determine the specific attenuation coefficients *a* and *b* at the frequencies at interest from :

$$a = \frac{1}{2}[a_h + a_v + (a_h - a_v)\cos^2\theta\cos 2\tau]$$

$$b = \frac{1}{2a}[a_h b_h \_ a_v b_v + (a_h b_h - a_v b_v)\cos^2\theta\cos 2\tau]$$

where

- τ is the polarisation tilt angle relative to the horizontal.
- a_h and b_h are the regression coefficients for horizontal polarisation.
- a_v and b_v are regression estimates for vertical polarisation.

This regression coefficients are shown in Table 3-3 (from CCIR Rep.721-2).
If circular polarisation is τ = 45°, hence

$$a = \frac{a_h + a_v}{2}$$

$$b = \frac{a_h b_h + a_v b_v}{2a}$$

f [GHz]	**a_h**	**a_v**	**b_h**	**b_v**
1	0.0000387	0.0000352	0.912	0.880
2	0.000154	0.000138	0.963	0.923
4	0.000650	0.000591	1.121	1.075
6	0.00175	0.00155	1.308	1.265
7	0.00301	0.00265	1.332	1.312
8	0.00454	0.00395	1.327	1.310
10	0.0101	0.00887	1.276	1.264
12	0.0188	0.0168	1.217	1.200
15	0.0367	0.0355	1.154	1.128

20	0.0751	0.0691	1.099	1.065
30	0.187	0.167	1.021	1.00
35	0.263	0.233	0.979	0.963
40	0.350	0.310	0.939	0.929
45	0.422	0.393	0.903	0.897
50	0.536	0.479	0.873	0.868
60	0.707	0.642	0.826	0.824
70	0.851	0.784	0.793	0.793
80	0.975	0.906	0.769	0.769
90	1.06	0.999	0.753	0.754
100	1.12	1.06	0.743	0.744
120	1.18	1.12	0.731	0.732
150	1.31	1.27	0.710	0.711
200	1.45	1.42	0.689	0.690
300	1.36	1.35	0.688	0.689
400	1.32	1.31	0.683	0.684

Table 3-3 Regression Estimation of Specific Attenuation

5. Determine the following empirical constants for each *p* of interest.

$z = 3.8 - 0.6 \ln R_p$

$x = 2.3 R_p^{-0.17}$

$y = 0.026 - 0.03 \ln R_p$

$U = \frac{1}{z} \ln\{x e^{yz}\}$

6. The mean slant-path rain attenuation at each probability of occurrence *p* is then found by :

$$A(p) = \begin{cases} \dfrac{aR_p^B}{\cos\theta}\dfrac{e^{UbD}-1}{Ub} & \text{if} \quad 0 < D \le z \\ \dfrac{aR_p^B}{\cos\theta}\left[\dfrac{e^{Ubz}-1}{Ub} - \dfrac{x^b e^{ybz}}{y^b} + \dfrac{x^b e^{ybD}}{y^b}\right] & \text{if} \quad z < D \le 22.5 \end{cases}$$

If D > 22.5, calculate A(*p*) with D = 22.5 but use the rain rate $R_{p'}$ at the value *p'* = *p*[22.5/D] instead of *p*.

7. Estimate the upper and lower bound of the mean slant-path attenuation (standard deviation measurement about the model) using Table 3-4.

Percent of Year	Percent Standard Deviation
1.0	± 39
0.1	± 32
0.01	± 32
0.001	± 39

Table 3-4 Mean Attenuation

For example, a mean prediction of 10 dB at 0.01 % yields an upper bound of (10.0 ± 3.2) dB.

3.2.3.2. MODIFIED CCIR/SAM MODEL

The simplified Attenuation Model was developed for NASA to provide a simplified technique for hand calculation. This model [IPPO89, PRAT86] assume that the rain extends from the earth station elevation H_0 [km] to an effective storm height H_e [km].

Assume that the rain rate, R, is constant over a path length, L. The attenuation , A, caused by the rain is :

$$A = aR^bL \text{ [dB]} \quad (3.21)$$

The coefficient a and b depend strongly on frequency and weakly on raindrop temperature, polarization and other factors.
A good approximation is :

$$a = \begin{cases} 4.21\times10^{-5} f^{2.49} & \text{for } 2.9 \le f \le 54 \text{ GHz} \\ 4.09\times10^{-2} f^{0.699} & \text{for } 54 \le f \le 180 \text{ GHz} \end{cases} \quad (3.22)$$

$$b = \begin{cases} 1.41 f^{-0.0779} & \text{for } 8.54 \le f \le 25 \text{ GHz} \\ 2.63 f^{-0.272} & \text{for } 25 \le f \le 164 \text{ GHz} \end{cases} \quad (3.23)$$

For an elevation angle, θ, and an earth station altitude, h_s, the path length, L, can be computed by :

$$L = \frac{H_e - H_s}{\sin\theta} \quad \text{[km]} \quad (3.24)$$

where the 0° C isotherm height H_e can be predicted for typical summer values from the earth station latitude, Λ_s, with

$$h_i = \begin{cases} 4.8 & |\Lambda_s| \le 30 \deg \\ 7.8 - 0.1|\Lambda_s| & |\Lambda_s| > 30 \deg \end{cases} \quad (3.25)$$

and the rain rate R

$$h_e = \begin{cases} h_i & R \le 10 mm/h \\ h_i + \log_{10}(\frac{R}{10}) & R > 10 mm/h \end{cases} \quad (3.26)$$

For determining a rain rate, pick a climate zone A to P for the transmitting or receiving location from the CCIR rain Climate Regions map, shown in Figure 3-2. Then look up the rain rate from Table 3-5.

% of time	A	B	C	D	E	F	G	H	J	K	L	M	N	P
1.0	-	1	-	3	1	2	-	-	-	2	-	4	5	12

0.3	1	2	3	5	3	4	7	4	13	6	7	11	15	34
0.1	2	3	5	8	6	8	12	10	20	12	15	22	35	65
0.03	5	6	9	13	12	15	20	18	28	23	33	40	65	105
0.01	8	12	15	19	22	28	30	32	35	42	60	63	95	145
0.003	14	21	26	29	41	54	45	55	45	70	105	95	140	200
0.001	22	32	42	42	70	78	65	83	65	100	150	120	180	250

Table 3-5 Cumulative Rain Rate Statistics for Rain Climate Regions

The equal probability attenuation , A(p), is now :

$$\begin{cases} aR^b L & R \le 10mm/h \\ aR^b \dfrac{1-\exp(-\gamma b \ln(\frac{R}{10}) L \cos\theta)}{\gamma b \ln(\frac{R}{10}) \cos\theta} & R > 10mm/h \end{cases} \quad (3.27)$$

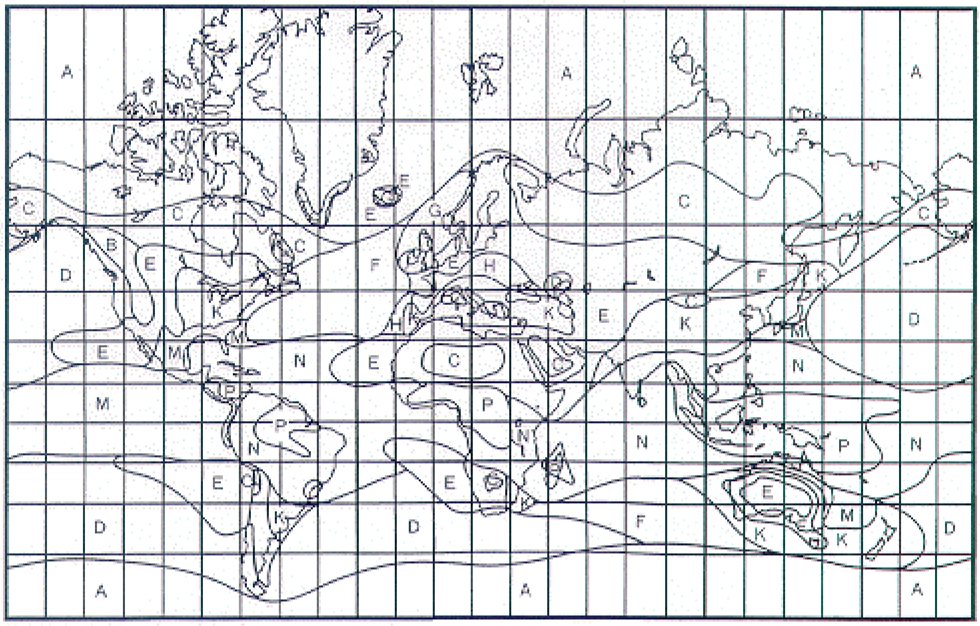


Figure 3-2 CCIR Rain Climate Regions

3.2.3.3. Climate Zone CCIR Model (CCIR 563)

To compute the attenuation for CCIR climate zone model :

1. Pick a climate zone from Figure 3-2.
2. Pick a rain rate, R0.01, from Table 3-5.
3. Determine the effective rain height, H_r, for the altitude, Λ_s, of the station :

$$H_r = \begin{cases} 4.0 & 0 < \Lambda_s < 36\deg \\ 4.0 - 0.075(\Lambda_s - 36) & \Lambda \ge 36\deg \end{cases} \quad (3.28)$$

4. Calculate slant path length, L_s, horizontal projection, D; and reduction factor, r_p, from the following equations:

$$L_s = \begin{cases} \dfrac{H_r - h_s}{\sin\theta} & \theta \le 5\deg \\ \dfrac{2H_r - h_s}{\sqrt{\sin^2\theta + \dfrac{2(H_s - h_s)^2}{R_e}} + \sin\theta} & \theta > 5\deg \end{cases} \quad (3.29)$$

where the average radius of the earth is R_e = 6371 km.

$$D = L_s \cos\theta \quad (3.30)$$

$$r_{0.01} = \frac{1}{1 + 0.045D} \quad (3.31)$$

5. Obtain the specific attenuation factors from Table 3-3.

$$a = \frac{1}{2}[a_h + a_v + (a_h - a_v)\cos^2\theta\cos 2\tau] \quad (3.32)$$

$$b = \frac{1}{2a}[a_h b_h + a_v b_v + (a_h b_h - a_v b_v)\cos^2\theta\cos 2\pi\tau] \quad (3.33)$$

where τ is the polarisation tilt angle relative to the horizontal.

6. Calculate attenuation exceeded for 0,01% of the time as follows :

$$A_{0.001} = L_s r_p a R_{0.01}^b \quad (3.34)$$

7. Calculate attenuation exceed for p% of the time :

$$Ap = 0.12 A_{0.01} p^{-(0.546+0.043\log p)} \qquad 0.0001\% \le p \le 1.0\% \quad (3.35)$$

3.2.4. ANTENNA POINTING LOSSES

The antenna gain pattern varies with the off-axis angle (elevation angle) and may be a function of the azimuth angle. If the antenna is not pointed accurately at the receiver, the full expected gain is not obtained. This difference is called the pointing loss.

The antenna aperture distribution can e defined as in the following equation :

$$G_{n,u}(\Theta) = 4[j_1 \frac{(u)}{u}]^2 \qquad \text{for circular aperture} \quad (3.36)$$

$$G_{n,u}(\Theta) = 64[j_2 \frac{(u)}{u}]^2 \qquad \text{for parabolic aperture} \quad (3.37)$$

where

- $u = \pi D/\lambda$, θ= off-axis angle
- J_1(u) = first order Bessel function of the first kind
- J_2(u) = second order Bessel function of the first kind

The half power beam width, a useful parameter by which you can approximate the spreading of the beam, is defined as the angle at which the power at the edge is one half that at the center. For a uniform aperture distribution, $G_{n,u}$ (Θ) = ½ occurs at

1.02λ/D [rad] or 58.5λ/D [degree] For parabolic aperture distribution, half-power beamwidth is 1.27λ/D [rad] or 72.2λ/D [degree].

Normally, the antenna pointing error is kept within a third of the half-power beamwidth. For example, if the antenna has a half-power of 0.06 [rad] as computed from the preceding equations, the pointing error should be kept at no more than 0.02 [rad] or 1.14 [degree]. This means that the antenna needs to be pointed at the bore sight of the receiver within 1.14 [degree] or the power delivered is much less than half. Using this number you can compute the associated gain loss from:

$G_{n,u}(0.02) = 0.757$ or equivalently in dB $-10 \log_{10}(0.757)$ or 1.2 dB

This is the standard recommended value for non-auto-tracked antennas. Spacecraft antenna at higher frequencies are often auto-tracked to keep these losses low. It is possible to use a number other than the one computed by the model to reflect the values that the manufacturer provided.

3.2.5. FADING DUE TO LOW ELEVATION ANGLE

Amplitude fluctuations occur when the angle of elevation is low and the signal traverses a significant amount of atmospheric distance. A method given for calculating and hence gain degradation due to the incident turbulence for a propagation distance of L_t [km] and impinging on a circular aperture of D[m] diameter.

$$L_t = [H_t^2 - h_s^2 + 2R_e(H_t - h_s) + ((R_e + h_s)\sin\theta)^2]^{\frac{1}{2}} - (R_e + h_s)\sin\theta \qquad (3.38)$$

where

- R_e is the earth radius
- H_t is the mean turbulence height
- h_s is the height above sea level
- θ is the elevation angle

The fading loss, F_L , is :

$$F_L = 10\log_{10}\frac{I_c + I_i[\frac{B^2}{2.77\sigma_2^2 + B^2}]^2}{I_c + I_i} \qquad (3.39)$$

where *B* is the half-power beam-width as defined previously or as computed for the type of antenna used.

$$I_i = 1 - e^{-\frac{L_t}{L_o}}; \qquad L_0 = 180 \text{ km}$$

$$I_c = \frac{1 - I_i}{1 + \sigma_1^2}$$

In the preceding equations, the following holds true :

$$\sigma_1^2 = \text{electric field amplitude variance} = 2.6\times10^{-7} f^{7/12} L_t^{11/6}$$

σ_2^2 = angle of arrival variance $= 5.67 \times 10^{-6} L_t^{1.56} D^{(-1/3)}$

These values are significant only for an angle of elevation below 10 degrees. These losses are transient and must be simulated if link margins become negative.

3.2.6. CCIR TROPOSPHERIC SCINTILLATION LOSS

Rapid fluctuations in attenuation are called scintillation. Microwave signals passing through the atmosphere experience variations in amplitude, phase, and angle of arrival due to inhomogeneties in the refractivity of the tropospheric layer. Additionally, waves can arrive simultaneously from different propagation paths, causing multipath fading. The effects occur at time scales shorter than a minute and on spatial scales shorter than a kilometer. At elevation angle below about 10 degrees, these effects are significant and must be considered.

Scintillation losses can be calculated as follows :

1. Determine L_t, the slant path distance to the horizontal thin turbulent layer from :

$$L_t = \sqrt{(h_t^2 + 2R_e h_t + R_e^2 \sin^2\theta)} - R_e \sin\theta \qquad (3.40)$$

where h_t = 6 km is the effective turbulence height, and R_e = 6371 km is the mean earth radius.

2. Determine the parameter z from :

$$z = 0.685 \frac{D}{\sqrt{L_t / f}} \qquad (3.41)$$

3. Determine the aperture averaging factor G(z) from :

$$G(z) = \begin{cases} 1.0 - 1.4z & for\, 0 < z \le 0.5 \\ 0.5 - 0.4z & for\, 0.5 < z \le 1 \\ 0.1 & for\, z > 1.0 \end{cases} \qquad (3.42)$$

4. The Root Mean Square (RMS) amplitude scintillation, expressed in σ_x, the standard deviation of the log of the received power, is given by :

$$\sigma_x = 0.025 f^{7/12} 0.85 \cos\theta \sqrt{G_z} \qquad (3.43)$$

The values computed by the method are long-term averaging values. Short-term fluctuations can be exceed these values by several orders of magnitude.

Propagation impairments are dependent on the following :

Operating Frequency : with the exception of signal attenuation by gases absorption, the severity of tropospheric impairments increase with frequency.

Antenna Elevation angle and Polarization : the length of the path of the propagation path passing through the troposphere varies inversely with elevation angle. Accordingly, propagation losses, noise, and depolarization also increase with increasing the decreasing elevation angle. Rain attenuation is slightly polarization sensitive. Depolarization is also polarization-sensitive, with circular polarization being the most susceptible.

Earth Station Altitude : because less of the troposphere is included in paths from higher altitude sites, impairments are less.

Earth Station Noise Temperature : This effects the level of sky noise temperature to system noise temperature, thus effect of sky noise on the downlink signal-to-noise-ratio.

Local Meteorology : The amount and nature of the rainfall in the vicinity of the Earth station are the primary factors in determining the frequency and extend of most propagation impairments.

3.3. SUMMARY

This Section has identified uplink module parameters to be modelled. Similar parameters are also valid for the downlink.

The atmospheric attenuation is computed from the water vapor density, ambient temperature, frequency, elevation angle and altitude of the ground station.

The rain loss is computed from frequency, rain rate, latitude and altitude of the ground station , and path elevation angle from the ground station to the satellite.

C/N and Eb/No are computed from atmospheric loss, rain loss, propagation loss, antenna efficiency, link margin, transmit antenna pointing loss and coding.

The parameters required for the uplink channel model and possible values are:

Uplink Parameters	Possible Values
distance [km] between ground station and satellite	35787-41138 km
elevation angle [rad] ground station to satellite	π to $\pi/18$ rad
altitude [km] of ground station	-1 to 30 km
latitude [rad] of ground station	- $\pi/18$ to $\pi/18$ rad
Transmission frequency [GHz].	C-band: 6GHz, Ku band:14GHz, Ka band: 30GHz
Polarization [deg].	0-360 deg
Bandwidth [MHz]	2-140 MHz
Data rate [Mbps]	1-100 Mbps
Transmit antenna efficiency	0.4-0.8
Transmit antenna diameter [m]	0.6-20 m
Transmit antenna power [Watts]	1-100 Watts
Transmit antenna pointing loss [dB]	0.5-3 dB
Temperature [degrees C]	Night Time Winter: 0.0 degrees C

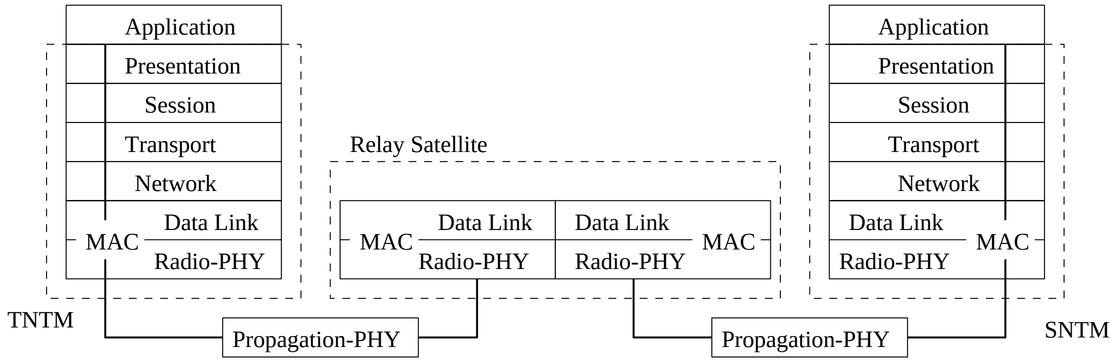
	Day Time Winter: 6.0 degrees C Night Time Summer: 15 degrees C Day Time Summer: 20 degrees C
Water vapor level [g/m^3]	Dry: 3.0 g/m^3 Medium: 5.0 g/m^3 High: 8.0 g/m^3 Very High: 12.0 g/m^3
Rain rate [mm/h]	see Table 3-5 depending on region
Link Margin [dB]	1-3 dB
G/T	-5 - -15
Multiple Access	TDMA, FDMA, CDMA
Number of Users (simultaneous)	1-500
Modulation	BPSK, QPSK, DPSK, MQPSK
Coding Scheme	Convolutional, Block or Reed Solomon Codes

Table 3-6 Possible Uplink Parameter Values

4. GEO SATELLITE CHARACTERISTICS

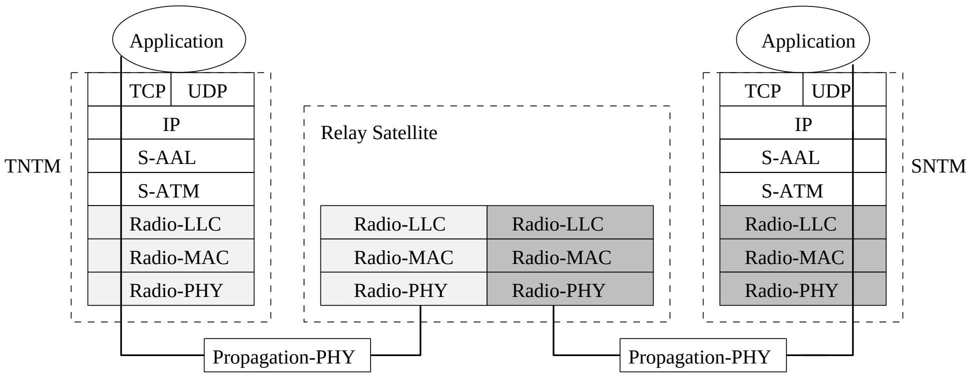
4.1. GEO REPEATER SATELLITE CHARACTERISTICS

The protocol stack for a satellite network using relay satellites according to the OSI and ATM reference model is shown in Figure 4-1 and Figure 4-2 respectively.



MAC:Medium Access Control Sublayer
PHY:Physical Layer
TNTM:Terrestrial Network Termination Module
SNTM:Satellite Network Termination Module

Figure 4-1 OSI protocol layer stack



S-AAL:Satellite ATM Adaptation Layer
S-ATM:Satellite ATM Layer
LLC:Logical Link Control
MAC:Medium Access Control Sublayer
PHY:Physical Layer
TNTM:Terrestrial Network Termination Module
SNTM:Satellite Network Termination Module

Figure 4-2 ATM Protocol Layer Stack for Relay satellite

The repeater satellite is only introducing a small processing delay and can therefore be modelled by a delay module.

4.2. GEO ON-BOARD PROCESSING (OBP) SATELLITE CHARACTERISTICS

OBP is in itself a vast domain that is the subject of much activity in the USA, Japan, and Europe. All commercial civil satellites to date have used transparent transponders which consist of nothing more than amplifiers, frequency changers and filters. These satellites adapt to changing demands, but at the cost of high space segment tariffs and high-cost, complex earth terminals. OBP aims to put the complexity in the satellite and to reduce the cost of the use of the space segment and the cost of the earth terminals. This is not without problems (details in [EVAN91]) and varying degrees of processing can be applied:

- regenerative transponder (modulation and coding)
- on-board switching
- access format conversion (e.g. FDMA-TDM)
- flexible routing.

They may not all be present in one payload and the exact mix will be a function of the application

The advantages rendered by the use of OBP are summarised [EVAN91]:

- Regenerative transponders

The advantage of the regenerative scheme is that the up- link and down-links are now separated and can be designed independently of each other. With conventional satellites $(C/N)_U$ and $(C/N)_D$ is additive, with regenerative transponders they are separated. This can be translated into an improved BER performance as reduced degradation are now present. Regenerative transponders can withstand much higher levels of interference for the same overall $(C/N)_T$.

- Multirate communications

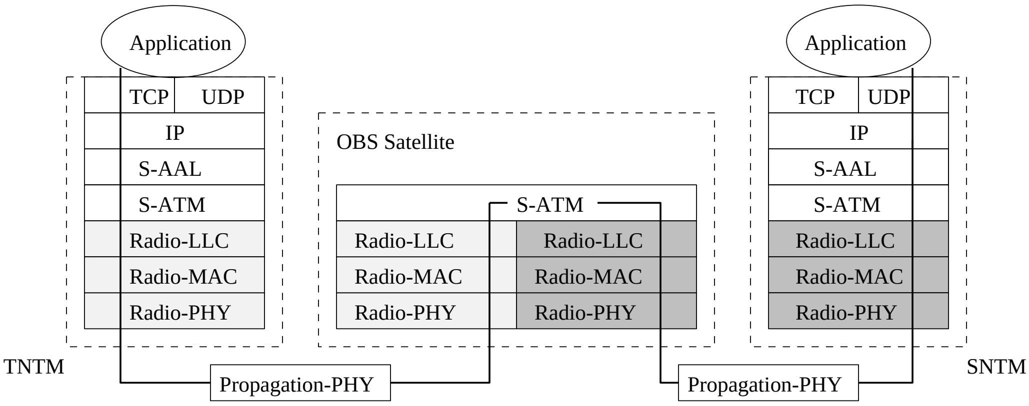
With OBP it is possible to convert on the satellite between low- and high-rate terminals. This allows ground terminals operating at various rates to communicate with each other via a single hop. Transparent transponders would require rate conversion terrestrially and hence necessitate two hops. Multirate communications implies both multicarrier demodulators and baseband switches.

- Reduced complexity earth-stations

The effects of employing OBP on ground terminals can be summarised as follows:

> - Lower earth-station transmit power/gain due to the reduced $(C/N)_U$
>
> - Reduced complexity receivers as the TDM downlink means no burst mode demodulators.

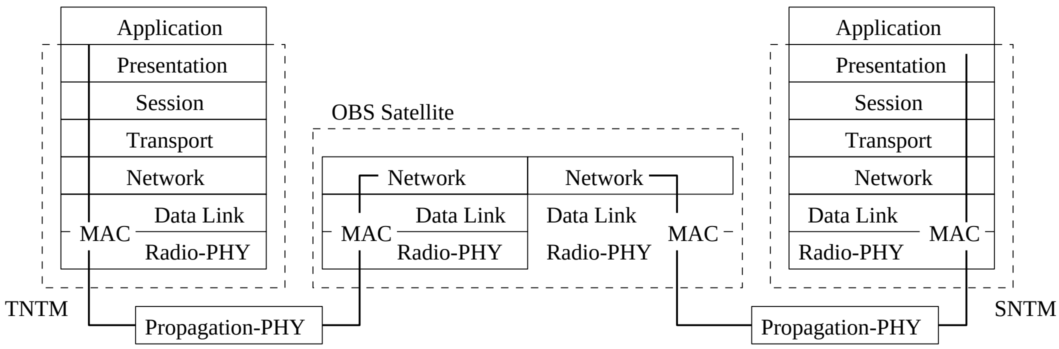
These add up to much reduced complexity and cheaper ground terminals.



S-AAL:Satellite ATM Adaptation Layer
S-ATM:Satellite ATM Layer
LLC:Logical Link Control Layer
MAC:Medium Access Control
PHY:Physical Layer

OBS:On-Board-Switching
TNTM:Terrestrial Network Termination Module
SNTM:Satellite Network Termination Module

Figure 4-3 ATM Protocol Layer Stack for on-board switching satellite



MAC:Medium Access Control Sublayer
PHY:Physical Layer

OBS:On-Board Switching
TNTM:Terrestrial Network Termination Module
SNTM:Satellite Network Termination Module

Figure 4-4 OSI Protocol Layer Stack for on-board switching satellite

4.2.1. ON-BOARD SWITCHING (OBS)

On-board processing (OBP) satellites with high-gain multiple spot-beams and on-board switching (OBS) capabilities have been considered as key elements of new-generation satellite communications systems. These satellites support small, cost-effective terminals and provide the required flexibility and increased utilisation of resources in a bursty multimedia traffic environment. The ATM and OSI protocol architecture for OBS satellites is shown in Figure 4-3and Figure 4-4 respectively.

Although employing an on-board switch function results in more complexity on-board the satellite, the following are the advantages of on-board switches.

- Lowering the ground station costs.

- Providing bandwidth on demand with half the delay.
- Improving interconnectivity.
- Offering added flexibility and improvement in ground link performance, i.e., this allows earth stations in any uplink beam to communicate with earth stations in any downlink beam while transmitting and receiving only a single carrier.

One of the most critical design issues for on-board processing satellites is the selection of an on-board baseband switching architecture. Four types of on-board switches are proposed:

- Circuit switch
- Fast Packet switch
- Hybrid switch
- Cell switch (ATM switch)

These have some advantages and disadvantages, depending on the services to be carried which are summarised in Table 4-1.

From an efficiency-of-bandwidth point of view, circuit-switching is advantageous under the condition that the major portion of the network traffic is circuit-switched. However, for bursty traffic, circuit-switching results in a lot of wasted capacity.

Fast packet switching may be an attractive option for a satellite network carrying both packet-switched traffic and circuit-switched traffic. Furthermore fast packet switching may be advantageous if the terrestrial network is IP based. The bandwidth efficiency for circuit-switched traffic will be slightly less due to packet overheads.

Switching Architecture	Circuit switching	Fast packet switching	Hybrid switching	Cell switching (ATM switching)
Advantages	• Efficient bandwidth utilisation for circuit switched traffic. • Efficient if network does not require frequent traffic reconfiguration • Easy to control congestion by limiting access into the network	• Self-routing • Does not require control memory for routing • Transmission without reconfiguring of the on-board switch connection • Easy to implement autonomous private networks • Provides flexibility and efficient bandwidth utilisation for packet switched traffic • Can accommodate circuit-switched traffic • Compatible with IP standards.	• Handles a much more diverse range of traffic • Optimisation between circuit switching and packet switching • Lower complexity on-board than fast packet switch • Can provide dedicated hardware for each traffic type	• Self-Routing with a small VC/VP • Does not require control memory for routing • Transmission without reconfiguring on-board switch connection • Easy to Implement Autonomous Private Networks • Provides flexibility and efficient bandwidth utilisation for all traffic sources • Can accommodate circuit-switched traffic • Compatible with ATM standards • Fixed size packets • Speed comparable to Fast packet switching
Disadvantages	• Reconfiguration of earth station time/frequency plans for each circuit set-up • Fixed bandwidth assignment (not flexible) • Very inefficient bandwidth utilisation when supporting packet-switched traffic • Difficult to implement autonomous private networks	• For circuit switched traffic higher overheads than circuit switching due to packet headers. • Contention and congestion may occur	• Can not maintain maximum flexibility for future services because the future distribution of satellite circuit and packet traffic is unknown • Waste of satellite resources in order to be designed to handle the full capacity of satellite traffic	• For circuit switched traffic somewhat higher overheads than packet switching due to 5 byte ATM header. • Contention and congestion may occur

Table 4-1 Comparison of various switching techniques

In some situations, a mixed-switch configuration, called hybrid switching and consisting of both circuit and packet switches, may provide an optimal on-board processor architecture. However, the distribution of circuit- and packet-switched traffic is unknown, which makes the implementation of such a switch a risk.

Finally, fixed-size fast-packet-switching, called cell-switching, is currently an attractive solution for both circuit- and packet-switched traffic. Using statistical multiplexing of cells, it could achieve the highest bandwidth efficiency despite a relatively large header overhead (5 bytes) per cell (53 bytes).

In addition, due to on-board mass and power-consumption limitations, the ATM switch is especially well suited to satellite switching because of the sole use of digital communications, and VLSI digital circuits limit mass and power consumption. For a terrestrial infrastructure that also uses ATM, it is apparent that the use of ATM switching for satellite systems is attractive, making seamless integration of terrestrial/satellite networks possible.

4.2.2. INTER-SATELLITE LINKS (ISLS)

The use of inter-satellite links (ISL) for traffic routing has to be considered. It has to be justified that this technology will bring a benefit which would make its inclusion worthwhile or to what extent on-board switching, or some other form of packet switching, can be incorporated into their use.

The issues which need to be discussed when deciding on the use of ISLs include :

- networking considerations (coverage, delay, handover)
- the feasibility of the physical link (inter-satellite dynamics)
- the mass, power & cost restrictions (link budget)

The mass and power consumption of ISL payloads are factors in the choice of whether to include them in the system, in addition to the possible benefits and drawbacks. Also the choice between RF and optical payloads is now possible as optical payloads have become more realisable and offer higher link capacity. The tracking capability of the payloads must also be considered, especially if the inter-satellite dynamics are high. This may be an advantage for RF ISL payloads.

Advantages of ISLs

- calls may be grounded at the optimal ground station through another satellite for call termination, reducing the length of the terrestrial 'tail' required.
- a reduction in ground-based control may be achieved with on-board baseband switching - reducing delay (autonomous operation).
- increased global coverage - oceans & areas without ground stations.
- single network control centre and earth station.

Disadvantages of ISLs

- complexity and cost of the satellites will be increased
- power available for the satellite/user link may be reduced
- handover between satellites due to inter-satellite dynamics will have to be incorporated
- replenishment strategy
- frequency co-ordination
- cross-link dimensioning

4.2.3. SATELLITE AVAILABILITY

Rec. I.356 [ITUT96a] provides the QoS class definitions and end-to-end network performance objectives. These objectives are given, for each performance parameter, as 'upper bound' that need to be met on a VC or VP for the duration of the connection. I.356 [ITUT96a] makes no reference to the ATM availability requirements although some preliminary ideas are given in draft Rec. I.357 [ITUT96b].

The total availability of the satellite network (A_{total}) is dependent on the availability of the satellite ($A_{satellite}$), the availability of the satellite link ($A_{propagation}$) and the availability of the satellite resources ($A_{congestion}$).

$$A_{total} = A_{satellite} \cdot A_{propagation} \cdot A_{congestion}$$

From a dependability point of view, a portion of a B-ISDN ATM semi-permanent connection should have the following properties:

- The fraction of time during which it is in a down state (i.e. unable to support a connection) should be as low as possible,
- Once a connection has been established, it should have a low probability of being either terminated (because of insufficient data transfer performance) or prematurely released (due to the failure of a network component).

Availability of a B-ISDN ATM semi-permanent connection portion is defined as the fraction of time during which the connection portion is able to support a connection. Conversely, unavailability of a portion is the fraction of time during which the connection portion is unable to support a connection (i.e. it is in the down state) [ITUT96b]. A common availability model which is also used in [ITUT96b] is depicted in Figure 4-5.

The model uses four states corresponding to the combination of the ability of the network to sustain a connection in the available state and the actual use of the connection.

Two independent perspectives are evident from the model:

1. The Service perspective, where availability performance is directly associated with the performance perceived by the user. This is represented in Figure 4-5 by states 1 and 2, even in the case of an on/off source since the user is only concerned with the connection availability performance whilst attempting to transmit packets.
2. The Network perspective, where availability performance is characterised independently of user behaviour. All four states in Figure 4-5 are applicable.

Both service and network perspectives will be considered.

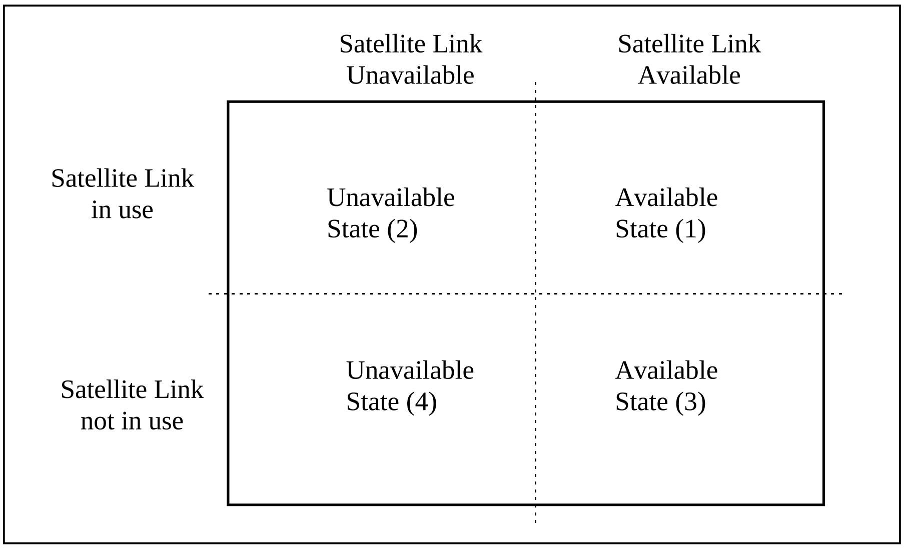


Figure 4-5 Availability Model

The criteria for entry into the unavailable state are for further study. In [ITUT96b] the onset of unavailability begins after 10 severely errored seconds (SES_{ATM}). These 10 seconds are part of unavailable time. A period of unavailability shall end with the occurrence of 10 consecutive seconds, none of which are SES_{ATM}. These 10 seconds are part of the available time. The 10-seconds criteria are supported using a sliding window with one-second granularity. A portion of a bi-directional B-ISDN connection is only available if both directions are available.

Two availability parameters are defined[ITUT96b]:

Availability Ratio (AR):

The service AR is defined as the portion of time that the connection portion is in the available state over an observation period, where the connection is in use. This is characterised in Figure 4-5 by the proportion of time in State 1 compared to the overall time in States 1 and 2.

The network AR is defined as the proportion of time that the connection is in the available state over an observation period, where the connection may not be in use. This is characterised in Figure 4-5 by the proportion of time in States 1 and 3 compared to the overall time in States 1 to 4.

Mean Time Between Outages (MTBO):

The service MTBO is defined as the average duration of a time interval during which the connection is available from the service perspective. Consecutive intervals of available time during which the user attempts to transmit cells are concatenated. The network MTBO is defined as the average duration of a continuos time interval, during which the connection is available from the network perspective.

More information about availability and can be found in [ITUT96b]. As mentioned before, the QoS limits must be guaranteed to the end-user for the duration of the connection. This means that the ‘upper bounds’ should not be exceeded for the ‘available time’. The availability for satellite links should also comply with any other network availability objective. It is therefore proposed [ITUT96b] that ATM satellite links that are designed to carry all QoS classes should offer the highest availability possible. In this thesis it is assumed that the QoS objectives are met for 99.8% of time (any month), or equivalently 99.96% of the year (in accordance to Rec. S.614 [ITUR96a] and S.1062 [ITUR96b]).

5. GEO SATELLITE DOWNLINK CHARACTERISTICS

The downlink carrier power-to-noise power spectral density ratio is expressed similar to the uplink as:

$$\left(C / N_0\right)_D = EIRP_D \left(\frac{1}{L}\right)_D \left(\frac{G_r}{T_r}\right) \frac{1}{k}$$

where

$(EIRP)_D = P_t G_t$ is the effective isotropically radiated power on the downlink

T_r the equivalent noise temperature of the receiving ground terminal. The downlink path loss LD is the overall attenuation of the carrier power on its way from the satellite transmitting antenna to the earth terminal receiving antenna. As for the uplink, it builds up from two components: the free space loss (L_{FS}), and the additional losses (L_a). L_a depends on:

- gaseous atmospheric absorption
- rain attenuation
- antenna pointing losses

which were described in detail in Section 3.

The parameters for the downlink are similar to the uplink namely:

Downlink Parameters	Possible Values
distance [km] between ground station and satellite	35787-41138 km
elevation angle [rad] ground station to satellite	π - π/18 rad
altitude [km] of ground station	-1 to 20 km
latitude [rad] of ground station	-π/18 to π/18 rad
Transmission frequency [GHz].	C-band: 4GHz, Ku band:12GHz, Ka band: 20GHz
Polarization [deg].	0-360 deg
Bandwidth [MHz]	2-140
Data rate [Mbps]	1-100 Mbps
Transmit antenna efficiency	0.4-0.8
Transmit antenna diameter [m]	0.6-20 m
Transmit antenna power [Watts]	1-100 Watts
Transmit antenna pointing loss [dB]	0.5-3 dB
Temperature [degrees C]	Night Time Winter: 0.0 degrees C Day Time Winter: 6.0 degrees C Night Time Summer: 15 degrees C Day Time Summer: 20 degrees C
Water vapor level [g/m^3]	Dry: 3.0 g/m^3 Medium: 5.0 g/m^3 High: 8.0 g/m^3 Very High: 12.0 g/m^3
Rain rate [mm/h]	see Table 3-5 depending on region
Link Margin [dB]	1-3 dB
G/T	-5 - -15
Modulation	BPSK, QPSK, DPSK, MQPSK
Coding Scheme	Convolutional, Block or Reed Solomon Codes

Table 5-1 Possible Downlink Parameter Values

6. SATELLITE NETWORK TERMINATION MODULE CHARACTERISTICS

The Satellite Network Termination Module (SNTM) does very similar tasks as the Terrestrial Network Termination Module (TNTM). The SNTM's major impact on the traffic is delay due to buffering and shaping.

Shaping is required in order to satisfy the delay variation requirements of various applications. A shaping buffer is used to space the packets in order to give them the same characteristics as at the entrance of the TNTM.

7. SATELLITE NETWORK SCENARIOS

The role of satellites in high-speed networking will evolve according to the evolution of the terrestrial network. However two main roles can be identified in two scenarios of the broadband network development:

- The introduction phase when satellites will compensate the lack of sufficient terrestrial high bit rate links mainly by interconnecting a few regional or national distributed broadband networks, usually called 'Broadband Islands'.
- The maturation phase when the terrestrial broadband infrastructure will have reached some degree of maturity. In this phase, satellites are expected to provide broadcast service and also cost effective links to rural areas complementing the terrestrial network. At this phase satellite networks will provide broadband links to a large number of end users through a user access interface. This allows high flexibility concerning topology, reconfiguration and network expansion. Satellites are also ideal for interconnecting mobile sites and provide a back-up solution in case of failure of the terrestrial systems.

7.1. INTERCONNECTION OF BROADBAND NETWORKS SCENARIO

In the broadband network interconnection scenario shown in Figure 7-1, satellite links provide high bit rate links between broadband nodes or broadband islands. The RACE CATALYST project was a demonstrator for this scenario and showed the compatibility of satellite technology with ATM and the terrestrial B-ISDN [SUN96]. The interfaces with satellite links in this mode are of the Network Node Interface (NNI) type. This scenario is characterised by a relatively small number of large earth stations which have a relatively large average bit rate. The cost and the size of the earth station has a small impact on the suitability of the satellite solution.

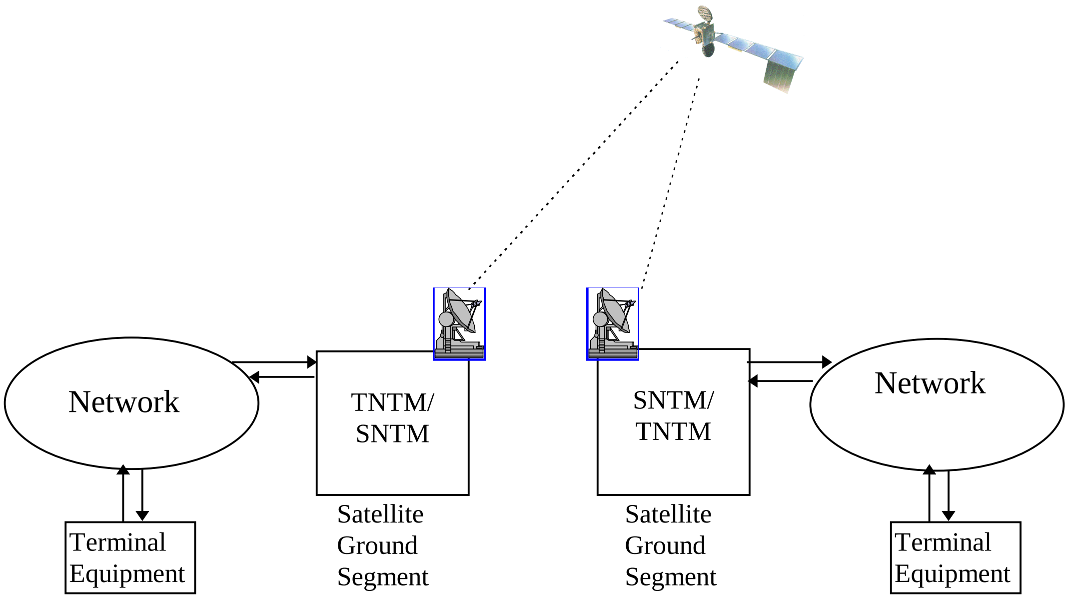


Figure 7-1 Interconnection of broadband networks scenario

Uplink and downlink parameters for a interconnection of broadband network scenario are provided in Table 7-1 and Table 7-2.

Uplink Parameters	Possible Values
distance [km] between ground station and satellite	41138 km
elevation angle [rad] ground station to satellite	π/18 rad
altitude [km] of ground station	0.1 km
latitude [rad] of ground station	π/2 rad
Transmission frequency [GHz].	C-band: 6GHz, Ku band:14GHz, Ka band: 30GHz
Polarization [deg].	45 deg
Bandwidth [MHz]	20-36 MHz
Data rate [Mbps]	14-34 Mbps
Transmit antenna efficiency	0.8
Transmit antenna diameter [m]	12 m
Transmit antenna power [Watts]	20 Watts
Transmit antenna pointing loss [dB]	0.3 dB
Temperature [degrees C]	Night Time Winter: 0.0 degrees C Day Time Winter: 6.0 degrees C Night Time Summer: 15 degrees C Day Time Summer: 20 degrees C
Water vapor level [g/m^3]	Medium: 5.0 g/m^3
Rain rate [mm/h]	28 mm/h for 0.01 % of the year
Link Margin [dB]	1 dB
Satellite G/T	-10
Multiple Access	TDMA

Number of Users (simultaneous)	100
Modulation	QPSK
Coding Scheme	Convolutional Code CC3

Table 7-1 Uplink Parameters for Interconnection Scenario

Downlink Parameters	Possible Values
distance [km] between ground and satellite	41138 km
elevation angle [rad] ground to satellite	$\pi/18$ rad
altitude [km] of ground station	0.1 km
latitude [rad] of ground station	$\pi/18$ -$\pi/2$ rad
Transmission frequency [GHz].	C-band: 4GHz, Ku band:12GHz, Ka band: 20GHz
Polarization [deg].	90 deg
Bandwidth [MHz]	36
Data rate [Mbps]	32 Mbps
Transmit antenna efficiency	0.6
Satellite EIRP	35 dBW
Transmit antenna pointing loss [dB]	0.5-3 dB
Temperature [degrees C]	Night Time Winter: 0.0 degrees C Day Time Winter: 6.0 degrees C Night Time Summer: 15 degrees C Day Time Summer: 20 degrees C
Water vapor level [g/m^3]	Dry: 3.0 g/m^3 Medium: 5.0 g/m^3 High: 8.0 g/m^3 Very High: 12.0 g/m^3
Rain rate [mm/h]	see Table 3-5 depending on region
Link Margin [dB]	1-3 dB
Receiver G/T	32 dB/K
Modulation	BPSK, QPSK, DPSK, MQPSK
Coding Scheme	Convolutional or Block Codes

Table 7-2 Downlink Parameters for Interconnection Scenario

7.2. Direct Access to Broadband Network Scenario

In the direct access scenario shown in Figure 7-2, the satellite system provides access links to a large number of users.

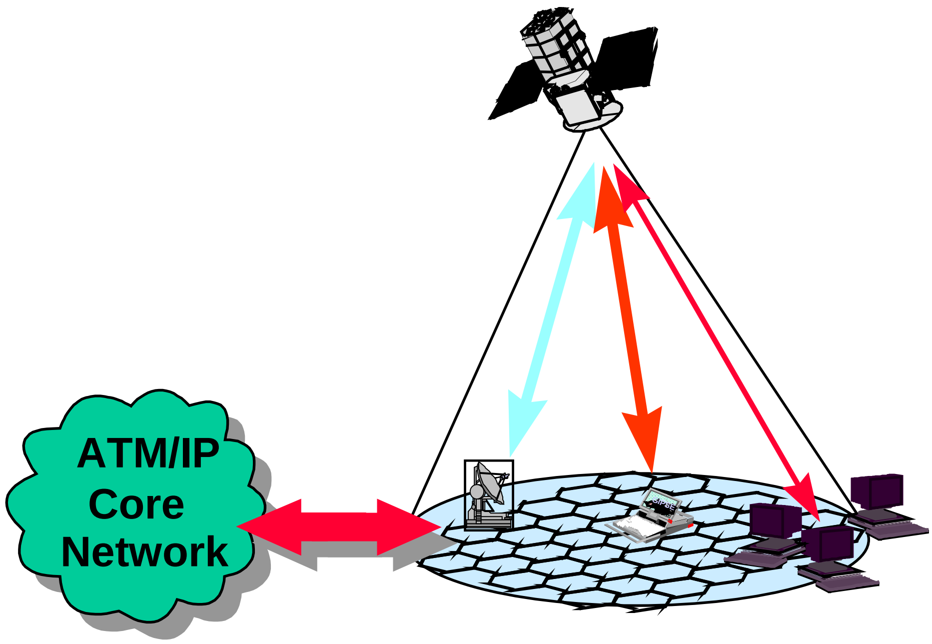


Figure 7-2 Direct Access to broadband network

The direct access scenario is characterised by a large number of terminals whose average and peak bit rates are limited. The traffic at the terminals is expected to show large fluctuations. Therefore the multiple access scheme will considerably effect the performance of the system. Furthermore the cost and size of the terminal have a large impact on the suitability of the satellite solution.

Several GEO multimedia satellite communication systems such as Cyberstar, Astrolink, GE*Star and EuroSkyWay have been proposed for this scenario [ELIZ96, FERN97, BULL97, LOSQ97]. They plan to use Ka-band, due to the larger bandwidth available at those frequencies and to facilitate multimedia services to fixed and portable terminals, which are delivered over ’ATM like’ transport in the satellite network.

Uplink and downlink parameters for a direct access scenario are provided in Table 7-3 and Table 7-4.

Uplink Parameters	Possible Values
distance [km] between ground station and satellite	41138 km
elevation angle [rad] ground station to satellite	$\pi/18$ rad
altitude [km] of ground station	0.1 km
latitude [rad] of ground station	$\pi/18$ -$\pi/2$ rad
Transmission frequency [GHz].	C-band: 6GHz, Ku band:14GHz, Ka band: 30GHz
Polarization [deg].	45 deg
Bandwidth [MHz]	3 MHz
Data rate [Mbps]	2 Mbps
Transmit antenna efficiency	0.6
Transmit antenna diameter [m]	0.6-1.2 m
Transmit antenna power [Watts]	1-10 Watts
Transmit antenna pointing loss [dB]	0.3 dB
Temperature [degrees C]	Night Time Winter: 0.0 degrees C Day Time Winter: 6.0 degrees C Night Time Summer: 15 degrees C Day Time Summer: 20 degrees C
Water vapor level [g/m^3]	Medium: 5.0 g/m^3
Rain rate [mm/h]	28 mm/h for 0.01 % of the year
Link Margin [dB]	1 dB
Satellite G/T	-10
Multiple Access	TDMA
Number of Users (simultaneous)	10-100
Modulation	QPSK
Coding Scheme	Convolutional Code 3

Table 7-3 Uplink Parameters for Direct Access Scenario

Downlink Parameters	Possible Values
distance [km] between ground station and satellite	41138 km
elevation angle [rad] ground station to satellite	$\pi/18$ rad
altitude [km] of ground station	0.1 km
latitude [rad] of ground station	$\pi/18$ -$\pi/2$ rad
Transmission frequency [GHz].	C-band: 4GHz, Ku band:12GHz, Ka band: 20GHz
Polarization [deg].	90 deg
Bandwidth [MHz]	36
Data rate [Mbps]	32 Mbps
Transmit antenna efficiency	0.4-0.8
Satellite EIRP	35 dBW
Transmit antenna pointing loss [dB]	0.5-3 dB
Temperature [degrees C]	Night Time Winter: 0.0 degrees C Day Time Winter: 6.0 degrees C Night Time Summer: 15 degrees C Day Time Summer: 20 degrees C
Water vapor level [g/m^3]	Dry: 3.0 g/m^3 Medium: 5.0 g/m^3 High: 8.0 g/m^3 Very High: 12.0 g/m^3
Rain rate [mm/h]	see Table 3-5 depending on region
Link Margin [dB]	1-3 dB
Receiver G/T	32 dB/K
Modulation	BPSK, QPSK, DPSK, MQPSK
Coding Scheme	Convolutional, Block or Reed Solomon Codes

Table 7-4 Downlink Parameters for Direct Access Scenario

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