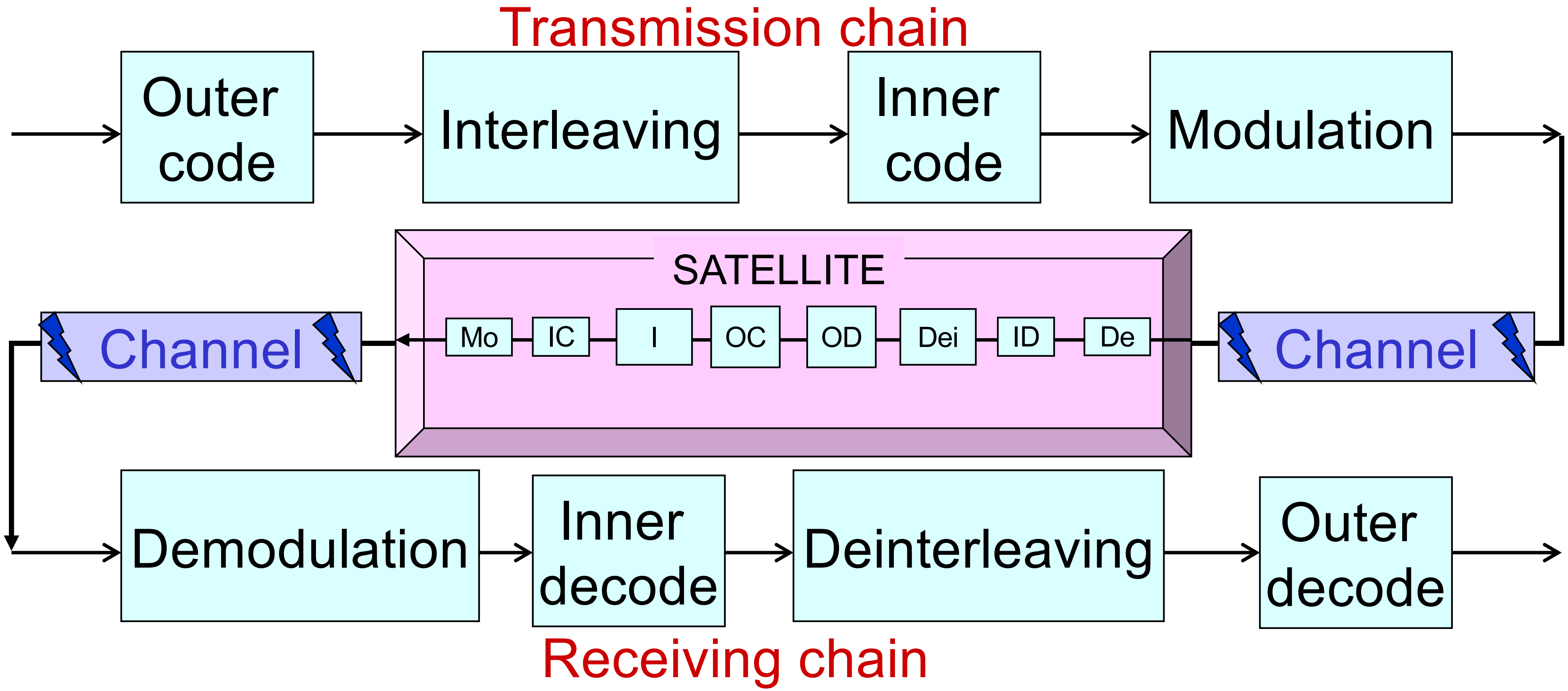
PHYSICAL LAYER

Application	Application
Presentation	
Session	
Transport	Transport
Network	Internet
Data Link	Network Interface
Physical Layer	Physical

Physical layer issues

- Channel Encoding
- Modulation
- Interleaving
- Multibeam coverage
- Interference
- OBP capabilities



Channel Coding

- **Basic concept: introducing redundancy in the information flow according to algebraic operations among bits to protect data from channel errors***
- **Condition: satellite propagation channel very harsh**

- **Concatenated coding**, consisting in the utilization of two codes sequentially implemented to better protect data against errors
- It is an efficient means to obtain very low error probabilities (10^{-10}), required for bulk data transfer, transmission of compressed images or TV signals
- OUTER CODE (burst errors) + INNER CODE (random errors)

* To not confuse with source coding (compression) and with cryptography coding.

Reed Solomon (RS) and Bose-Chaudhuri-Hocquenghem (BCH) codes

- Linear-cyclic block codes
- Normally utilized in a systematic manner
- The error correction capability is given by the generator polynomial
- RS may be considered as non-binary BCH codes
- The Reed-Solomon code RS (n, t, e) is defined as the set of all n-tuples c = (c_0, c_1, . . . , c_{n-1}) in F^n such that the corresponding polynomial $C(X) = \sum_{i=0}^{n-1} c_i X_i$ has α^e, α^{e+1} , . . . , α^{e+2t-1} as roots. In other words, RS (n, t, e) is cyclic with $G(X) = \prod_{i=e}^{e+2t-1} (X - \alpha^i)$ as the generator polynomial.
- Decoding
  - The Guruswami-Sudan decoding algorithm
  - The Koetter-Vardy decoding algorithm
  - Frequency-domain decoding

Outer Coding (1/3)

- RS codes are a block coding technique, the data stream is broken up into blocks and redundant data is then added to each block, the data is further subdivided into a number of symbols.
- DVB uses a RS (204,188) code, utilizing sixteen check symbols per 188 information symbols for a total codeword length of 204 symbols. RS encoding then consists of the generation of these check symbols from the original data.
- The process is based upon finite field arithmetic so named because the result of any operation is still an element of the field. The field elements are all values from 0 to 2 *m* -1, where *m* is the number of bits per symbol.
- The field polynomial is used to determine the order of the elements in the finite field, DVB uses 8 bit symbols {*m* =8} and a field polynomial of 285

$$p(x) = x^8+x^4+x^3+x^2+1 .$$

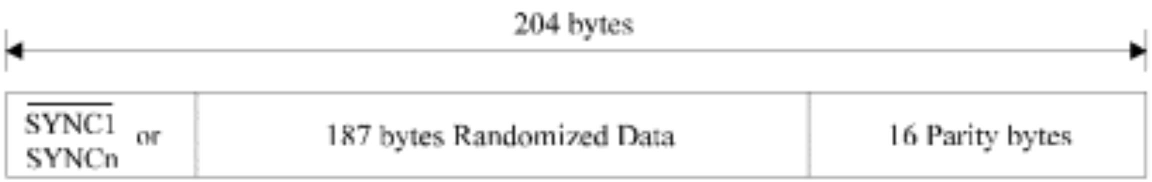
- The last item that needs to be known to generate a particular RS implementation is the generator polynomial starting root, DVB uses a generator polynomial starting at root zero

$$g(x) = (x+a^0)\,(x+a^1)\ldots\,(x+a^{15}) \quad \text{with } a = 02_{HEX}.$$

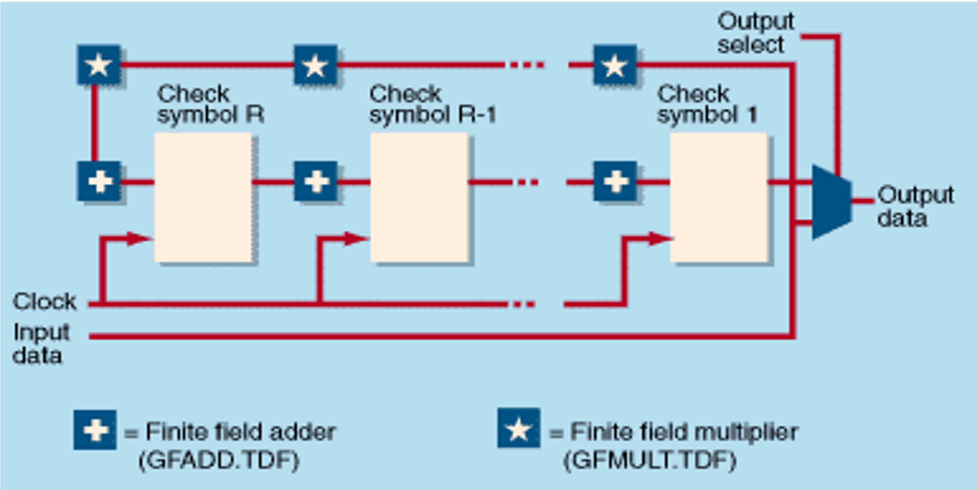
Outer Coding (2/3)

- DVB RS [204,188] code can correct (204-188)/2 or 8 errors per 204-symbol codeword. A burst error of 57 to 64 consecutive bits (dependent upon whether the error starts on a symbol boundary) can be corrected by that RS code. If these same errors are more evenly spaced within the codeword, however, it will require many more check symbols to correct all of the errors. For this reason, RS codes are generally combined with other coding methods such as Convolutional, which is more suited to correct evenly distributed errors.

- The shortened RS code can be implemented by adding 51 bytes, all set to 0, before the information bytes at the input of a (255,239) encoder. After the RS coding procedure these null bytes shall be discarded.

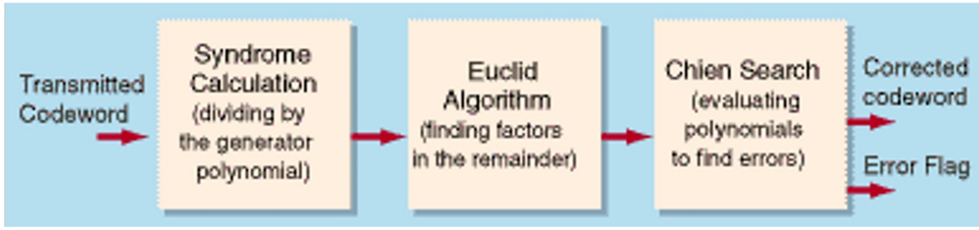


Outer Coding (3/3)



Input data stream is clocked back out of the function while being fed back into the check symbol generation circuitry. A series of finite field adds and multiplies results in each register containing one check symbol after the entire input data stream has been entered. Check symbols are shifted out at the end of the original message.

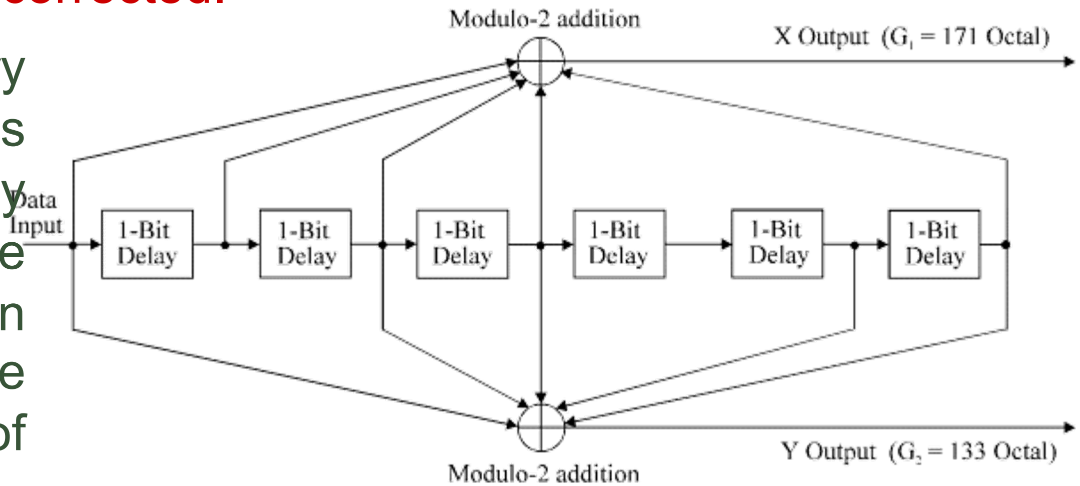
On the receiver side the incoming symbols are divided into the generator polynomial in the Syndrome calculation block.



The check symbols, which form the remainder in the encoder section, will cause the syndrome calculation to be zero in the case of no errors. If there are errors, the resulting polynomial is passed to the Euclid algorithm, where the factors of the remainder are found. The result is then evaluated for each of the incoming symbols over many iterations, and any errors are found and corrected.

Convolutional codes

- Convolutional coding is used to prevent and correct random errors from reducing the power of the interleaver scheme.
- Following the interleaver, the data are fed to a shift register. The contents of the shift register produce 2 outputs that represent different parity checks on the input data so that bit errors can be corrected.
- There will be 2 output bits for every input bit therefore the coder is described as a ½ coder but any rate between 1 and ½ may be realized by means of puncturing, in this way it is possible to adjust the correcting power as a function of the link quality.



Decoding

- Viterbi algorithm

Concatenated code performance

- Reed Solomon (outer code) + convolutional (inner code)
- Typical coding ratios:
  - (255,239) able to correct up to 16 errors
  - shortened to (208,192) or (204,188) (DVB) or (80,64) able to correct up to 8 errors

BER	E_b/N_0 (no coded)	RS	Conv. Rate	E_b/N_0 (coded)
10^{-10}	~ 12 dB	208, 192	1/2	3.1 dB
10^{-10}	~ 12 dB	208, 192	3/4	4.1 dB
$5 \cdot 10^{-6}$	10.5 dB	80, 64	1/2	2.8 dB

Low Density Parity Check (LDPC) Codes

- Linear block codes
- Performance comparable or better than Turbo codes
- Very flexible and high-speed decoder implementations
- Adopted in DVBS-2 standard as inner code (BCH outer)
- Definitions:
  - the null-space of a parity-check matrix whose entries are almost all zero
  - a linear block code that has a low density of non-zero entries in its parity check matrix
  - a linear block code (k, n) such that the number of non-zero entries in its parity check matrix is proportional to n as the length of the code grows
- The code can be either systematic or non-systematic
- Code rate ≤ 1/2.

LDPC decoding

- Sparseness of the matrix helps easy decoding
- Decoder makes use of iterative algorithms
- Hard or soft algorithm
- The most efficient hard decision type LDPC decoder proposed by Gallager
- Sum-product decoding procedure is an iterative soft-decision algorithm

Turbo codes

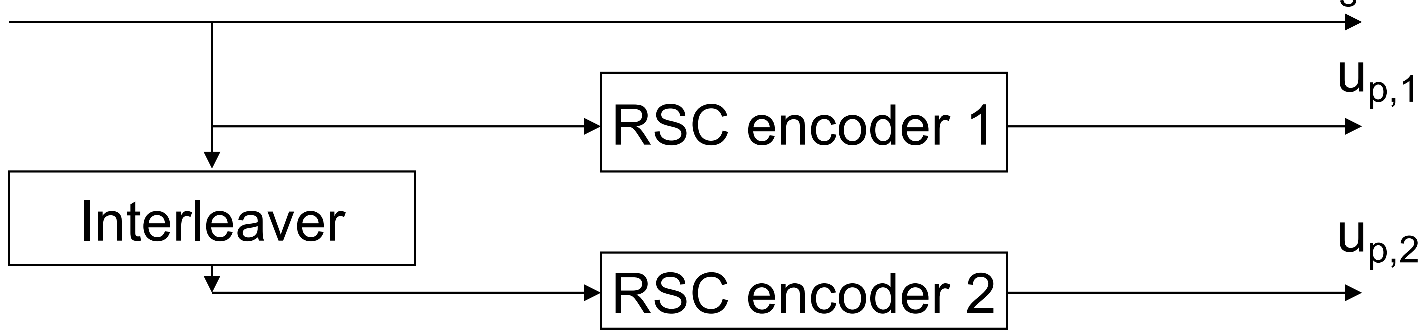
- High-performance error correcting codes finding widespread of use in deep-space satellite communications
- Iterated decoding convolutional codes
- Small memory order
- Closely approach the theoretical limits imposed by Shannon's theorem
- Much less computational complexity than the Viterbi algorithm for decoding convolutional codes with large constraint lengths, which would be required for the same error performance
- Increased bandwidth and power efficiency, when compared to the classical (non-iterative) FEC solutions

Turbo codes (2)

- Classical Turbo codes make use of **parallel** or **serial** concatenated Recursive Systematic Convolutional (RSC) encoders component encoders separated by interleavers.
- Parallel Concatenated Convolutional Code (PCCC) and Serial Concatenated Convolutional Code (SCCC) represent a class of Turbocoding schemes based on convolutional codes.
- Hybrid Concatenated Convolutional Code (HCCC) combines both PCCC and SCCC structures
- The Turbo code interleaver permutes the information bit sequence and the output is passed to the second RSC encoder.
- The interleaver
  - generates a long block code from convolutional encoders with small memory orders.
  - decorrelates the Turbo decoder inputs (extrinsic information and channel values) by spreading out the burst errors.
  - breaks the low-weight input sequences and, hence, increases the free distance of the code.
- The error performance is improved by increasing the interleaver size, an increase by N reduces the BER by a factor N (interleaving performance gain).

Parallel Concatenated Convolutional Code (PCCC) Encoding scheme

- Two RSC encoder components that are linked together in parallel through an interleaver

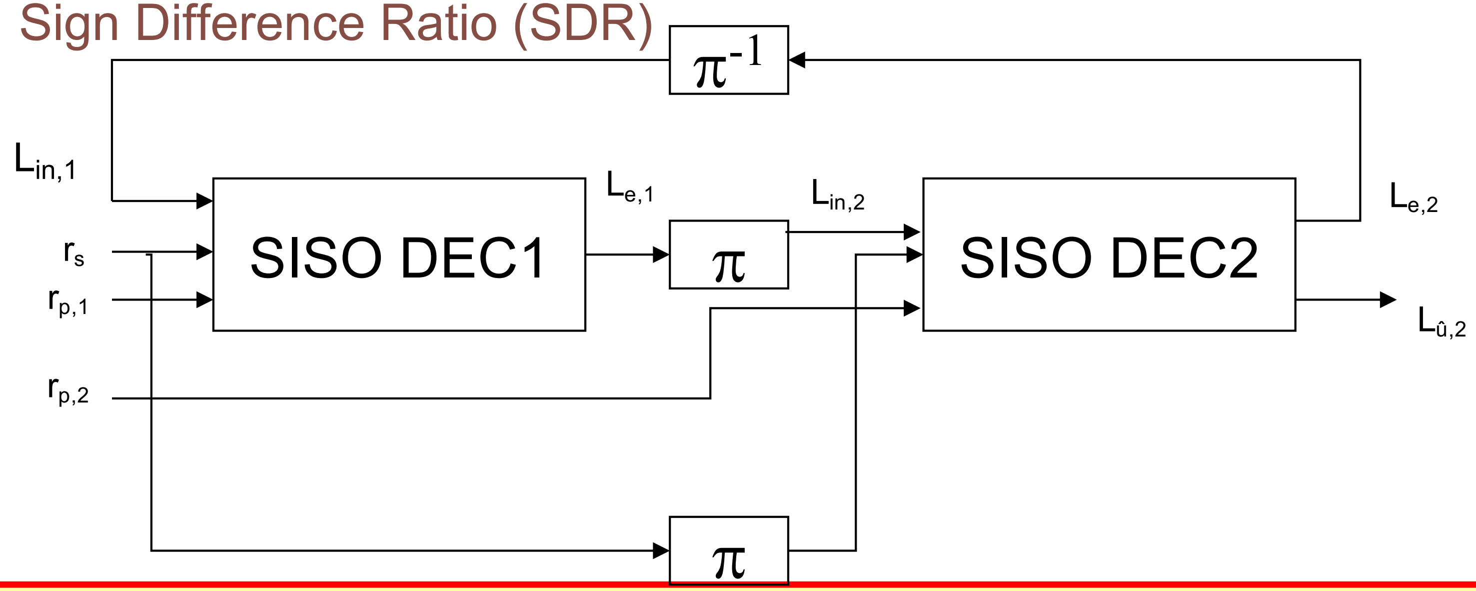


Serial Concatenated Convolutional Code (SCCC)

- Two RSC serially linked through an interleaver.
- If the outer and inner RSC components have a coding rate of $r_o=k/p$ and $r_i=p/n$, respectively, then the overall concatenated code has a coding rate of $r = r_o \cdot r_i = k/n$.
- The most used Turbocodes make use of binary RSC encoders
- Block Turbocode (BTC), frequently called Turboproduct code (TPC), is a serial concatenation of two linear block codes (C1, C2), separated by a row-column permutation

Turbo decoding

- Relies on iterative process
- After a certain number of iterations, hard decisions are taken from the second decoder output
- Stopping criteria
  - Cyclic Redundancy Check (CRC)
  - Cross Entropy (CE)
  - Sign Change Ratio (SCR)
  - Sign Difference Ratio (SDR)



Interleaving between inner and outer code

- To counteract burst errors codes designed to counteract random errors are ineffective
- Rearrange the order of a sequence in deterministic way and then rebuild the original sequence
- The bits can be arranged in rows of a matrix and transmitted in columns
- Finite and infinite length.
- Block or convolutional (same performance)
- Block interleaving requires about twice the memory and delay. Hence the convolutional scheme is recommended, unless framing considerations suggest otherwise
- The interleaver size is defined by two parameters:
  - Length equal to one RS codeword.
  - Depth must be greater than the maximum length (in bytes) of the error bursts at the output of the inner convolutional code, namely the length in bits divided by 8.

Matrix filled in rows

Bits transmitted in columns

Error burst

1	1	0	1	1	1	1	1	0
1	0	0	0	0	1	1	1	1
1	0	1	0	0	0	0	1	0
1	1	1	1	1	1	0	0	1
0	1	1	0	0	1	0	0	0
0	0	0	1	1	1	1	1	1
1	1	1	0	0	1	1	1	0
1	1	0	1	1	0	1	0	1
0	1	0	1	1	1	1	1	0
1	0	0	0	0	0	0	0	1
0	0	1	0	0	1	0	0	0
1	1	1	0	1	0	0	1	1
1	1	0	1	1	1	0	0	0
0	0	1	0	0	1	0	0	1

Interleaving (to combat channel fluctuations due to multipath)

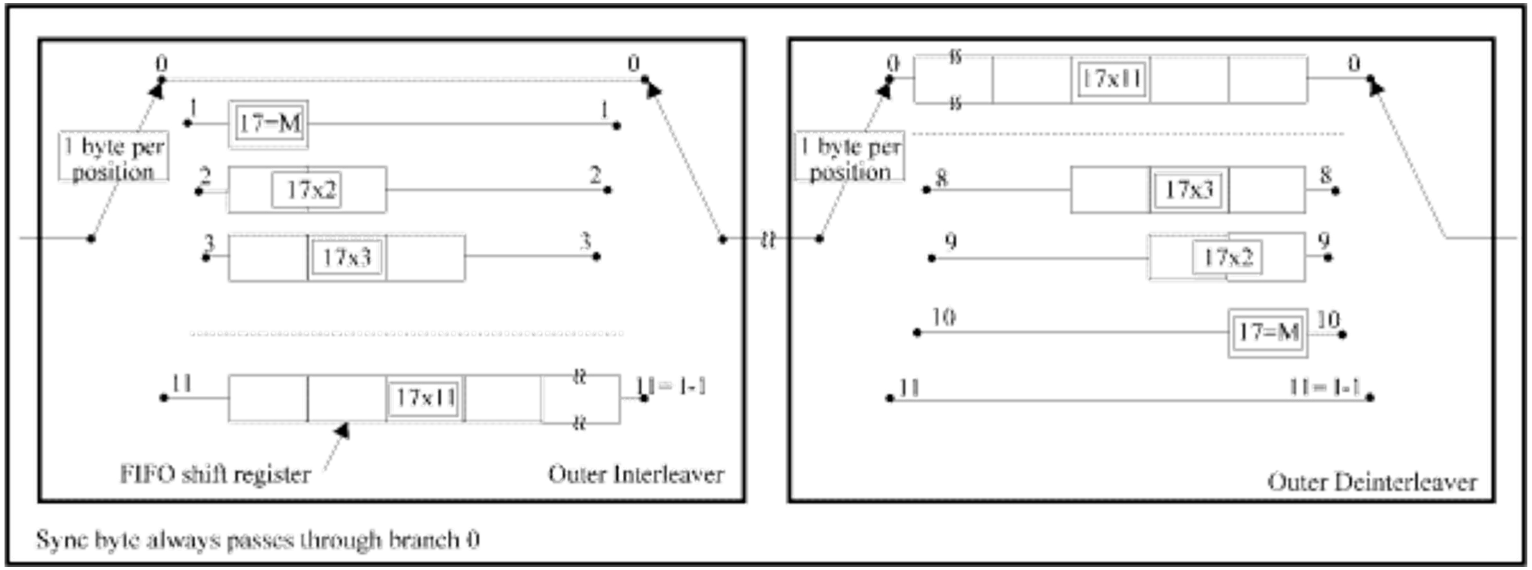
- Fluctuations due to multipath is probably on the order of milliseconds or tens of milliseconds
- Interference due to multipath is the sum of several contributions
- The amplitude of the diffuse component be much smaller than the line-of-sight (LOS) one
- Rice parameter ζ (ratio of the LOS and diffuse component) > 10 - 13 dB
- Interleaving is required if $\zeta \leq 20$ dB and $B_0T_s < 0.1$
  - B_0 is the multipath bandwidth
  - T_s is the time separation between channel symbols (i.e., coded bits)

Interleaving (to combat channel fluctuations due to multipath) (cont'd)

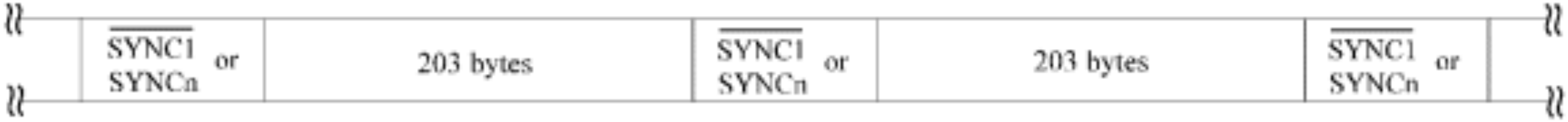
- Without interleaving, if $B_0T_s << 0.1$ the expected degradation can be (with respect to $\zeta=\infty$) around 4-5 dB, 2 dB, and a few tenths of a dB for ζ =10 dB, 13 dB, and 20 dB respectively (preliminary; the degradation depends on the code). With ideal interleaving these figures are reduced to about 1.2, 0.6, and 0.1 dB.
- If the interleaver depth I satisfies the condition $B_0T_s I \geq 0.1$, the performance of ideal interleaving is approached within a few tenths of a dB.
- The interleaver length must be greater than the decoding span of the convolutional code. Hence, the length (in information bits) must be equal to about three times the constraint length of the code.
- Channel fluctuations due to scintillations have a much longer time scale (say, seconds) and can not be counteracted by interleaving. The required memory and delay would be extremely high, hence unacceptable for almost all applications.

Convolutional interleaving

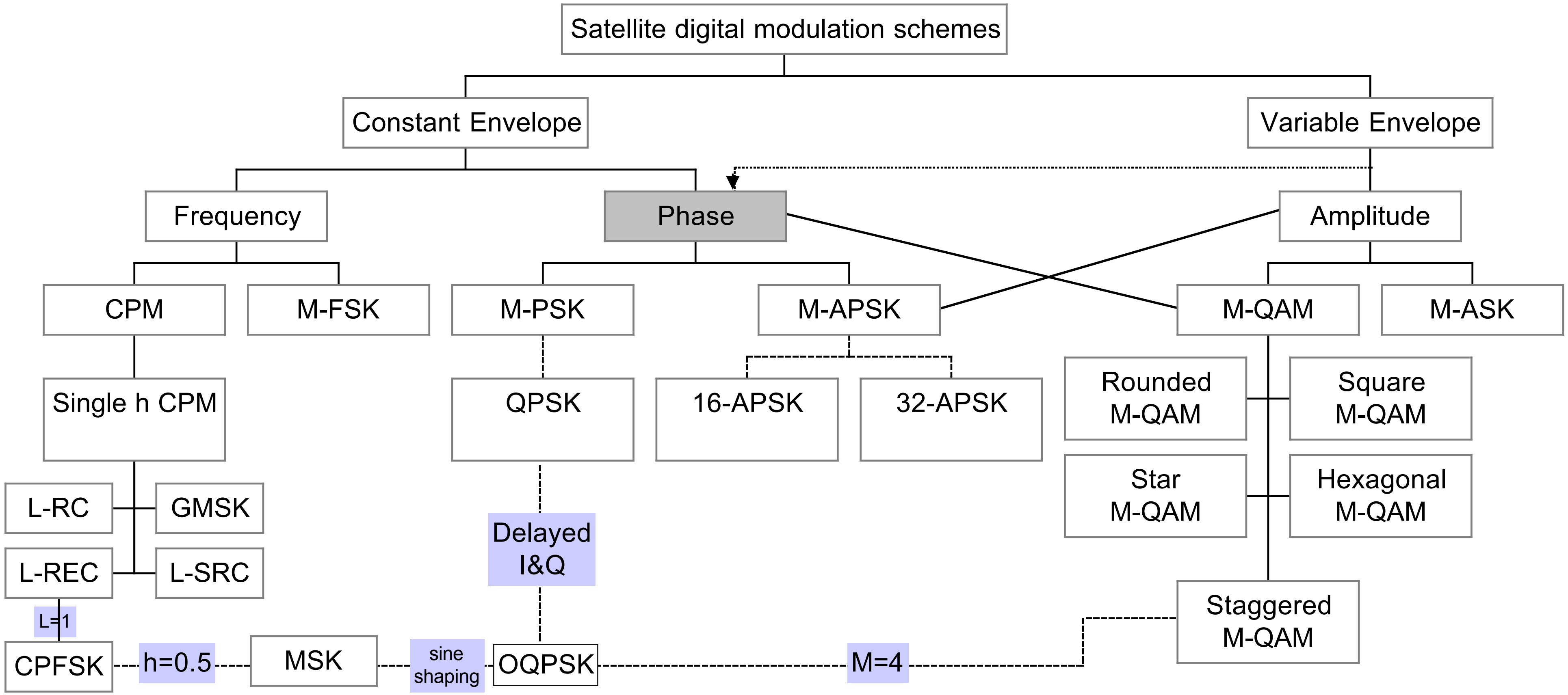
It is not economic to cover every code word against burst because they do not occur often enough. The solution is to use a technique known as interleaving.



Based on the Forney approach, it is composed of I=12 branches, each one of these contains a shift register whose depth depends on the branch. For synchronization purpose, the sync bytes shall always be routed in the branch "0" corresponding to a null delay.



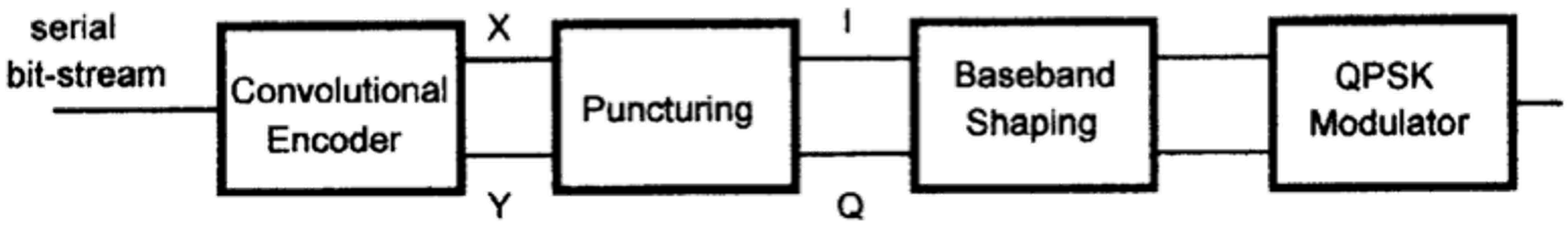
Modulation schemes classification



Modulation

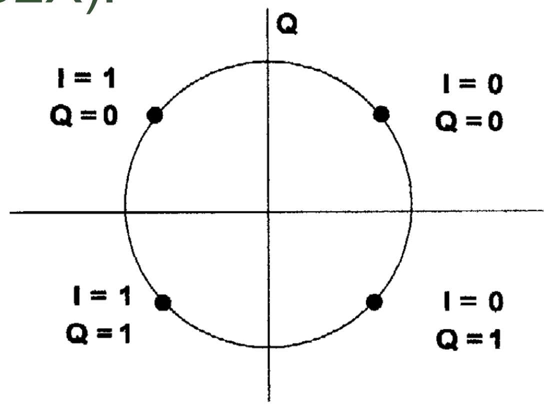
- Very robust modulation scheme is needed due to very critical propagation
- Phase modulation preferred because more robust with respect to amplitude variations
  - BPSK, QPSK, 8PSK, 16PSK
- QPSK one of the most used scheme
  - up to 20 years ago practically the only one used

Baseband shaping & Modulation



Before modulation, the I and Q signals shall be square root raised cosine filter with a roll-off factor α (up to 20 years ago 0.35 but now better values are obtained and used, see DVBS2 and DVBS2X).

Conventional Gray-coded QPSK modulation with absolute mapping (no differential coding).



On board antenna Multibeam Technology ...

Improves

- Spatial selectivity
- Gain
- Spectrum efficiency

Allows

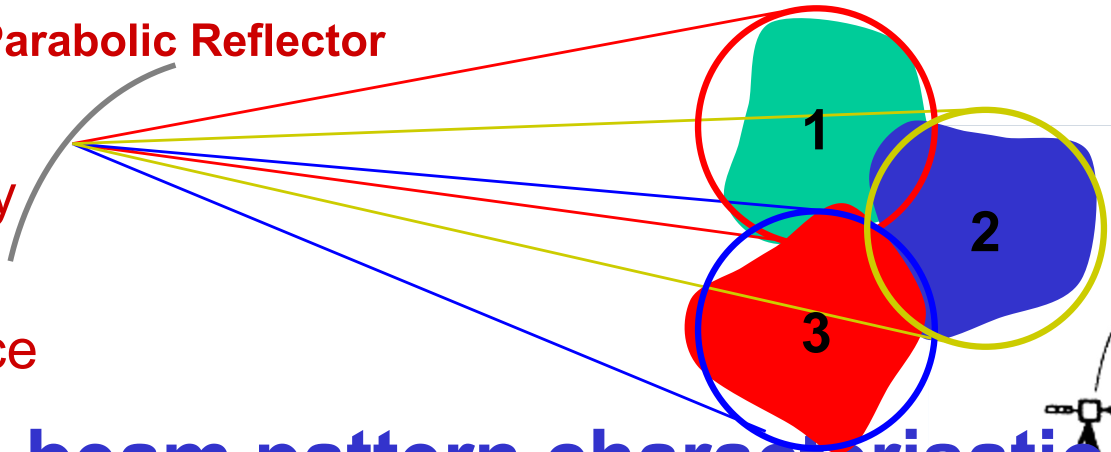
- Less critical terminal requirements
- Uneven power distribution
- More efficient traffic/power addressing

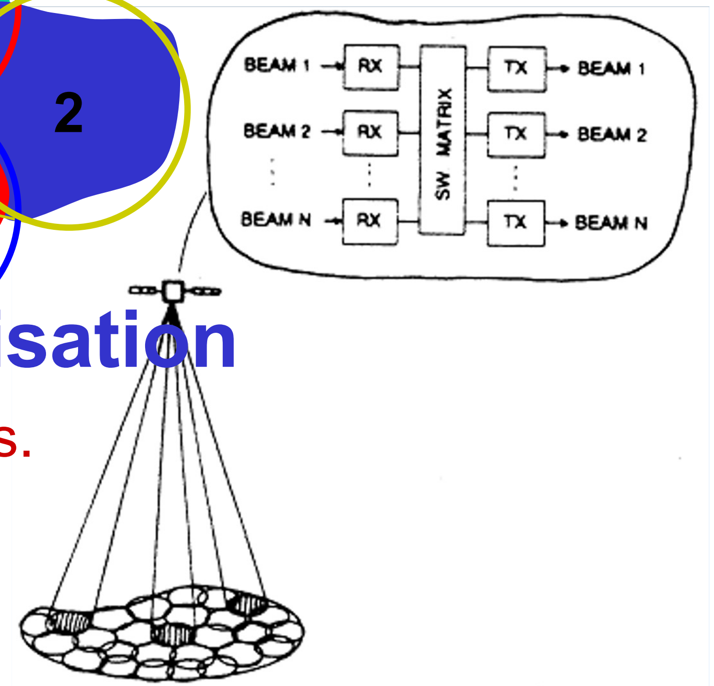
But ...

Increases

- Complexity
- Costs
- Interference

Parabolic Reflector



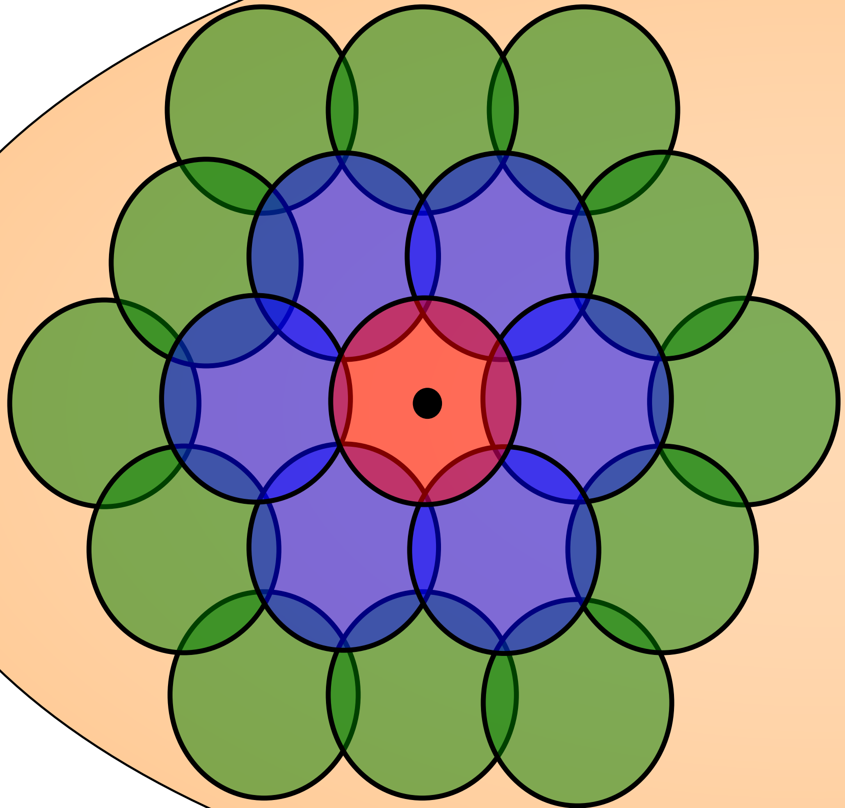


Multiple beam pattern characterisation

The satellite footprint can be subdivided in N cells.
To realise regular coverage:

- Circular crowns
- Cluster scheme

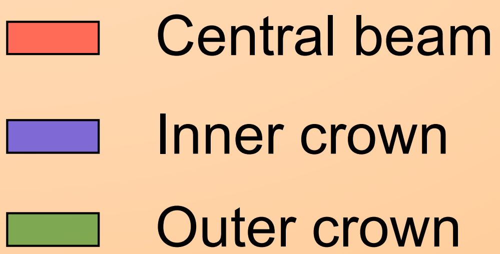
Circular crowns



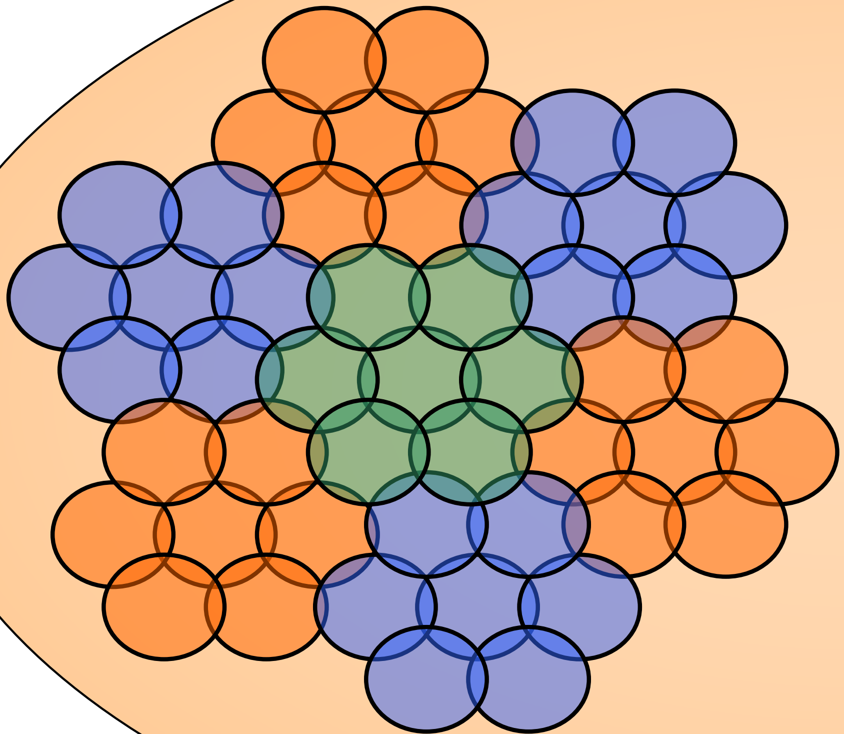
Number of cells

$$N_C = 1 + \sum_{i=1}^{M} 6 \cdot i$$

i: crown number



Cluster scheme

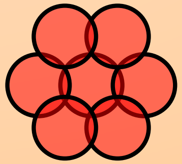


Number of cells

$$N = C \cdot N_C$$

C: cluster dimension

N_C: number of clusters



Cluster

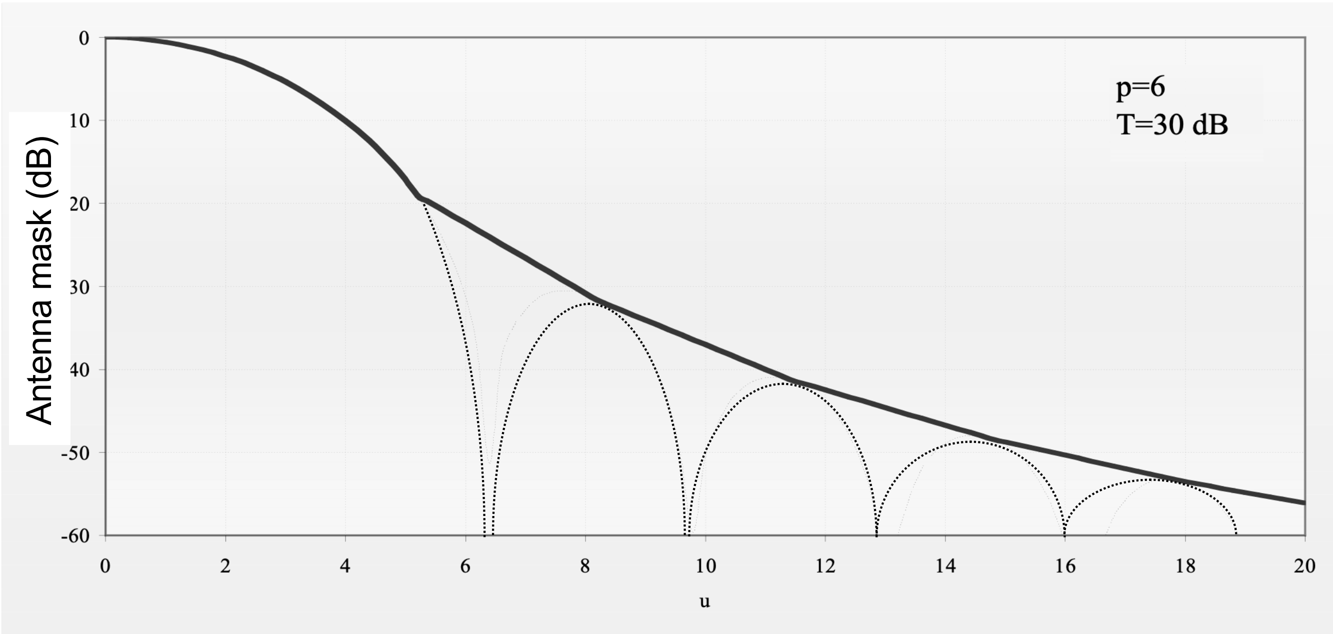
Antenna mask

$$F_j(\theta) = \hat{F}(u_j) = \frac{(p+1)(1-T)}{(p+1)(1-T)+T}\left(\frac{2J_1(u_j)}{u_j} + 2^{p+1}p!\frac{T}{1-T}\frac{J_{p+1}(u_j)}{u_j^{p+1}}\right)$$

$$u_j = \pi\frac{d_a}{\lambda}\sin\theta$$

T, p Shape parameters

d_a Aperture diameter

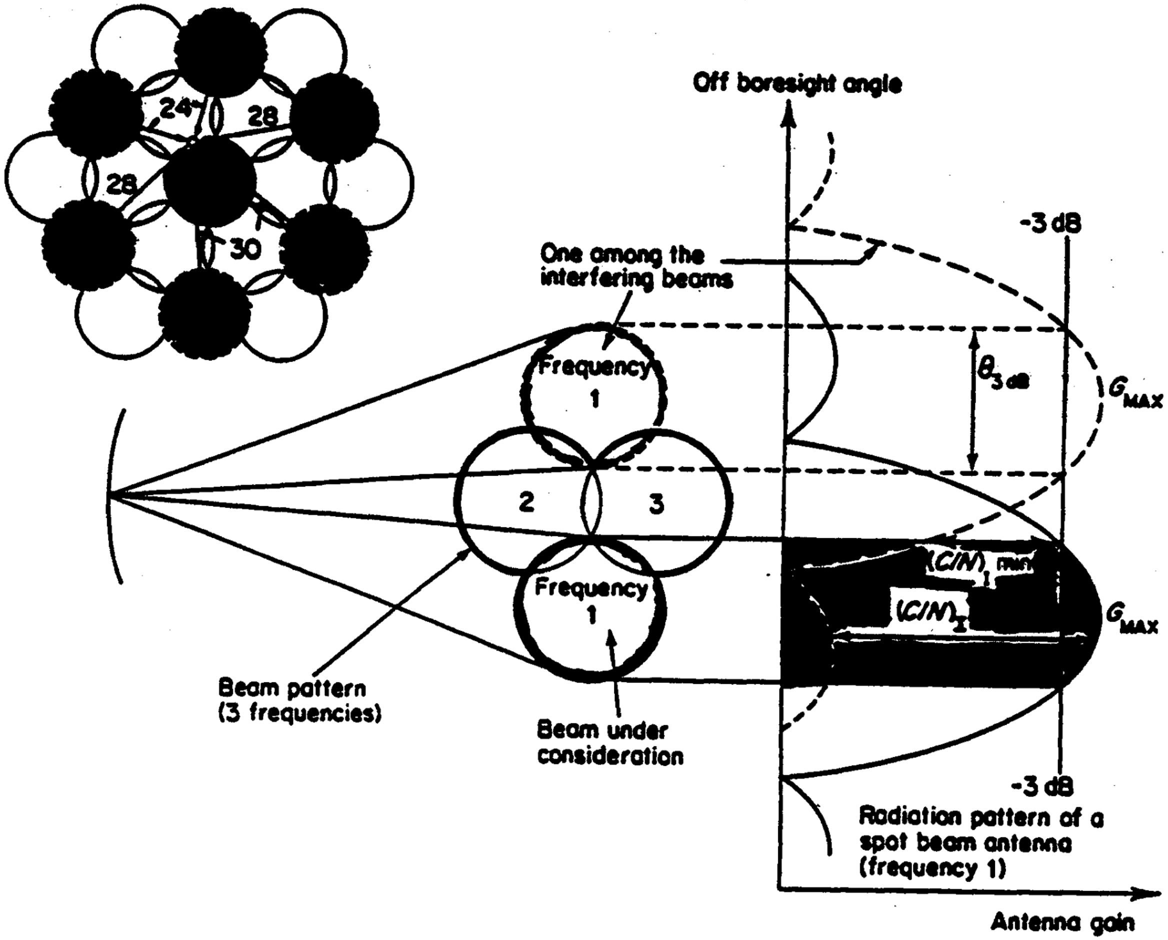


INTERFERENCE

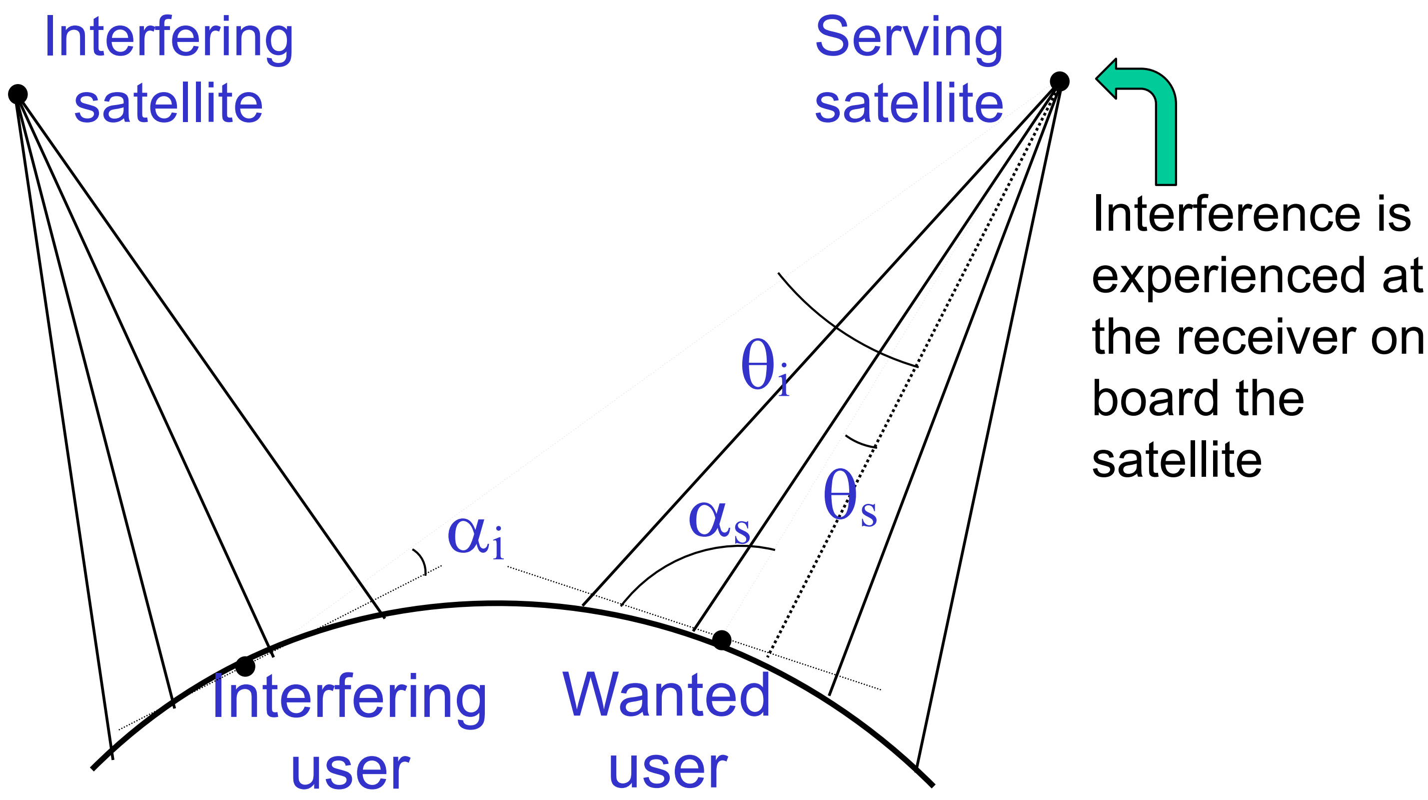
Type	Adjacent channel	Co-channel	Cross-channel	Adjacent system
System	Same	Same	Same	Different (even terrestrial)
Frequency	different	same	same	same
Polarization	same	same	orthogonal	same
Due to	Non ideal performance of filters	Non ideal (as we would like) performance of antennas	Non ideal polarization isolation	Non sufficient spatial (angular) separation

Co-Channel Interference

Construction of interference within a beam lattice with three frequencies

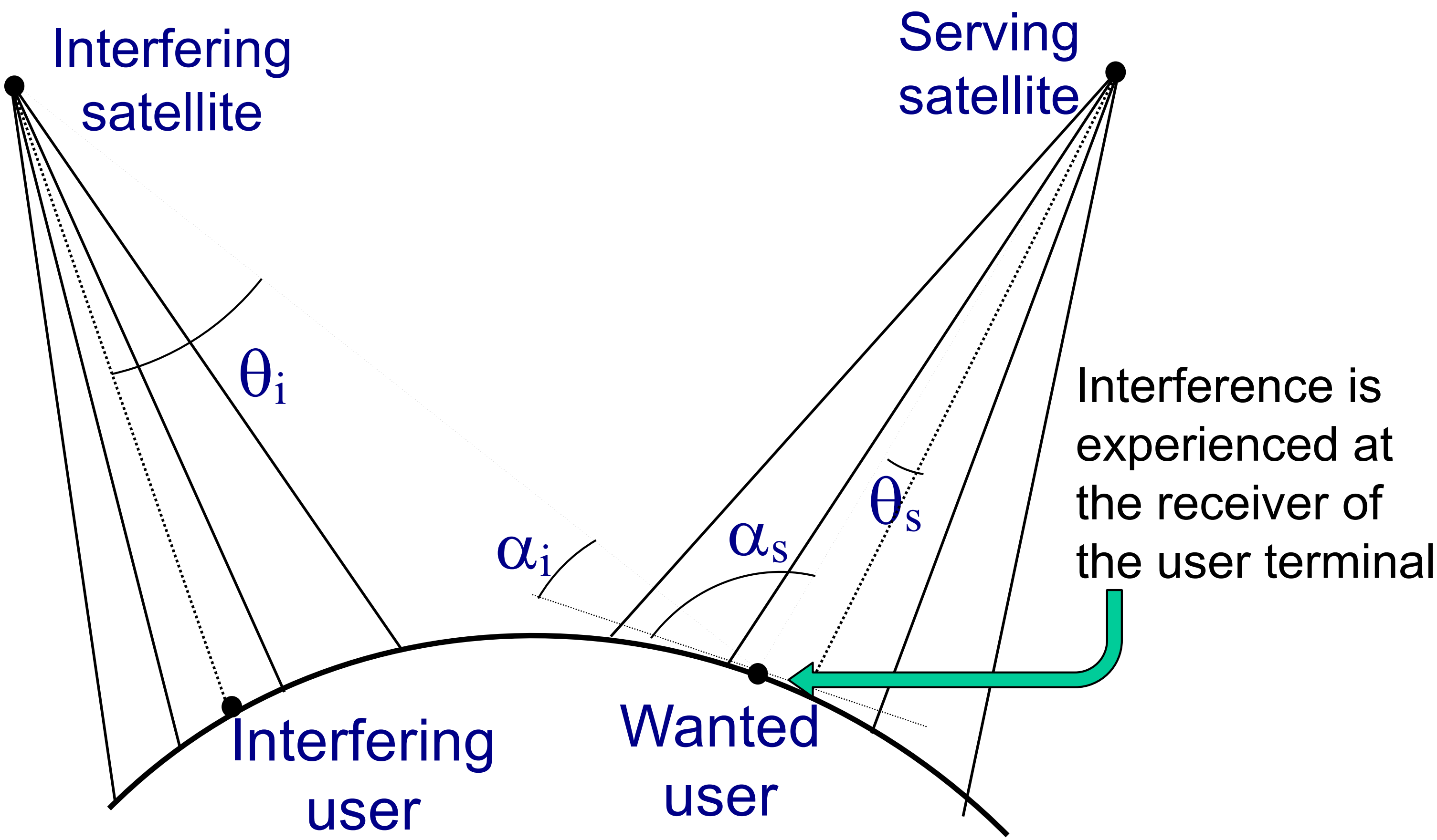


Geometrical structure for the up-link



Angles are the most important parameters because they determine the value of the antenna gain

Geometrical structure for the down-link

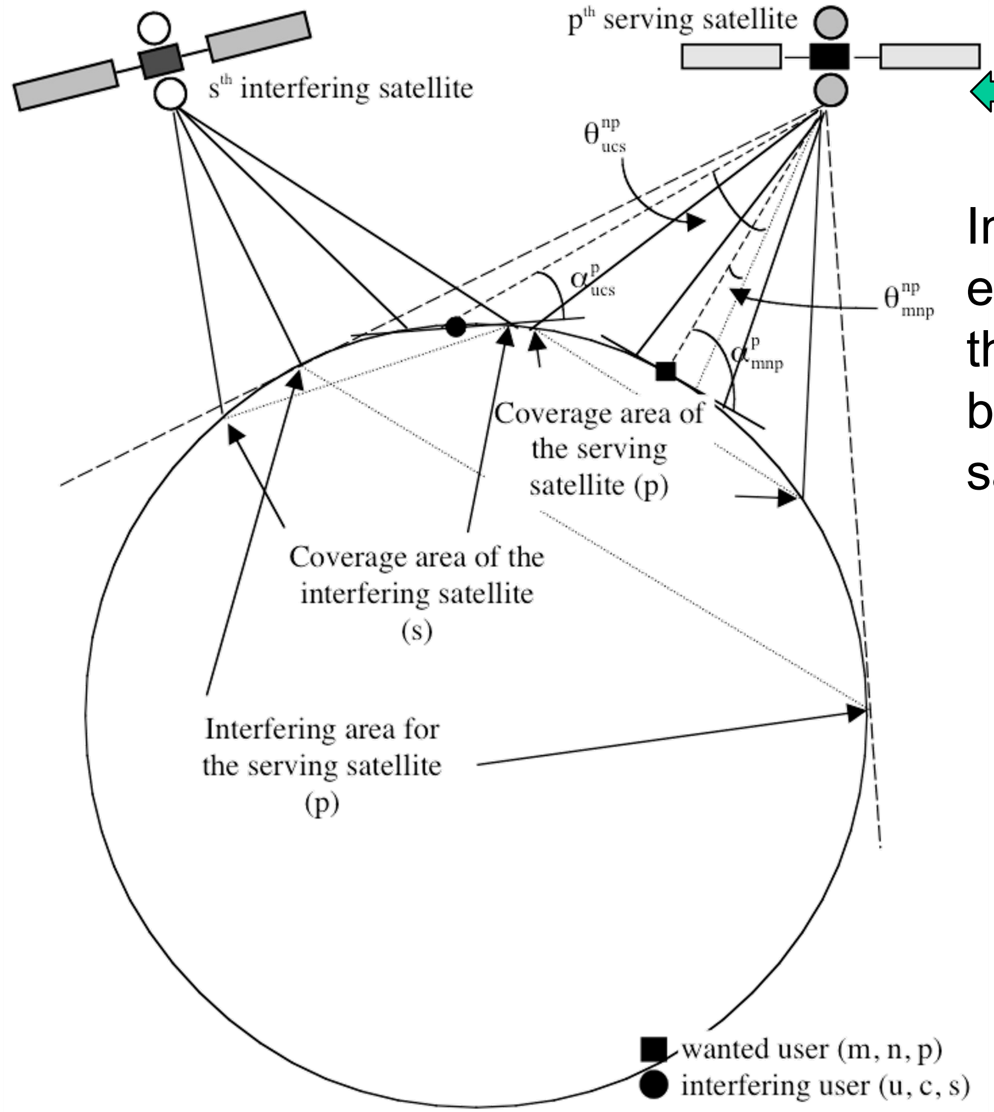


Angles are the most important parameters because they determine the value of the antenna gain

Multisatellite Multibeam interference scenario (up link)

Identification of the **interfering area**: area over which interfering users are located.

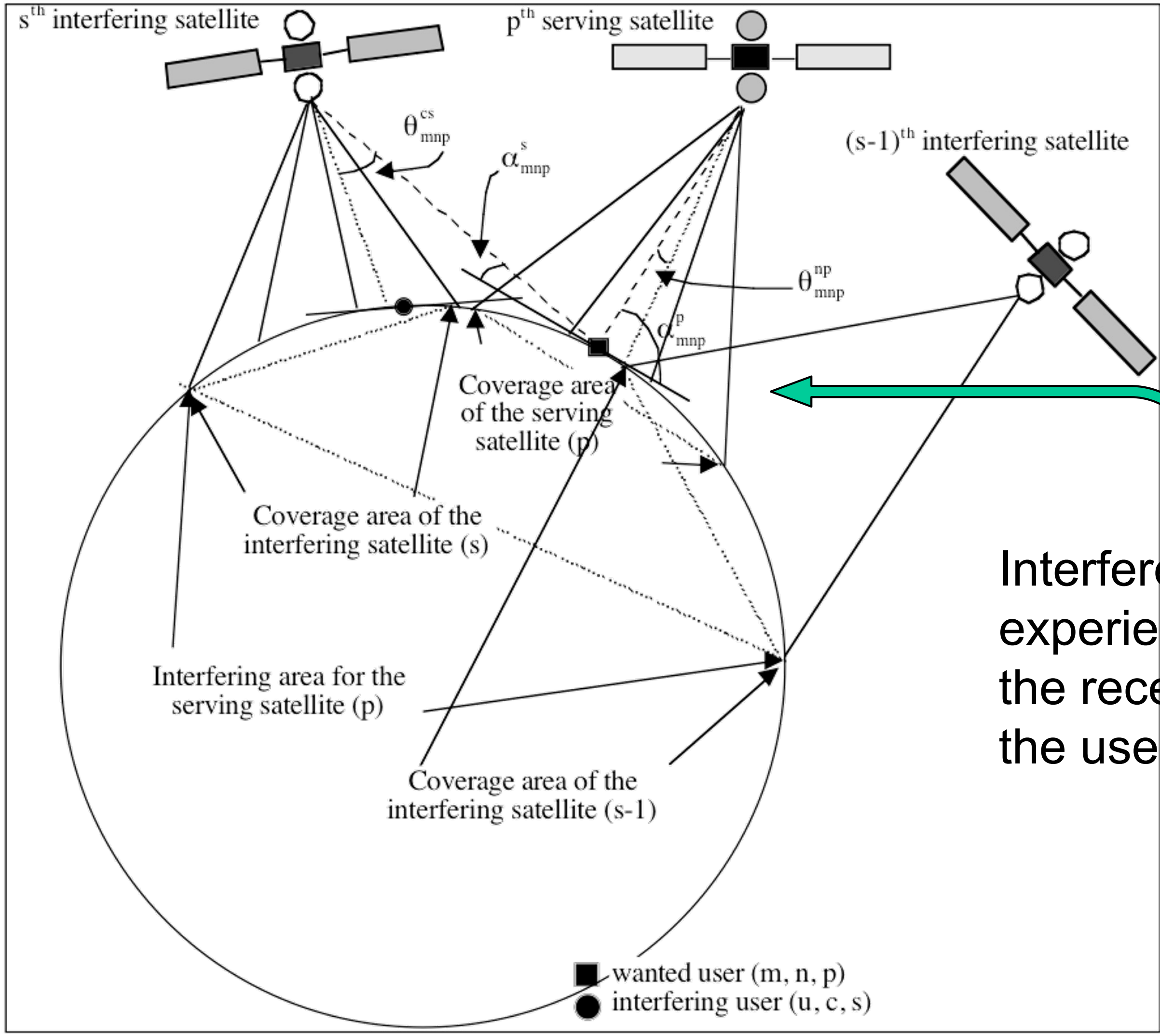
For the uplink **the whole area of visibility** (not the service area and in general larger than it) **of the serving satellite**. Also users served by other satellites may interfere.



Interference is experienced at the receiver on board the satellite

Multisatellite Multibeam interference scenario (down link)

Identification of the **interfering area**: <u>area over which interfering users are located</u>.
For the downlink it is **the union of service areas** (not the visibility areas) **of all the satellites in visibility by the wanted user**. Also users served by other satellite interfere.



Interference is experienced at the receiver of the user terminal

C/I parameters (1)

Symbol	Parameter
NU_{cs}	number of interfering users in the cell c of satellite s
NC	number of cells in a satellite
NS	number of satellites
NI	number of interfering cells ($1 \leq NS \leq N_{cell}$, where N_{cell} is the number of satellite antenna beam)
ucs	user number u ($1 \leq u \leq NU_{cs}$) of the cell number c ($1 \leq c \leq NS$) of the satellite number s ($1 \leq s \leq NS$)
mnp	wanted user index (m-th user in the n-th cell of the p-th satellite)
CD	cluster dimension
k	number of full cluster in the antenna pattern
q	cluster index ($0 \leq q \leq k-1$)
t	cell number in the cluster ($1 \leq t \leq CD$)
n	cell number in one satellite coverage ($n=CDq_m+t$ in FDMA)
A_{mnp}	Supplementary (e.g. due to atmospheric effects) attenuation experienced by the mnp user

C/I parameters (2)

$\lambda_{[ucs]}$	wave length of the user (*u, c, s*)
$w_{[ucs]}$	power transmitted by the mobile terminal (*u, c, s*)
$W_{[cs]}$	power transmitted to cell *c* by the satellite s
α^{s}_{ucs}	angle between the tangent to the earth in the location of the user (*u, c, s*) and the line between the satellite *s* and the user (*u, c, s*)
$g_{[ucs]}\left(\alpha^{s}_{ucs}\right)$	antenna gain of the mobile terminal (*u, c, s*) in the direction α^{s}_{ucs}
θ^{cs}_{ucs}	angle between the boresight of the cell *c* of the satellite *s* and the line between the satellite *s* and the user (*u, c, s*)
$G_{[cs]}\left(\theta^{cs}_{ucs}\right)$	satellite antenna gain in the cell *c* of the satellite *s* in the direction of θ^{cs}_{ucs}
d^{s}_{ucs}	slant range for the link from the user (*u, c, s*) to the satellite *s* (the one serving the wanted user)
e	type of environment (rural, suburban, urban)
$f_{ucs}\left(e,\alpha^{s}_{ucs}\right)$	mobile channel fading experienced by the user (*u, c, s*) depending on the environment *e* and on the angle α^{s}_{ucs}
γ^{mnp}_{ucs}	orthogonality factor between the user (*u, c, s*) and the user (*m, n, p*)
μ_{ucs}	activity factor of the user (*u, c, s*)
ρ^{np}_{cs}	polarization isolation factor between the cell (*c, s*) and the cell (*n, p*)
l_{mnp}	Latitude of the user mnp
L_{mnp}	Longitude of the user mnp

C/I evaluation: CDMA case

$$\left(\frac{\mathrm{C}}{\mathrm{I}}\right)_{\mathrm{uplink}} = \frac{\mathrm{C}_{\mathrm{up}}}{\sum_{\mathrm{i}=1}^{3} \mathrm{I}_{\mathrm{i-up}}}$$

$$\left(\frac{\mathrm{C}}{\mathrm{I}}\right)_{\mathrm{downlink}} = \frac{\mathrm{C}_{\mathrm{down}}}{\sum_{\mathrm{i}=1}^{3} \mathrm{I}_{\mathrm{i-down}}}$$

$$C_{up} = \frac{w_{[mnp]} g_{[mnp]}\left(\alpha_{mnp}^{p}\right) G_{[np]}\left(\theta_{mnp}^{np}\right)}{\left(\frac{4\pi d_{mnp}^{p}}{\lambda}\right)^{2} f_{mnp}\left(e,\alpha_{mnp}^{p}\right) A_{mnp}\left(\lambda, l_{mnp}, L_{mnp}, \alpha_{mnp}^{p}\right)}$$

$$C_{down} = \frac{W_{np} g_{[mnp]}\left(\alpha_{mnp}^{p}\right) G_{[np]}\left(\theta_{mnp}^{np}\right)}{\left(\frac{4\pi d_{mnp}^{p}}{\lambda}\right)^{2} f_{mnp}\left(e,\alpha_{mnp}^{p}\right) A_{mnp}\left(\lambda, l_{mnp}, L_{mnp}, \alpha_{mnp}^{p}\right)}$$

$$I_{1-up} = \sum_{u\begin{cases}=1\\ \neq m\end{cases}}^{NU_{np}} \frac{\gamma_{unp}^{mnp} \mu_{unp} w_{[unp]} g_{[unp]}\left(\alpha_{unp}^{p}\right) G_{[np]}\left(\theta_{unp}^{np}\right)}{\left(\frac{4\pi d_{unp}^{p}}{\lambda}\right)^{2} f_{unp}\left(e,\alpha_{unp}^{p}\right) A_{unp}\left(\lambda, l_{unp}, L_{unp}, \alpha_{unp}^{p}\right)}$$

$$I_{1-down} = \sum_{u\begin{cases}=1\\ \neq m\end{cases}}^{NU_{np}} \frac{\gamma_{unp}^{mnp} \mu_{unp} W_{[np]} g_{[mnp]}\left(\alpha_{mnp}^{p}\right) G_{[np]}\left(\theta_{mnp}^{np}\right)}{\left(\frac{4\pi d_{mnp}^{p}}{\lambda}\right)^{2} f_{mnp}\left(e,\alpha_{mnp}^{p}\right) A_{mnp}\left(\lambda, l_{mnp}, L_{mnp}, \alpha_{mnp}^{p}\right)}$$

$$I_{2-up} = \sum_{c\begin{cases}=1\\ \neq n\end{cases}}^{NC} \sum_{u=1}^{NU_{cp}} \frac{\gamma_{ucp}^{mnp} \mu_{ucp} w_{[ucp]} g_{[ucp]}\left(\alpha_{ucp}^{p}\right) G_{[np]}\left(\theta_{ucp}^{np}\right) \rho_{cp}^{np}}{\left(\frac{4\pi d_{ucp}^{p}}{\lambda}\right)^{2} f_{ucp}\left(e,\alpha_{ucp}^{p}\right) A_{ucp}\left(\lambda, l_{ucp}, L_{ucp}, \alpha_{ucp}^{p}\right)}$$

$$I_{2-down} = \sum_{c\begin{cases}=1\\ \neq n\end{cases}}^{NC} \sum_{u=1}^{NU_{cp}} \frac{\gamma_{ucp}^{mnp} \mu_{ucp} W_{[cp]} g_{[mnp]}\left(\alpha_{mnp}^{p}\right) G_{[cp]}\left(\theta_{mnp}^{cp}\right) \rho_{np}^{cp}}{\left(\frac{4\pi d_{mnp}^{p}}{\lambda}\right)^{2} f_{mnp}\left(e,\alpha_{mnp}^{p}\right) A_{mnp}\left(\lambda, l_{mnp}, L_{mnp}, \alpha_{mnp}^{p}\right)}$$

$$I_{3-up} = \sum_{s\begin{cases}=1\\ \neq p\end{cases}}^{NS} \sum_{c=1}^{NC} \sum_{u=1}^{NU_{cs}} \frac{\gamma_{ucs}^{mnp} \mu_{ucs} w_{[ucs]} g_{[ucs]}\left(\alpha_{ucs}^{p}\right) G_{[np]}\left(\theta_{ucs}^{np}\right) \rho_{cs}^{np}}{\left(\frac{4\pi d_{ucs}^{p}}{\lambda}\right)^{2} f_{ucs}\left(e,\alpha_{ucs}^{p}\right) A_{ucs}\left(\lambda, l_{ucs}, L_{ucs}, \alpha_{ucs}^{p}\right)}$$

$$I_{3-down} = \sum_{s\begin{cases}=1\\ \neq p\end{cases}}^{NS} \sum_{c=1}^{NC} \sum_{u=1}^{NU_{cs}} \frac{\gamma_{ucs}^{mnp} \mu_{ucs} W_{cs} g_{[mnp]}\left(\alpha_{mnp}^{s}\right) G_{[cs]}\left(\theta_{mnp}^{cs}\right) \rho_{np}^{cs}}{\left(\frac{4\pi d_{mnp}^{s}}{\lambda}\right)^{2} f_{mnp}\left(e,\alpha_{mnp}^{s}\right) A_{mnp}\left(\lambda, l_{mnp}, L_{mnp}, \alpha_{mnp}^{s}\right)}$$

C/I evaluation: FDMA case

$$\left(\frac{C}{I}\right)_{uplink} = \frac{C_{up}}{\sum_{i=2}^{3} I_{i-up}}$$

number of full clusters $k = \left\lfloor \frac{NC}{CD} \right\rfloor$

'NC' is not a multiple of 'CD'

number of cells

cluster dimension

$$\left(\frac{C}{I}\right)_{downlink} = \frac{C_{down}}{\sum_{i=2}^{3} I_{i-down}}$$

$$\begin{cases} NC = kCD \end{cases}$$

$$\nu = NC - k \cdot CD$$

number of interfering cells

$$NI = \begin{cases} k \longrightarrow & \forall t \le \nu \\ k-1 \longrightarrow & \forall t > \nu \end{cases}$$

t=cell number in the cluster

$$C_{up} = \frac{w_{[mnp]} g_{[mnp]}\left(\alpha^{p}_{mnp}\right) G_{[np]}\left(\theta^{np}_{mnp}\right)}{\left(\frac{4\pi d^{p}_{mnp}}{\lambda_{mnp}}\right)^{2} f_{mnp}\left(e,\alpha^{p}_{mnp}\right) A_{mnp}\left(\lambda, l_{mnp}, L_{mnp}, \alpha^{p}_{mnp}\right)}$$

$$C_{down} = \frac{W_{[np]} g_{[mnp]}\left(\alpha^{p}_{mnp}\right) G_{[np]}\left(\theta^{np}_{mnp}\right)}{\left(\frac{4\pi d^{p}_{mnp}}{\lambda_{mnp}}\right)^{2} f_{mnp}\left(e,\alpha^{p}_{mnp}\right) A_{mnp}\left(\lambda, l_{mnp}, L_{mnp}, \alpha^{p}_{mnp}\right)}$$

$$I_{2-up} = \sum_{q\begin{cases}=0\\ \neq q_m\end{cases}}^{NI} \frac{\mu_{m(CDq+t)p} w_{[m(CDq+t)p]} g_{[m(CDq+t)p]}\left(\alpha^{p}_{m(CDq+t)p}\right) G_{[np]}\left(\theta^{np}_{m(CDq+t)p}\right) \rho^{np}_{(CDq+t)p}}{\left(\frac{4\pi d^{p}_{m(CDq+t)p}}{\lambda_{mnp}}\right)^{2} f_{m(CDq+t)p}\left(e,\alpha^{p}_{m(CDq+t)p}\right) A_{m(CDq+t)p}\left(\lambda_{mnp}, l_{m(CDq+t)p}, L_{m(CDq+t)p}, \alpha^{p}_{m(CDq+t)p}\right)}$$

$$I_{2-down} = \sum_{q\begin{cases}=0\\ \neq q_m\end{cases}}^{NI} \frac{\mu_{m(CDq+t)p} W_{[(CDq+t)p]} g_{[mnp]}\left(\alpha^{p}_{mnp}\right) G_{[(CDq+t)p]}\left(\theta^{(CDq+t)p}_{mnp}\right) \rho^{(CDq+t)p}_{np}}{\left(\frac{4\pi d^{p}_{m(CDq+t)p}}{\lambda_{mnp}}\right)^{2} f_{mnp}\left(e,\alpha^{p}_{mnp}\right) A_{mnp}\left(\lambda, l_{mnp}, L_{mnp}, \alpha^{p}_{mnp}\right)}$$

$$I_{3-up} = \sum_{s\begin{cases}=1\\ \neq p\end{cases}}^{NS} \sum_{q=0}^{NI} \frac{\mu_{m(CDq+t)s} w_{[m(CDq+t)s]} g_{[m(CDq+t)s]}\left(\alpha^{p}_{m(CDq+t)s}\right) G_{[np]}\left(\theta^{np}_{m(CDq+t)s}\right) \rho^{np}_{(CDq+t)s}}{\left(\frac{4\pi d^{p}_{m(CDq+t)s}}{\lambda_{mnp}}\right)^{2} f_{m(CDq+t)s}\left(e,\alpha^{p}_{m(CDq+t)s}\right) A_{m(CDq+t)s}\left(\lambda_{mnp}, l_{m(CDq+t)s}, L_{m(CDq+t)s}, \alpha^{p}_{m(CDq+t)s}\right)}$$

$$I_{3-down} = \sum_{s\begin{cases}=1\\ \neq p\end{cases}}^{NS} \sum_{q=0}^{NI} \frac{\mu_{m(CDq+t)s} W_{[(CDq+t)s]} g_{[mnp]}\left(\alpha^{s}_{mnp}\right) G_{[(CDq+t)s]}\left(\theta^{(CDq+t)s}_{mnp}\right) \rho^{(CDq+t)s}_{np}}{\left(\frac{4\pi d^{s}_{mnp}}{\lambda_{mnp}}\right)^{2} f_{mnp}\left(e,\alpha^{s}_{mnp}\right) A_{mnp}\left(\lambda, l_{mnp}, L_{mnp}, \alpha^{s}_{mnp}\right)}$$

Interference reduction techniques (IRT)

1) beam/cell turnoff;
2) intraorbital plane frequency division;
3) interorbital plane frequency division;
4) use of two orthogonal polarizations;
5) power control;
6) position dependent frequency assignment;
7) frequency hopping;
8) multi-channel detection;
9) dynamic resource allocation;
10) optimum bandwidth (or code) assignment.

Comments on IRT (LEO-MEO case)

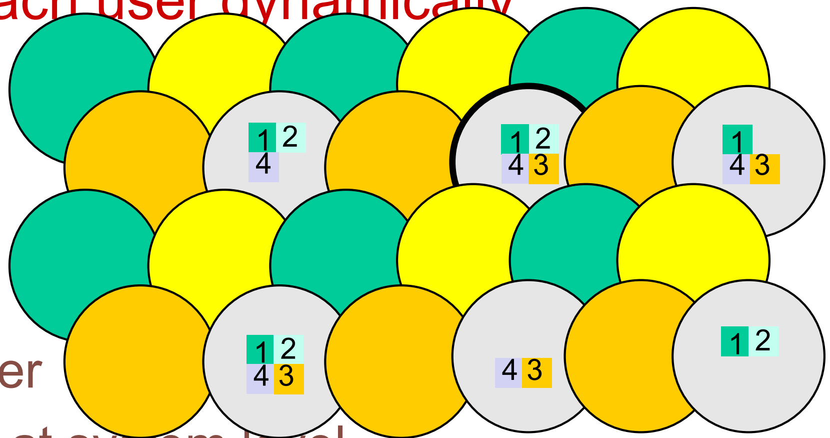
- 1) **beam/cell turnoff**, 2) **intraorbital plane frequency division** and 3) **interorbital plane frequency division** decrease spectrum efficiency
- 1) designed mainly for FDMA
  - avoids deleterious effects in case of overlapping beams of different satellites
  - benefits on the contributions originated from the other satellites (I_3).
  - best performing in terms of spectrum efficiency
  - not best improvement in terms of C/I
- 2) reduces part of the interference due to other satellites (I_3) belonging to the same orbit of the serving satellite.
  - less effective than 1).
- 1) and 2) can be jointly used; further improvement is achieved with respect to 1) and 2), with a small reduction in frequency reuse with respect to 2).

Comments on IRT (2)

- 3) **interorbital plane frequency division** offers the greatest advantage among 1) 2) and 3),
  - almost static interference situation as in the GEO case
  - worst spectrum efficiency
  - the interference due to the satellites belonging to the other orbits (I_3) can be strongly reduced
  - Combined with technique 2), it can get rid of all the interference caused by other satellites
- 4) **use of two orthogonal polarizations** increases beam to beam isolation
  - Reduces the contribution of the other beams (I_2 and I_3).
  - Further reuse the frequency band (number of available orthogonal channels doubles).
  - Not preserved for the multipath components (polarization reversal after reflection)
  - In a multi-satellite scenario, used to reduce the interference level rather than for further stressing the frequency reuse.

Comments on IRT (3)

- 5) **power control** 6) **position dependent frequency assignment** 7) **frequency hopping** and 8) **multi-channel detection** designed for FDMA but also for CDMA
- 5) compensates satellite gain variations within a beam
- 6) implies to assign frequency slots to each user dynamically taking into account the angle (position)
  - more effective for the up link
  - more suitable to geostationary systems
- 7) mainly applicable for FDMA
  - decreases the contributions from the other beams, thus I_2 and I_3 if it is implemented at system level,
  - decreases the contribution from the same beam I_1 if implemented at beam level
- 9) **dynamic resource allocation** minimizes intra-system interference and improves spectrum efficiency

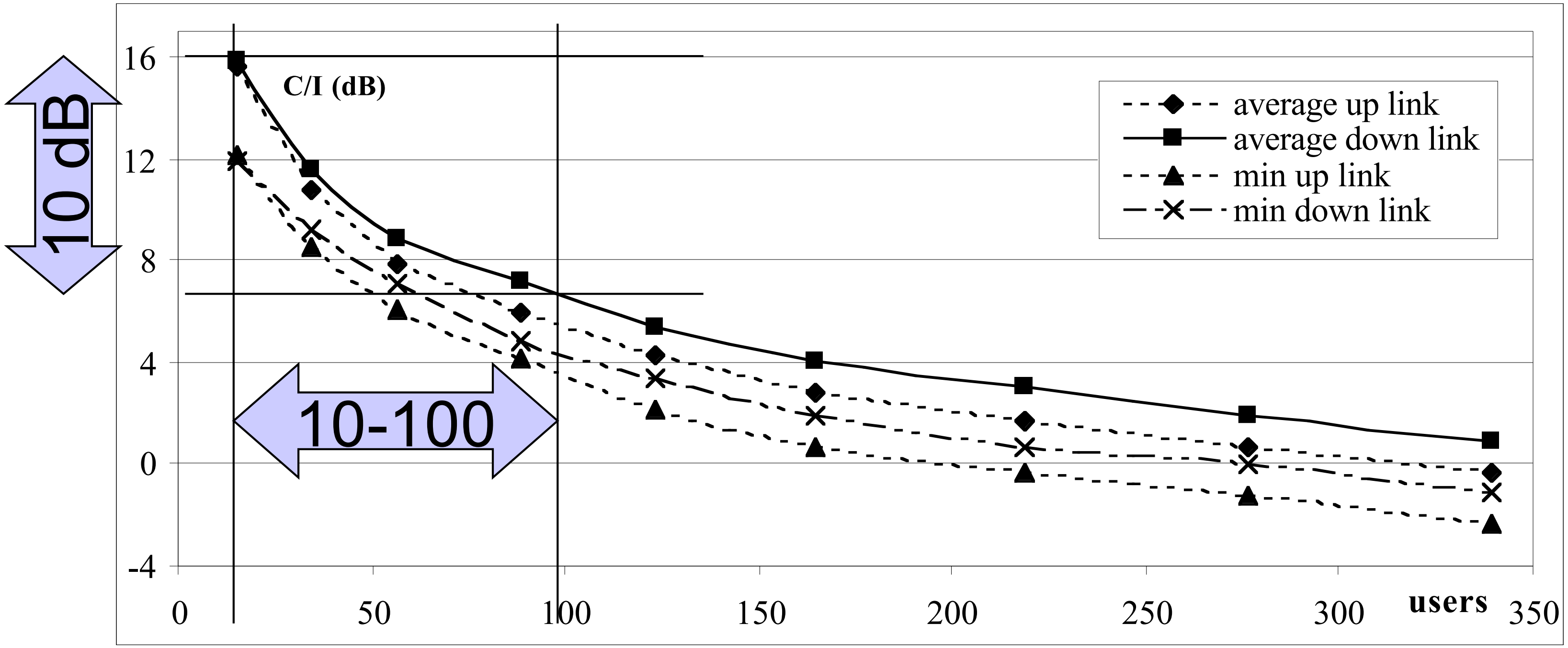


Comments on IRT (4)

- 10) **optimum bandwidth (or code) assignment** can be a very effective in case of uneven traffic (and interference) distribution
  - Reduces the contributions I_2 and I_3
  - Optimum bandwidth allocation for FDMA
  - Optimum code allocation for CDMA (depends on γ)

Interference vs capacity

- Interference limits capacity because it is generated by users: less users (less capacity) ➠ less interference
- Experimental results, assumptions:
  - Globalstar constellation
  - Uniform user distribution



On board processing capability

Basic concept: the capabilities to demodulate and modulate the signal are implemented on board the satellite

Better performance in terms of E_b/N_0 required

⇓

Reduced power needed on both links

⇓

Reduced intermodulation

Up link and down link are isolated avoiding direct transfer to the down link of noise accumulated on the up link

Demodulation and remodulation

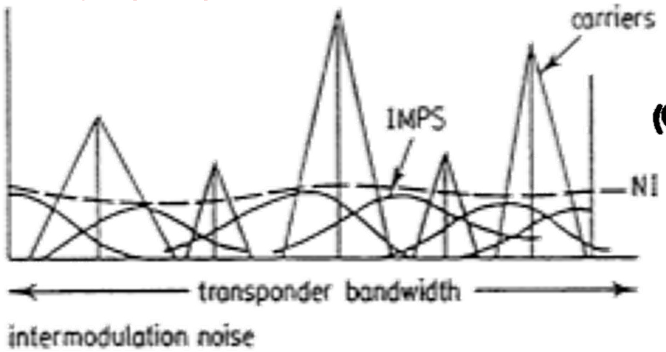
- The only bit errors are due to the hard decision
- Remodulation
  - eliminates the degradation caused by up link filter induced AM as well as the resulting phase modulation (PM) of the QPSK carrier produced when the up link signal is amplified directly by nonlinear TWTA
  - permits the carrier to be derived from a common source for all down link signals and eliminates station to station and Doppler differences encountered on the up link.

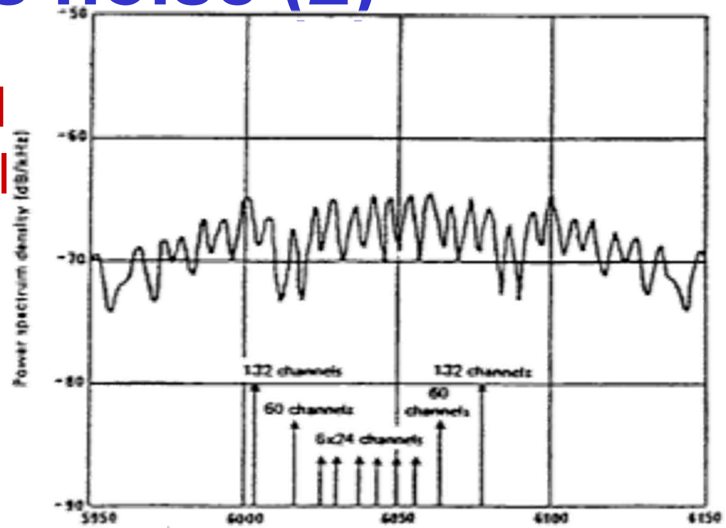
Intermodulation products noise

- Intermodulation products, due to non linearity of equipment, may appear at:
  - the output of the transmitting Earth station non linear power amplifier
  - the output of the satellite repeater
- These intermodulation products can interfere with the desired carriers, and hence be considered as noise called "intermodulation noise".
- With modulated carriers, the intermodulation noise is distributed over the entire frequency band.
- Example: Intermodulation noise spectrum for a typical TWT with 10 carriers (6 central carriers modulated by a multiplex of 24 telephone channels, two 64 channels carriers and two 132 channels carriers)

Intermodulation products noise (2)

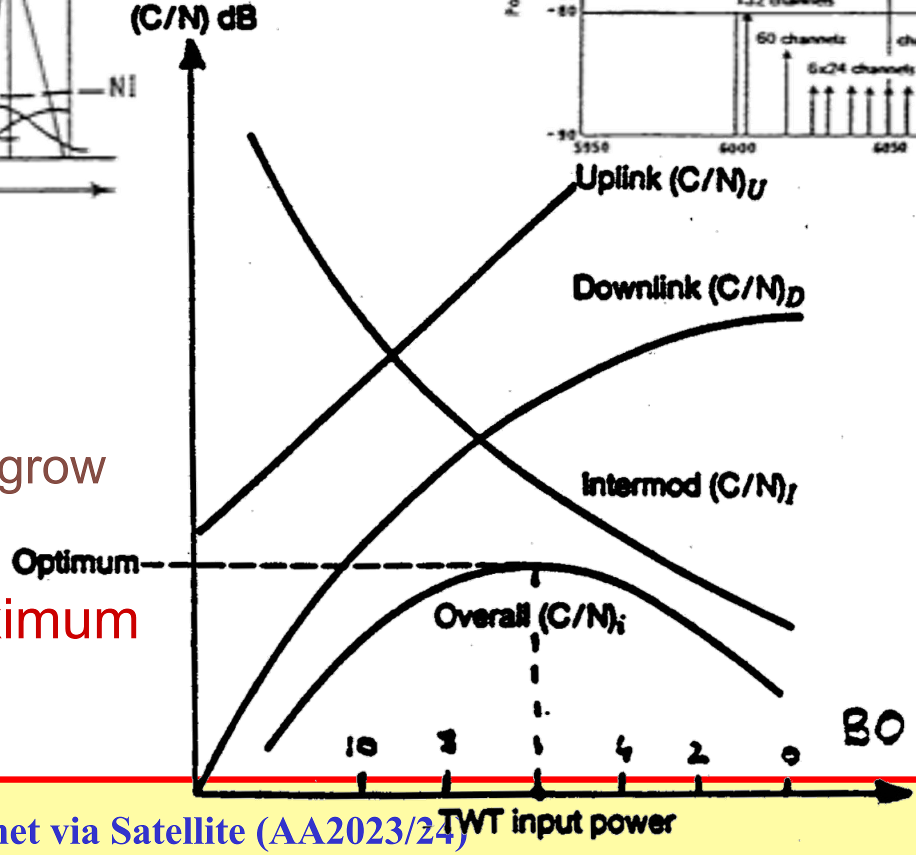
- Intermodulation products can be considered as filtered white noise with constant spectral density $(N_0)_{IM}$





Back off

- Close to saturation
  - $(C/N_0)_U$ and $(C/N_0)_D$ grow
  - $(C/N_0)_{IM}$ decreases
- $(C/N_0)_{Tot}$ shows a maximum
- Back Off



Link Dimensioning

It concerns the dimensioning of the transmission link between two earth stations, one transmitting and one receiving, via satellite.

The link is composed of two segments: the **uplink** from the transmitting earth station to the satellite and the **downlink** from the satellite to the receiving earth station.

- **LINK ANALYSIS**
  - Antenna parameters
  - Noise power
  - Influence of the propagation medium
  - Signal to noise ratio
  - Shadowing/ Multipath Fading

Characteristic Parameters of an Antenna (1)

- **Gain** is the ratio between the power radiated per unit solid angle by an antenna in a given direction and the power radiated per unit solid angle by an isotropic antenna fed with the same power. It is given by:

$$G_{max} = (4\pi / \lambda^2) A_{eff}$$

$\lambda = c / f$	wavelength of the electromagnetic wave,
c	velocity of the light,
f	frequency of the electromagnetic wave,
$A_{eff} = \eta A$	effective aperture area for an antenna with a circular aperture of diameter D and geometric surface $A=\pi D^2/4$
η	efficiency of antenna (typically 0.5-0.65 for a parabolic antenna).

$$G_{max} = \eta (\pi D/\lambda)^2 = \eta(\pi D f/c)^2$$

- The **efficiency** of antenna is the product of several factors:

  the illumination law
  the spill-over loss
  the surface impairments
  resistive and mismatch losses

$$\eta = \eta_i * \eta_s * \eta_f * \eta_z$$

Characteristic Parameters of an Antenna (2)

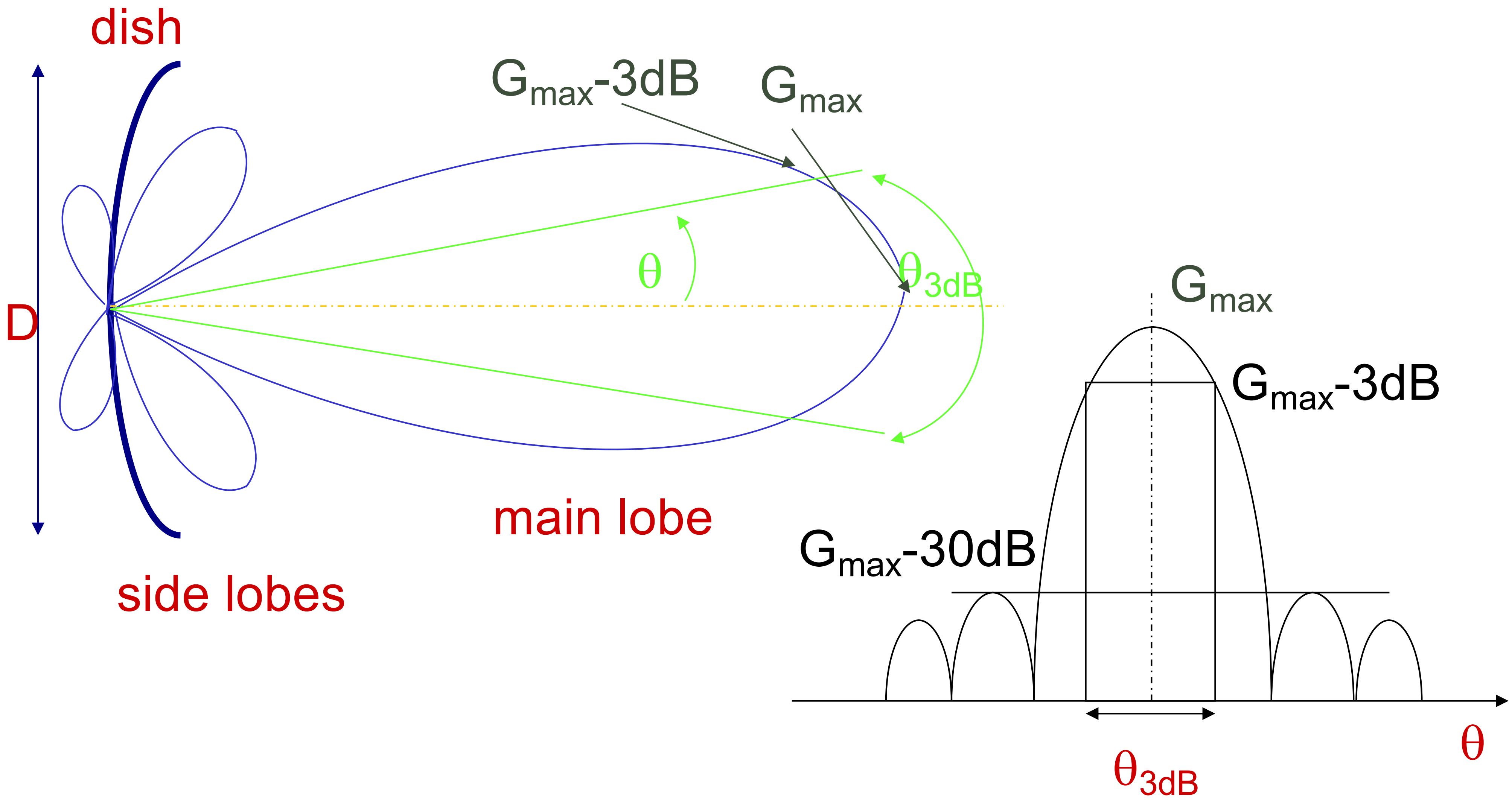
- The **Radiation pattern** indicates the variations of gain with direction. For an antenna with a circular aperture or reflector this pattern has rotational symmetry. The main lobe contains the direction of the maximum radiation while side lobes should be kept to a minimum.
- The **Angular Beamwidth** is the angle by the directions corresponding to a given gain fallout with respect to the maximum value. The **3 dB beamwidth** is often used, it corresponds to the angle between the directions in which the gain falls to half of its maximum value.
- It depends on λ/D by a coefficient. For uniform illumination it is 58.5° . With non uniform illumination the value commonly used is 70° which leads the following expression

$$\theta_{3dB} = 70\ (\lambda/D) = 70(c/f\ D)$$

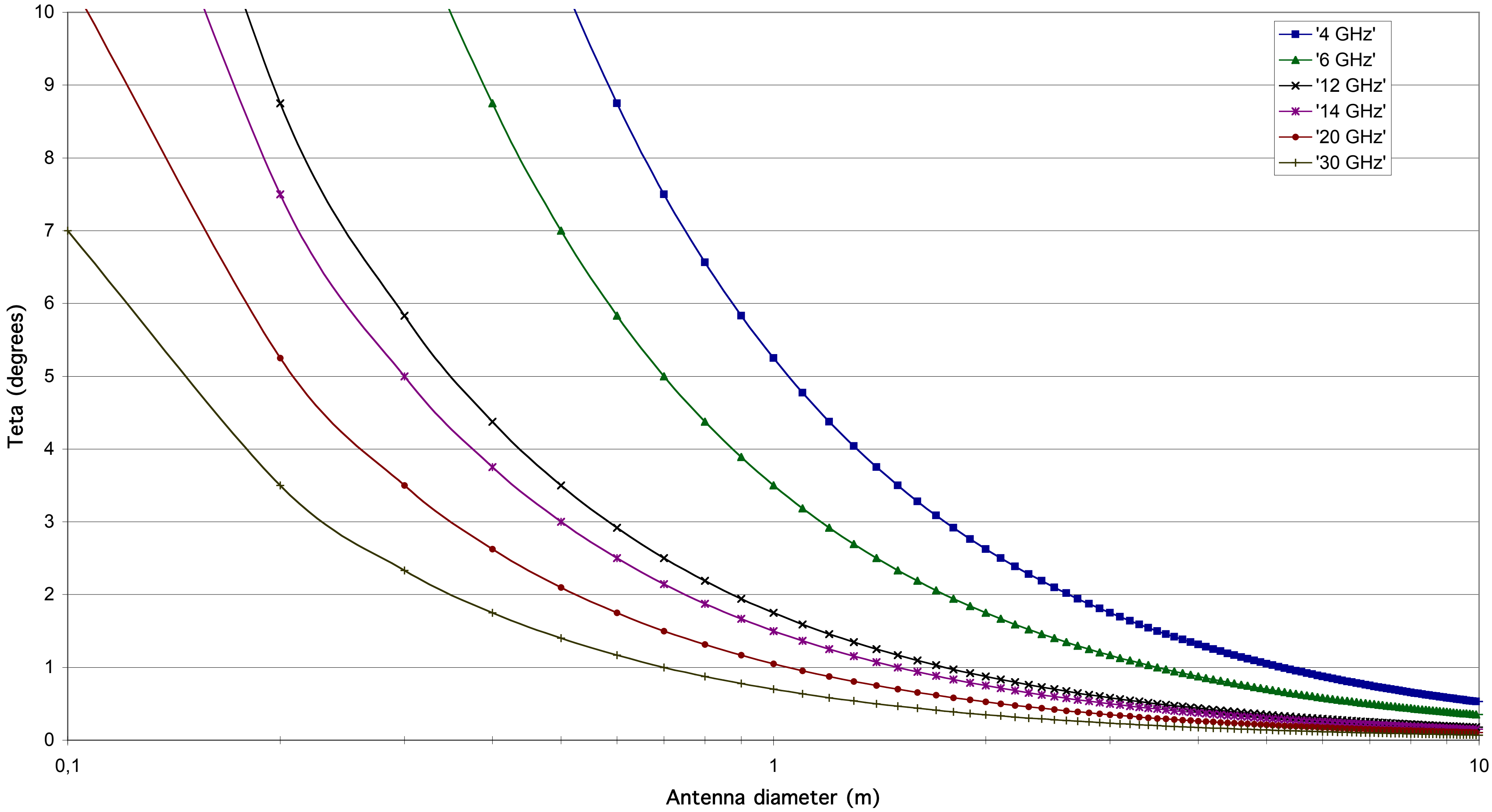
- Thus

$$G_{max} = \eta\ (\pi\ Df/c)^2 = \eta\ (\pi\ 70\ /\theta_{3dB})^2$$

Antenna radiation pattern characteristics



Teta 3dB


10
9
8
7
6
5
4
3
2
1
0
Teta (degrees)
0,1
1
10
Antenna diameter (m)
'4 GHz'
'6 GHz'
'12 GHz'
'14 GHz'
'20 GHz'
'30 GHz'

Characteristic Parameters of an Antenna (3)

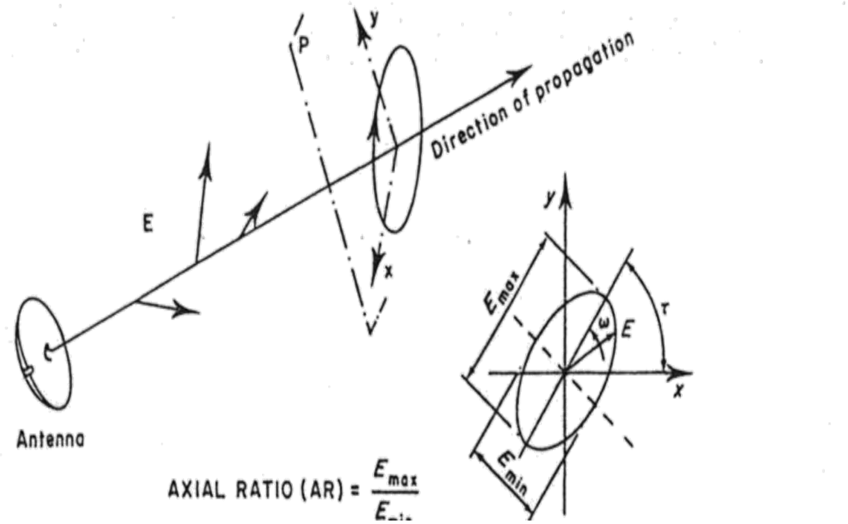
- **Polarisation,** convention is defined by the direction of the electric field. In general the direction of electric field is not fixed during one period, the extremity of the vector of e.f. describes an ellipse. Polarisation is characterized by:

Direction of rotation

Axial ratio = E $_{max}$ / E $_{min}$

Inclination of ellipse

- Two waves are in orthogonal polarisation if their electric fields describe identical ellipses in opposite directions.
- Orthogonal polarisations:
  - Circular: RHCP - LHCP
  - Linerar: HP - VP



Emitted Power

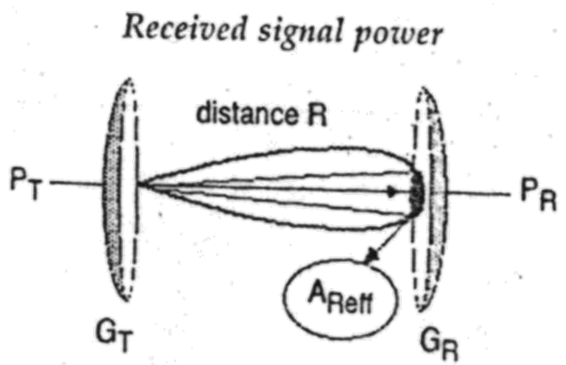
- Power radiated per unit solid angle by an isotropic antenna fed from a radio-frequency source of power P_t

  $$P_t/4\pi \quad \text{(W/steradian)}$$

  for a gain G_t any antenna radiates a power per unit solid angle equal to:

  $$G_t P_t / 4\pi$$

  The product $G_t P_t$ is called EIRP (Effective Isotropic Radiated Power)



Received Power

- A surface of area A located at a distance R from the transmitting antenna subtends a solid angle A/R^2 and receives a power:

$$P_r = (P_t G_t / 4\pi) A/R^2 = \Phi A \quad (W)$$

Φ: power flux density (W/m^2)

- A receiving antenna of effective aperture area A_{reff} located at distance R from the transmitting antenna receives the power

$$P_r = \Phi A_{Reff} = (P_t G_t / 4\pi R^2) A_{Reff}$$

with $$A_{Reff} = G_r / (4\pi/\lambda^2)$$

$$\mathbf{P_r = P_t G_t G_r / L_{fs}}$$

$L_{fs} = (4\pi R/\lambda)^2$ free space loss
(ratio of received and transmitted powers in a link with isotropic antennas)

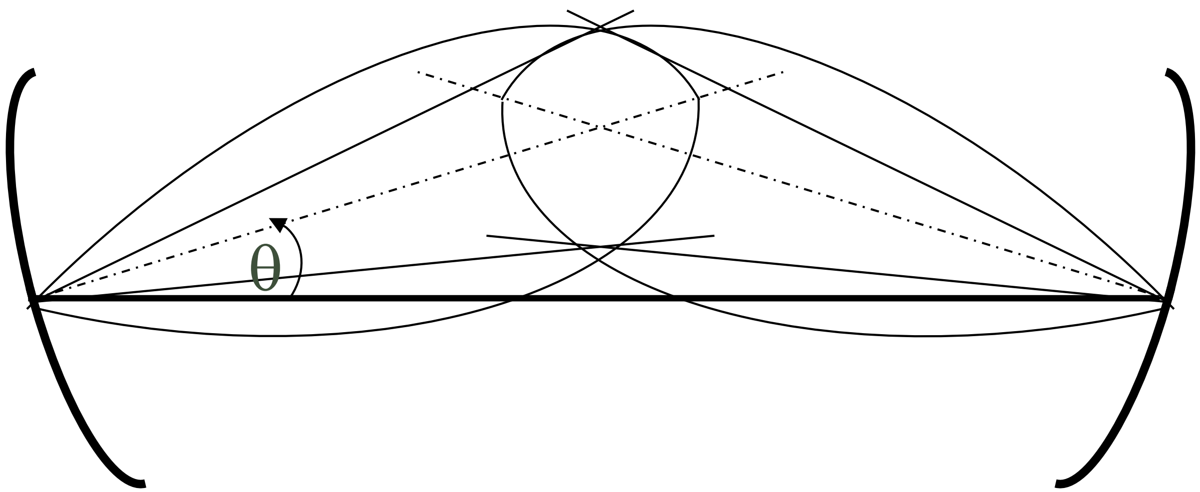
Other losses

- Transmitting and receiving losses due to waveguides
- Pointing losses
- Atmospheric losses (when applicable)
  - rain
  - clouds
  - gas (water vapour and oxygen)
  - tropospheric scintillation
- Polarization losses
- Mobile channel losses (when applicable)

$$L = L_{tx} + L_{rx} + L_p + L_a + L_{pol} + L_m$$

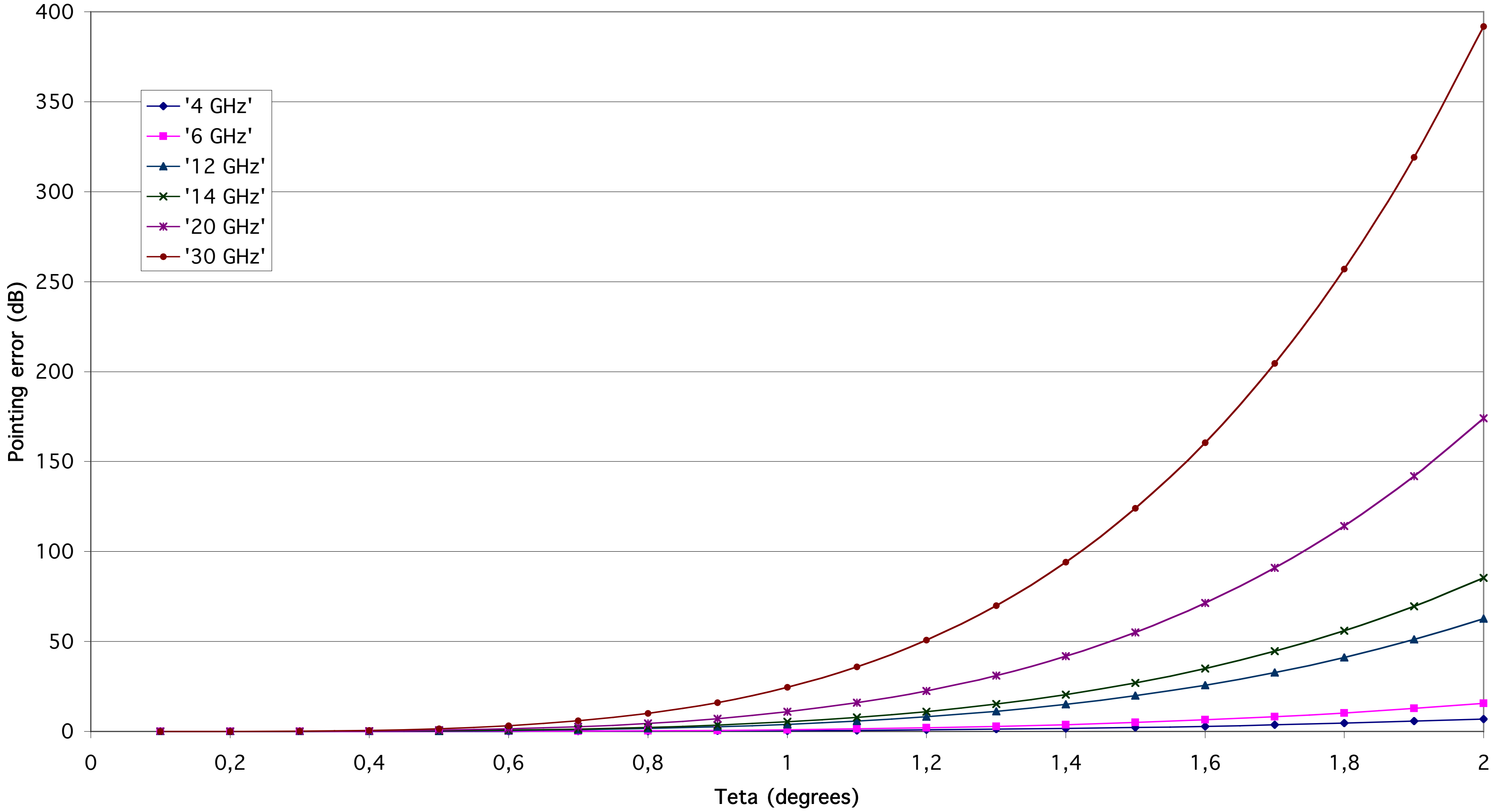
Pointing error

- The movement of the satellite causes the misalignment of the boresights of the two antennas
- It can be evaluated with the following formula:



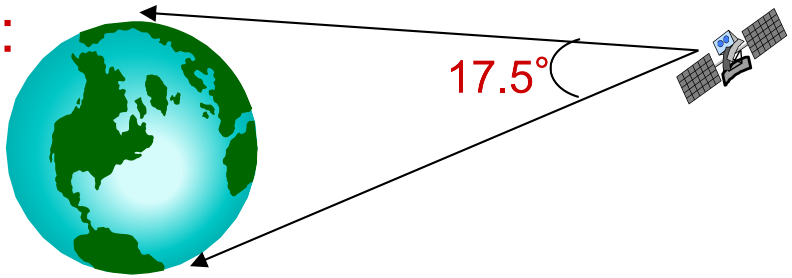
$$\varepsilon = 12\left(\frac{\theta}{\theta_{3dB}}\right)^2 dB$$

Pointing error plot



Antenna Noise Temperature: Satellite (uplink)

- Noise captured: earth and outer space
- Aiming the beam at covering only portions of the Earth the noise is mainly due to the Earth (excluding sidelobes)
- For GEO with $\theta_{3dB} < 17.5°$ the antenna noise temperature depends on:
  - Frequency
  - Orbital position
  - Area covered (oceans radiate less noise than land masses)

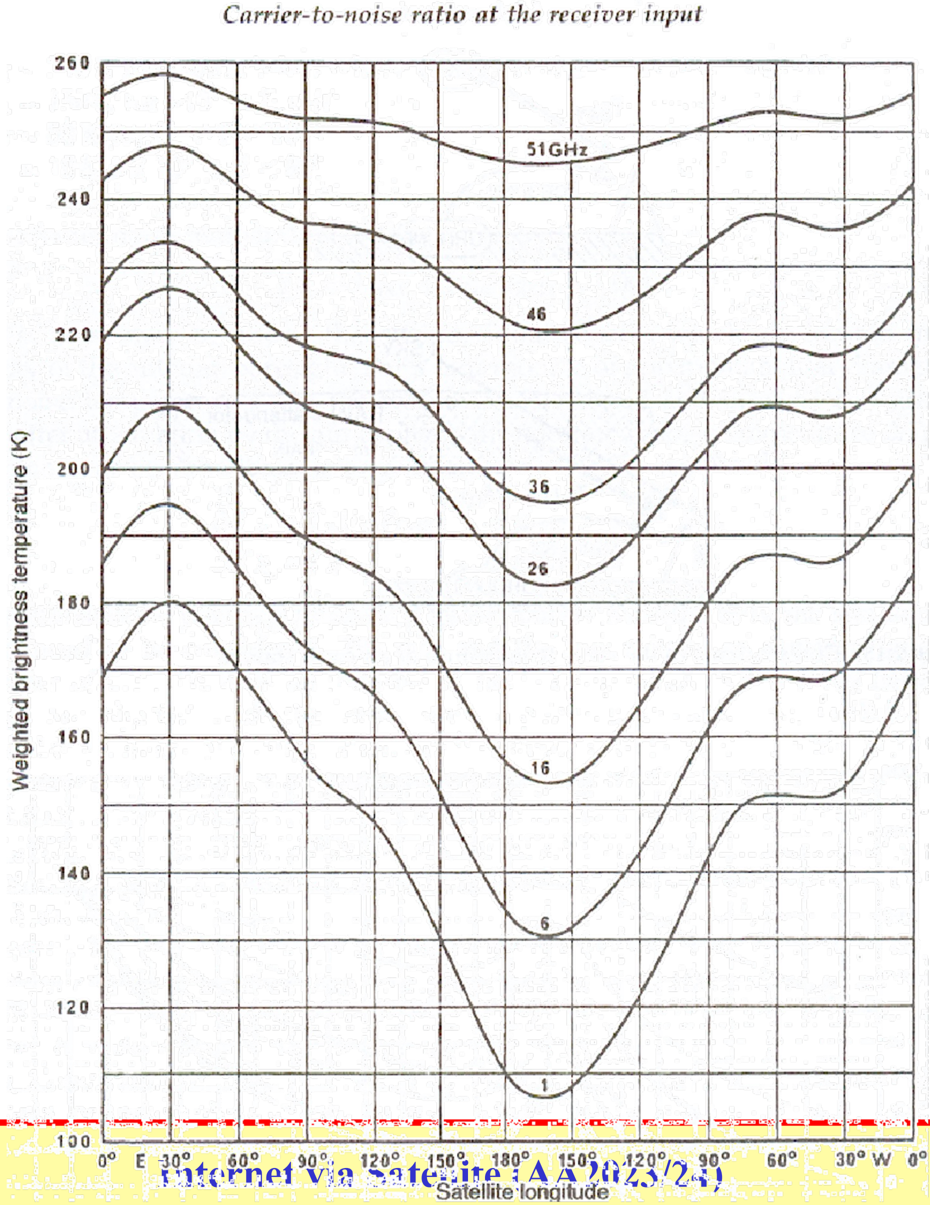


- 290 K is usually taken as conservative value

$$T_A = \left(\frac{1}{4\pi}\right) \int\int T_b(\theta, \varphi) G(\theta, \varphi) sin\theta d\theta d\varphi \qquad \text{K}$$

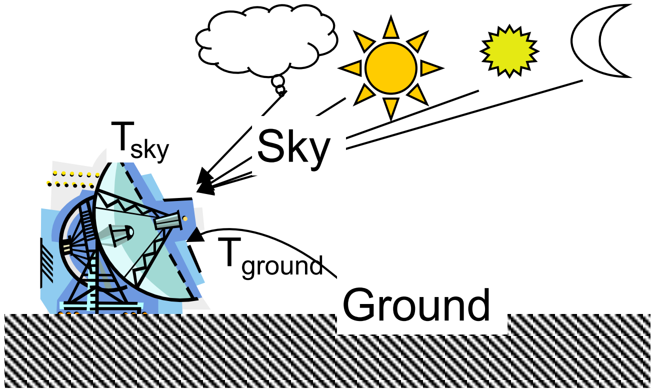
- T_b brightness temperature of the sky in (θ, φ) direction

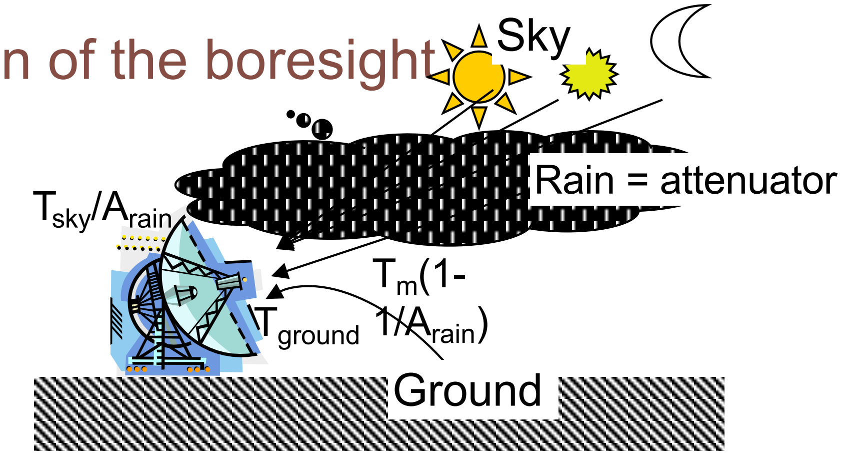
Brightness Temperature vs Longitude



Antenna Noise Temperature: Earth Station (downlink) Clear Sky

- Two sources: **SKY** and **EARTH**
  - Sky (atmosphere), in the direction of the boresight

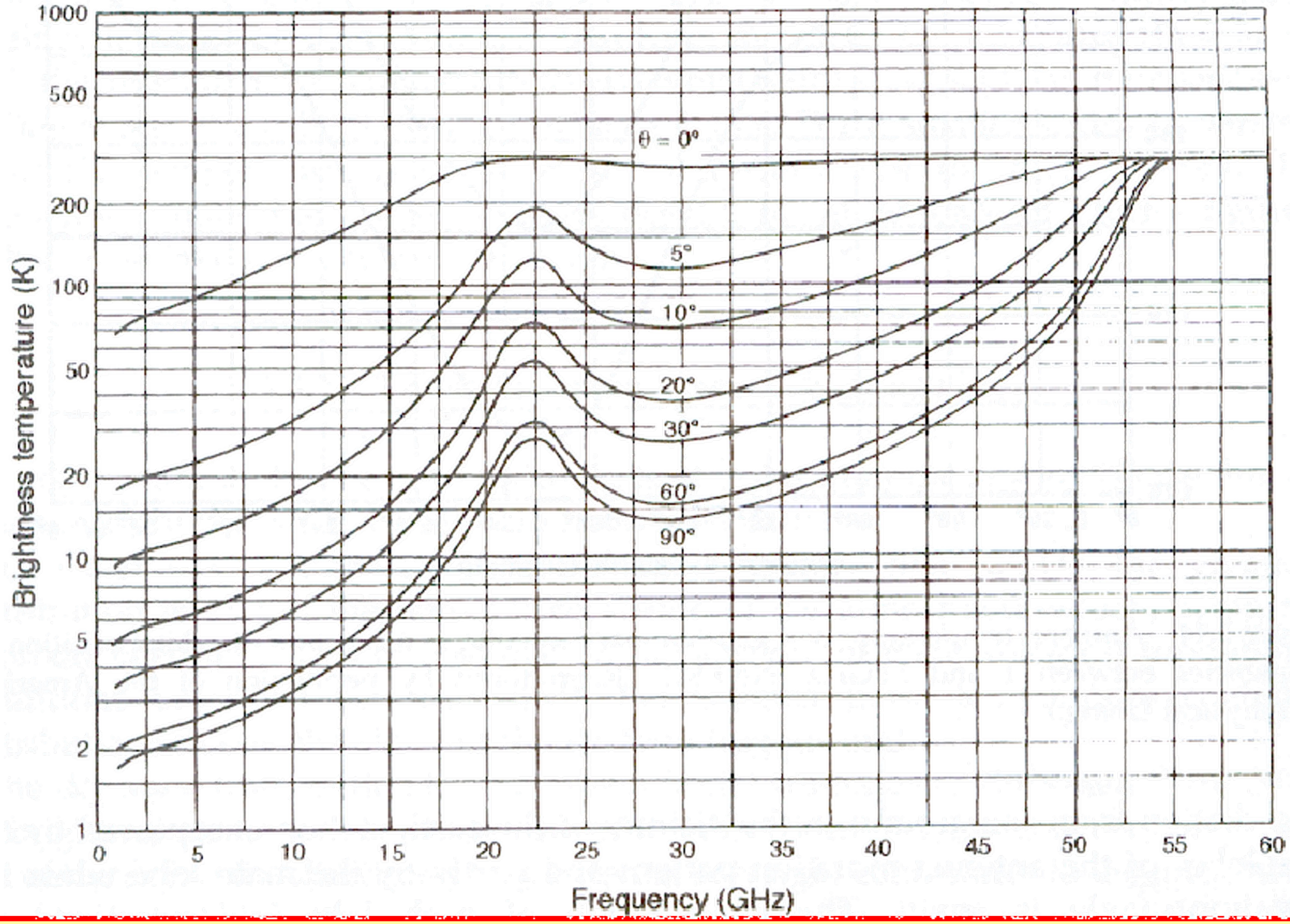




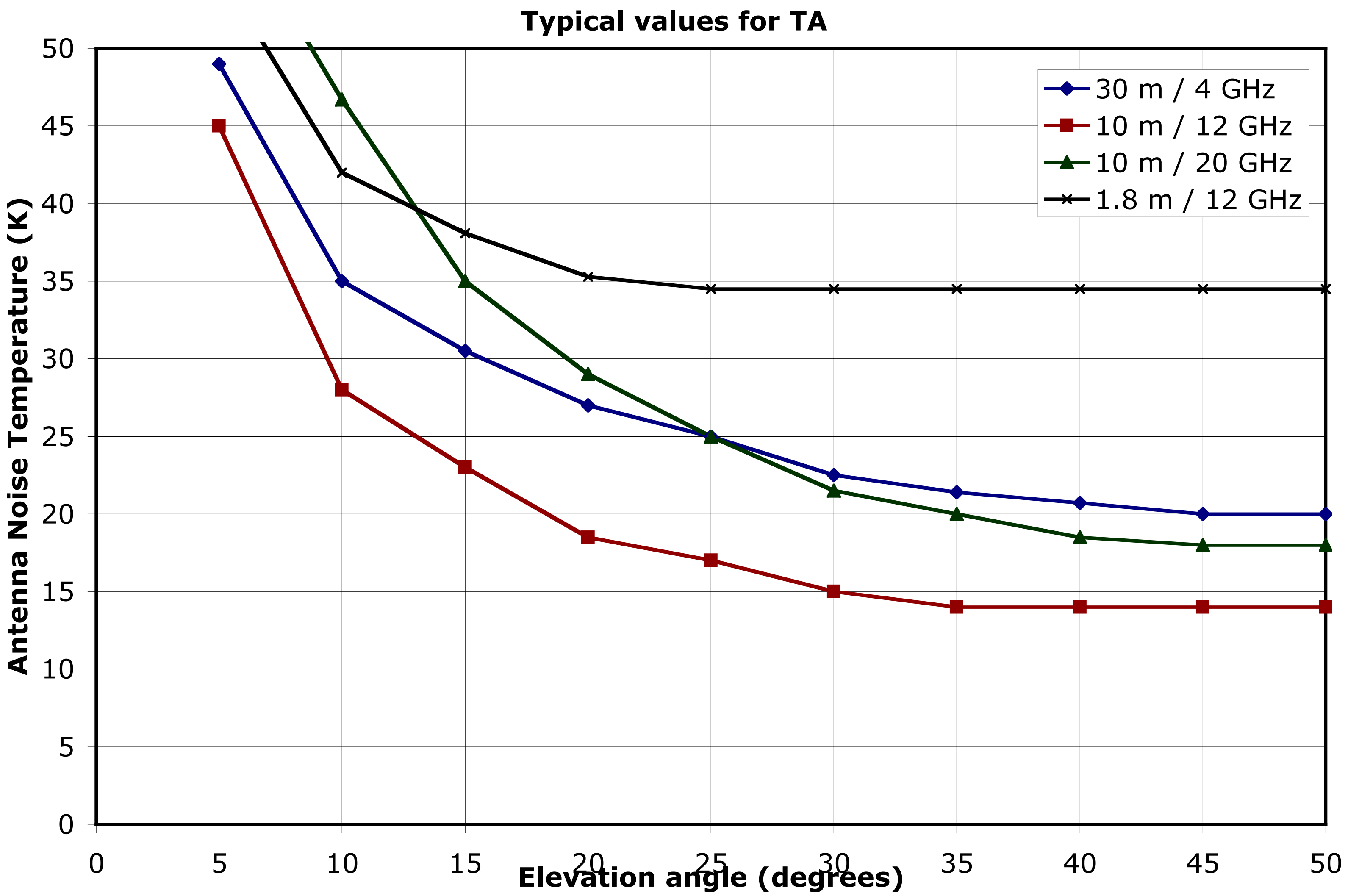
  - Radiation from the surrounding ground captured by the sidelobes (partly mainlobe for small elevation angle)
- $T_A = T_{sky} + T_{ground}$ (K)

T_G (K)	E (°)
290	<-10
150	-10↔0
50	0↔10
10	10↔90

Brightness Temperature vs Frequency and angle



T_A values in clear Sky



Antenna Noise Temperature: Earth Station (downlink) Rain

- As attenuation increases, so does emission noise. For earth stations with low-noise front-ends, this increase of noise temperature may have a greater impact on the resulting signal-to-noise ratio than the attenuation itself.

$$T_A = \mathrm{T}_{\mathrm{Sky}}/\mathrm{A}_{\mathrm{Rain}} + T_m\,(1 - 10^{-A/10}) + \mathrm{T}_{\mathrm{Ground}}$$

T_s : sky-noise temperature (K) as seen by the antenna

A_{Rain} : path attenuation (dB)

T_m : effective temperature (K) of the medium (typically 275 K).

- The effective temperature depends on the:
  - contribution of scattering to attenuation
  - physical extent of clouds and rain cells
  - vertical variation of the physical temperature of the scatterers,
  - antenna beamwidth (to a lesser extent).

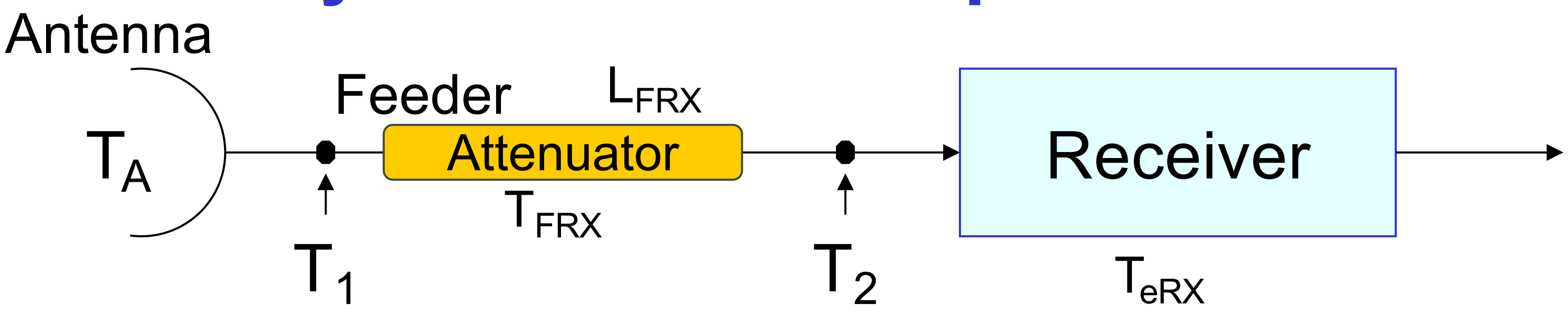
Noise Temperature (2)

- The effective temperature of the medium has been determined to lie in the range 260-280 K for rain and clouds along the path at frequencies between 10 and 30 GHz.
- When the attenuation is known, the following effective temperatures of the mediums may be used to obtain an upper limit to sky-noise temperature at frequencies below 60 GHz:

T_m = 280 K for clouds

T_m = 260 K for rain

System Noise Temperature



- The feeder introduces attenuation L_{FRX} at $T_F \approx T_0 = 290$ K
- T_{eRX} effective input noise of the receiver

$\Rightarrow T_1 = T_A + (L_{FRX}-1)T_{FRX} + T_{eRX}/G_{FRX}$ K (*)

$\Rightarrow T_2 = T_1/L_{FRX} = T_A/L_{FRX} + (1-1/L_{FRX})T_F + T_{eRX}$ K (**)

Thermal Noise

- Thermal noise characterized by power spectral density

$$N_0 = k\,T$$

  - k : Boltzman constant = $1.38 \cdot 10^{-23}$ Ws/K = -228.6 dBWs/K
  - T effective noise temperature

$$T = T_A + T_r$$

  - T_A: receiving antenna noise temperature
  - T_r: effective noise temperature of the receiver
- If noise figure N_r (dB) of the receiver is provided

$$T_r = (10^{N_r/10} - 1) \cdot 290 \text{ K}$$

Antenna	Noise Temperature (K)
Satellite	290
Earth terminal 90° elevation	3-10
Earth terminal 10° elevation	80

Signal to Noise Ratio: C/N & E_b/N_0

- $C = EIRP - L + G_R$ (dBW)

$$\frac{C}{N_0} = \frac{C}{kT} = \frac{P_t G_t}{L} \cdot \frac{G_R}{kT} = \frac{EIRP}{L} \cdot \frac{G/T}{k} \quad \text{(Linear units)}$$

- T given by (**)
- G/T figure of merit

$C/N_0 = P_t + G_t - L + G_R - k - T = EIRP - L + G/T - k$ dBHz

$C/N = C/(N_0 \cdot B_R)$ dB

- B_R noise equivalent bandwidth

$E_b/N_0 = (C/N_0) \cdot T_b = (C/N_0) \cdot (1/R_b)$ (Linear units)

$E_b/N_0 = C/N_0 - R_b = EIRP - L + G/T - k - R_b$ dB

Example 1: The uplink

- Antenna of an earth station with diameter D = 4m
- Antenna is fed with a power P = 100 W , 20 dBW, at a frequency f =14 GHz
- Antenna radiates this power towards a GEO satellite at a distance of 40000 km on the axis of antenna
- The beam of satellite receiving antenna has a width $\theta_{3dB} = 2°$
- Efficiency of the satellite antenna is $\eta = 0.55$ and of the earth station is $\eta = 0.6$

- **power flux density** at the satellite is $\Phi = P_t G_{tmax} / 4\pi R^2$
- **Gain of the earth station** is $G_{tmax} = \eta(\pi D / \lambda)^2 = 53.1$ dBi
- **Effective isotropic radiated power of earth** is

  $EIRP = P_t G_{tmax}$ = 53.1dBi + 20 dBW = **73.1** dBW

  Then the power flux density is -89.9 dBW/m^2
- The **power received by the satellite** is obtained using the follow

  equation: P_r= EIRP – attenuation of free space + gain of rx antenna

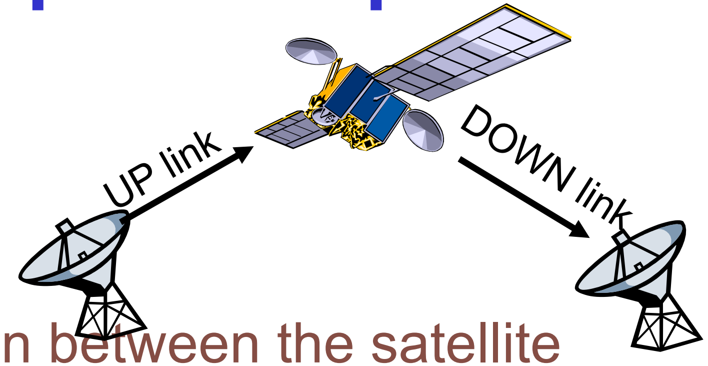
  L_{fs} = **207. 4** dB ; $G_{rmax} = \eta(70\pi/\theta)^2$ = 6650 = **38.2** dBi with a final value of power received of **-96.1** dBW

Example 2: The downlink

- Satellite antenna of GEO fed with P_t = 10 W, that is 10 dBW at frequency f = 12 GHz
- Beamwidth of 2°
- The same distance of previous example, and the same efficiency for the satellite and the earth station.

- **power flux density** at earth station $\Phi = P_t G_{tmax} / 4\pi R^2$
- **gain of satellite antenna** G_{tmax} = 38.2 dBi and **effective isotropic radiated power** EIRP = 10 dBW + 38.2 dBi = **48.2** dBW with a power flux density of –114.8 dBW/m^2
- L_{fs} = **206.1** dB, $G_{rmax} = \eta(70\pi/\theta)^2$ = 151597 = **51.8** dBi
- The **power received** by antenna of the earth station is obtained using the same expression of example 1 with a final value of **-106.1** dBW

Expression of $(C/N_0)_T$ for transparent repeater



Without interference or intermodulation

- $(N_0)_T = (N_0)_D + G(N_0)_U$ (W/Hz)
  - $G = G_{SR}G_TG_R/(L_{FTX}L_DL_{FRX})$ total power gain between the satellite receiver input and the earth station receiver input
    - G_T/L_{FTX} satellite tx antenna gain (including gain fallout and loss from the output of the power amplifier to the tx antenna)
    - G_R/L_{FRX} receiver station composite gain
    - L_D downlink path loss
    - G_{SR} satellite repeater gain
- $(C/N_0)_T^{-1}=(N_0)_T/C_D=[(N_0)_D+G(N_0)_U]/C_D=(N_0)_D/C_D+(N_0)_U/G^{-1}C_D$ (Hz^{-1})
  - $G^{-1}C_D$ = power at the satellite receiver input $\Rightarrow (N_0)_U/G^{-1}C_D = (C/N_0)_U^{-1}$
- $(C/N_0)_T^{-1}= (C/N_0)_U^{-1}+(C/N_0)_D^{-1}$ (Hz^{-1})

Expression of $(C/N_0)_T$ for transparent repeater (2)

With interference

- $N_0 = (N_0)$ without interference + $(N_0)_I$ (W/Hz)
- $[(N_0)_{wI} + (N_0)_I]/C = (N_0)_{wI}/C + (N_0)_I/C$
- $(C/N_0)_T^{-1} = (C/N_0)_U^{-1} + (C/N_0)_D^{-1} + (C/N_0)_{UI}^{-1} + (C/N_0)_{DI}^{-1}$ (Hz^{-1})

With interference and intermodulation

- $N_0 = (N_0)$ without interference + $(N_0)_I$ + $(N_0)_{IM}$ (W/Hz)
- $(C/N_0)_T^{-1} = (C/N_0)_U^{-1} + (C/N_0)_D^{-1} + (C/N_0)_I^{-1} + (C/N_0)_{IM}^{-1}$ (Hz^{-1})
- The value of $(C/N_0)_T$ is very close to the lowest value of its contributors. To improve $(C/N_0)_T$ it is worth to improve the lowest value.

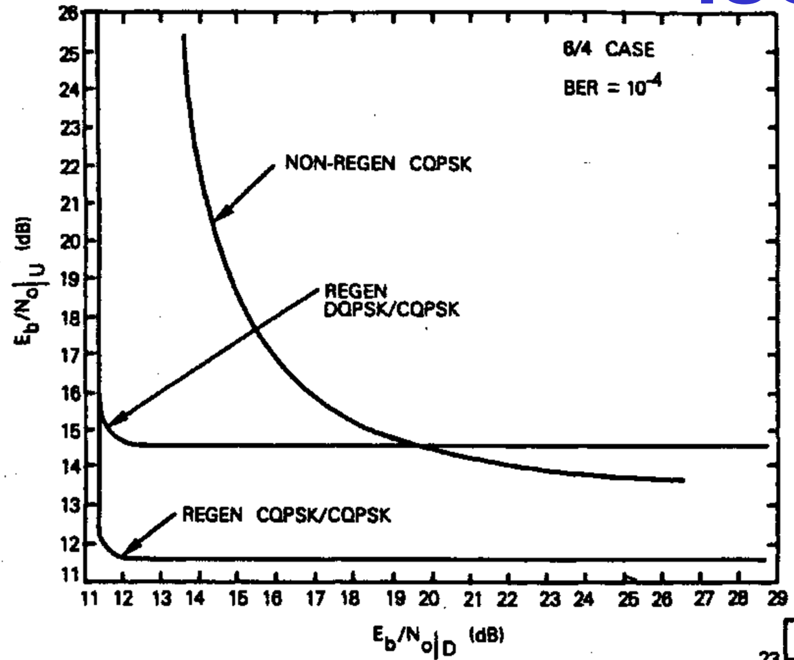
ISO-BER curves comparison

- Non regenerative link performance
  - $(E_b/N_0|_{up})^{-1} + (E_b/N_0|_{down})^{-1} = (E_b/N_0|_T)^{-1}$

- Regenerative link performance
  - $BER_{up} + BER_{down} = BER_T$

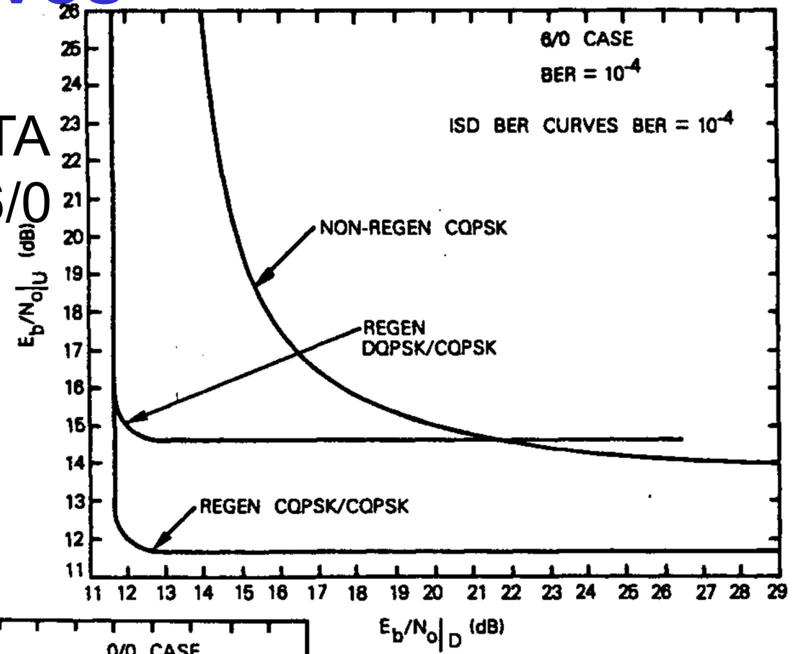
- Hypoteses:
  - CQPSK modulation, link degradation 1.8 dB, BER 10^{-4}, HPA/TWTA backoff 6/4, 6/0, 0/0

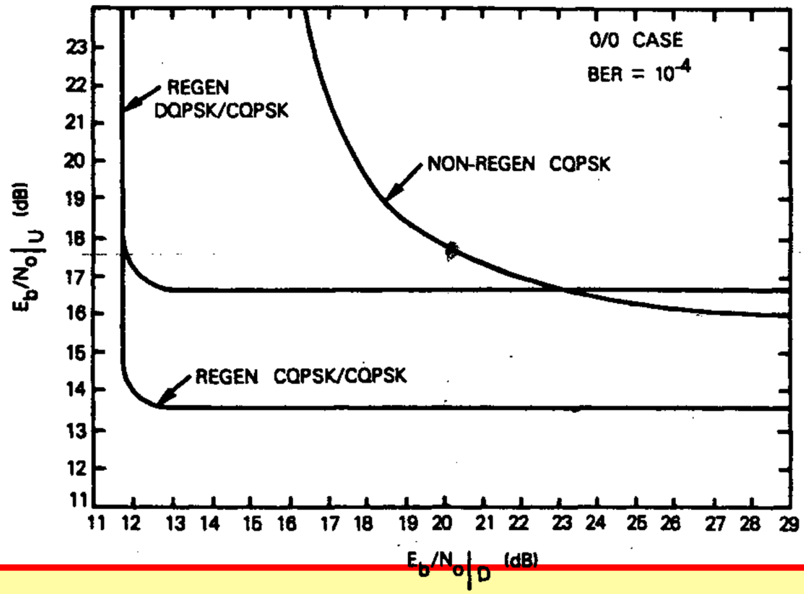
ISO-BER curves



HPA/TWTA backoff 6/4

HPA/TWTA backoff 6/0





HPA/TWTA backoff 0/0

Orbits and Frequencies: the Capacity Issue

Low Orbits

- *Low-Earth-Orbits*: an alternative to *Geostationary-Earth-Orbit* (GEO) for high capacity global systems
  - Capacity grows with d^{-2}
  - LEO/GEO capacity advantage is about $36^2 \approx 1300$

High Frequencies

- Traditional L band (frequency, f, about 1-2 GHz): low capacity
- New Ka band and beyond (20-30 GHz and higher): high capacity
  - Capacity grows with f^3
  - Ka/L capacity advantage is about $20^3 \approx 8000$

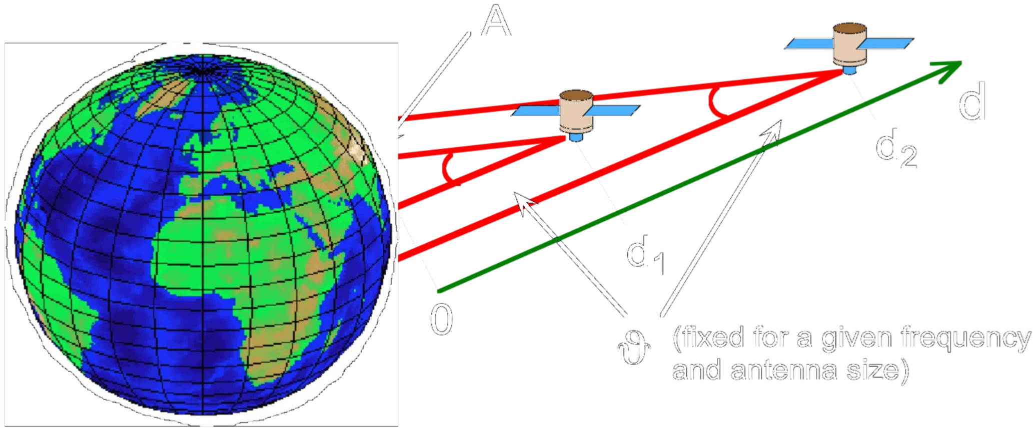
Low Orbits and High Frequencies

- Combing low orbits and high frequencies potentially provides a huge advantage
  - L-band GEO / Ka-band LEO capacity advantage
  - is 10 million times

Capacity Advantage as a Function of Satellite Altitude

Transmission capacity, C, can be expressed as: $\boxed{C \propto n}$

where $\propto$ means "proportional" and n is the number of "cells"



$\boxed{n \propto A^{-1}}$

$\boxed{A \propto d^2}$

$\boxed{n \propto d^{-2}}$ $\Rightarrow$ $\boxed{C \propto d^{-2}}$

For a given antenna size:

- A is the cell area
- ϑ is the angular width of the antenna beams
- d is the satellite altitude

Orbit Altitude Trade-offs

As H is reduced we have the following advantages:

- The footprint of each on board antenna spot is reduced
  - Reducing the footprint ("cell") brings a larger frequency reuse (with the inverse of the square of cell radius).
- The free-space loss (FSL) is reduced
  - Reducing the FSL allows to set less stringent requirements both on board the satellite and to the user terminal. Reducing the power per channel on board is a basic factor towards the optimum use of the spectrum (this is analogous to cellular systems).
  - To the low power of the terminal the benefits of low consumption and less radiation hazard are associated.
- The propagation delay is reduced
  - A short propagation delay allows more complex signal processing to contrast the channel impairments and/or allows the double-hop via satellite.

Capacity Advantage as a Function of Frequency

Transmission capacity, C, can be expressed as: $\boxed{C \propto B \cdot k}$

where $\boxed{B \propto f}$

– B is the available band

– k is the number of times B is reused

$\boxed{k \propto A^{-1}}$

$\boxed{A \propto \vartheta^2}$

$\boxed{\vartheta \propto f^{-1}}$

$\Rightarrow \boxed{k \propto f^2}$

$\boxed{C \propto f^3}$

For a given antenna size:
- A is the cell area
- ϑ is the angular width of the antenna beams