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# LINK BUDGET and FADE MITIGATION TECHNIQUES

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## CONTENT OF PRESENTATION

- LINK ANALYSIS and PERFORMANCES OBJECTIVES
- CARRIER POWER BUDGET and PROPAGATION IMPAIRMENTS
- NOISE POWER BUDGET and SYSTEM NOISE TEMPERATURE
- LINK PERFORMANCE
- FADE MITIGATION TECHNIQUES (FMT)
- FMT IMPLEMENTATION
- SYSTEM PERFORMANCE & CONCLUSION
- To probe further: "Satellite communications Systems", G. Maral & M. Bousquet, Wiley 4th ed 2002, reprinted Dec 2004

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## LINK ANALYSIS OBJECTIVES

*GIVEN A TRANSMITTER AND A RECEIVER :*

- **WHAT IS THE SIGNAL POWER RECEIVED FROM THE TRANSMITTER AT THE RECEIVER INPUT ?**
  - **This power is that of the modulated carrier : C (W)**
- **HOW LARGE IS THE CONTRIBUTION OF UNWANTED SIGNALS AT THE RECEIVER INPUT ?**
  - **The overall contribution can be considered as noise, with constant power spectral density : $N_0$ (W/Hz)**
- **HOW DOES THE LINK PERFORM ?**
  - **There are 2 aspects to that question :**
    - RF link performance, in terms of $C/N_0$ ratio
    - User's link performance, which depends on type of signals and modulation

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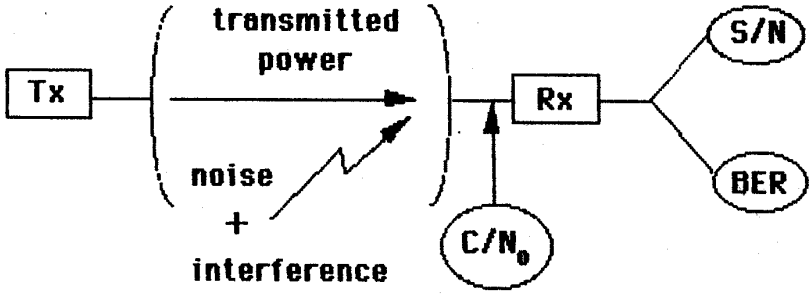
# LINK PERFORMANCE EVALUATION

- **RF LINK PERFORMANCE**
  - **Characterized by $C/N_0$ ratio at receiver (Rx) input, where :**
    - C : power of received carrier (W)
    - $N_0$ : Power Spectral Density of noise (W/Hz)




- **USER LINK PERFORMANCE**
  - **RF link performance conditions quality of baseband signal delivered to end user**

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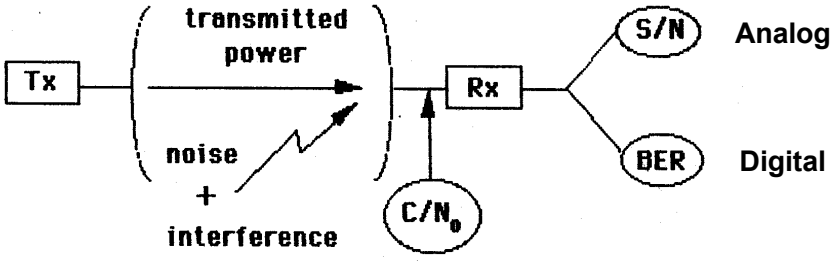
# PERFORMANCE MEASUREMENT AT USER'S END




- **ANALOG TRANSMISSION**
  - Link performance expresses in terms of signal-to-noise power ratio (S/N) at demodulator output
  - S/N is related to $(C/N_0)_T$ depending on the type of considered waveform

- **DIGITAL TRANSMISSION**
  - Link performance expresses in terms of Bit Error Probability (or BER)
  - BER is related to $(C/N_0)_T$ depending on Bit Rate & Coding and Modulation format

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## PERFORMANCE OBJECTIVES

- **SIGNAL QUALITY OBJECTIVES**
  - **In terms of thresholds which must not be exceeded for more than a given % of time**
    - Example: BER smaller than $10^{-6}$

- **SYSTEM AVAILABILITY OBJECTIVES**
  - **Asys = (required time - down time) / required time**

| | |
|---|---|
| **Required time :** | period of time during which the user required the link to be in condition to perform a required function |
| **Down time :** | cumulative time of link interruption within the required time |
| **Interruption :** | period of time during which there is : a complete or partial signal loss ***or*** excessive noise ***or*** a discontinuity or a severe signal distortion |

- **PROPAGATION TIME**
  - **The overall link propagation time should not exceed a maximum value which depends on the user's requirement**

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## SYSTEM AVAILABILITY

- **AVAILABILITY DEFINITION**
  - **AVAILABILITY ($A_{sys}$) implies quality objectives to be complied during a given time percentage (typically between 99 % and 99.9 %)**
  - **This requires the link $(C/N_0)_T$ ratio to be larger or equal to a specified value for the considered time percentage**
  - **$(C/N_0)_T$ ratio varies according to :**
    - **Propagation effects : attenuation (mainly rain), scintillation and depolarisation**
    - **Implementation losses : mainly antenna depointing or equipment failures**

- **SYSTEM AVAILABILITY :**

$$A_{sys} = A_{T_x} \cdot A_{sat} \cdot A_{link} \cdot A_{R_x}$$

where :
$A_{tx,Rx}$ : transmitting/receiving ES availability
$A_{sat}$ : satellite availability
$A_{link}$ : link availability

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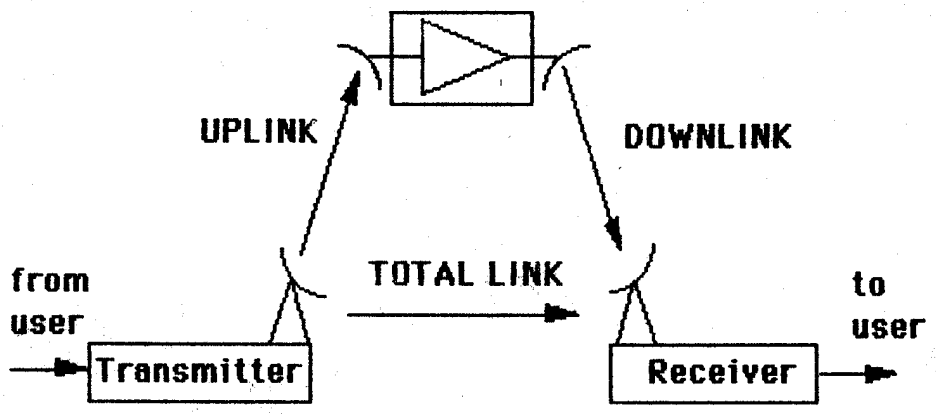
## LINK ARCHITECTURE




- TOTAL (OR OVERALL) RF LINK PERFORMANCE DEPENDS ON :
  - RF uplink performance
  - RF downlink performance

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# ANTENNA PARAMETERS : GAIN

## ❒ ANTENNA GAIN DEFINITION

➢ Ratio of the power per unit solid angle radiated/received by the antenna in a given direction, to the power per unit solid angle radiated/received by an isotropic antenna supplied by the same power

➢ Antenna gain is maximum @ boresight : $G_{\max} = \frac{4\pi}{\lambda^2} \cdot A_{eff}$

➛ where : $\lambda = C / F$ is the radiofrequency wavelength (m)

➛ and : $A_{eff}$ is the antenna effective aperture area ($m^2$)

## ❒ REFLECTOR ANTENNA

➢ Aperture : disc of diameter D whose area : $A = \frac{\pi D^2}{4}$

➢ Antenna effective aperture area : $A_{eff} = \eta \, . \, A$

$$\Longrightarrow \boxed{G_{\max} = \eta \left( \frac{\pi D}{\lambda} \right)^2}$$

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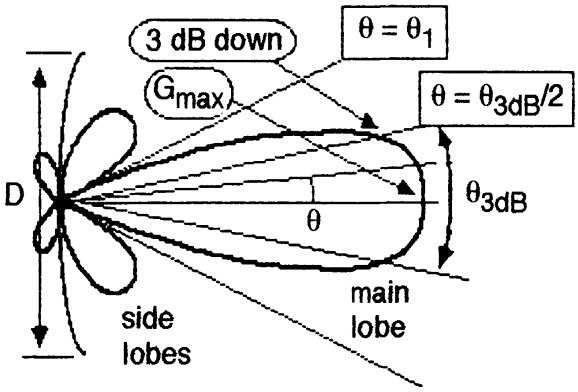
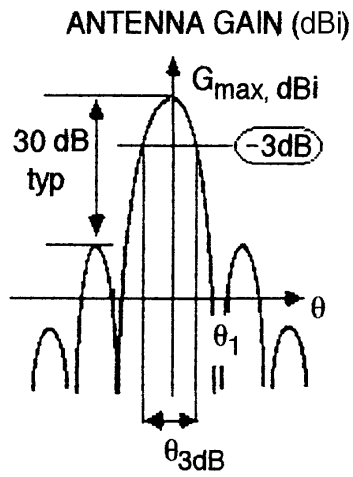
# ANTENNA PARAMETERS : RADIATION PATTERN

## ❒ DEFINITION

➢ Gain variation as a function of the angle $\alpha$ relative to boresight

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# ANTENNA PARAMETERS : RADIATION PATTERN

- **DEFINITION**
  - Gain variation as a function of the angle $\alpha$ relative to boresight

- **HALF POWER BEAMWIDTH**
  - $\theta_{3dB}$ : full angular width between the two directions where the gain is 3 dB below maximum (°) :

$$\theta_{3dB} \approx 70 \cdot \frac{\lambda}{D}$$

- **GAIN VARIATION**
  - For small off-axis angle $\alpha$ :

    where : $G_{max,dB}$ = 10 LOG ($G_{max}$)

$$G(\alpha)_{dB} = G_{\max,dB} - 12\left(\frac{\alpha}{\theta_{3dB}}\right)^2$$

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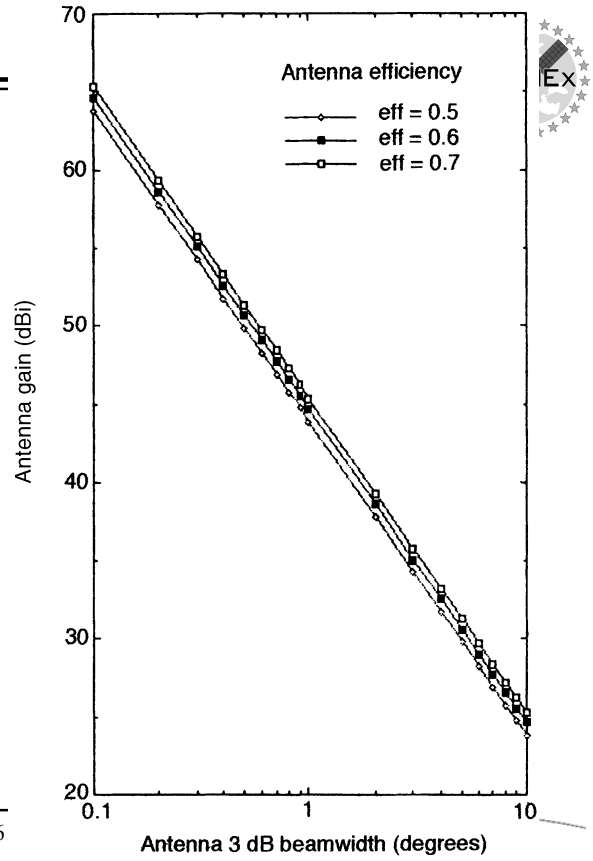
# GAIN VS BEAMWIDTH

$$G_{\max} = \eta\left(\frac{\pi D}{\lambda}\right)^2$$

$$\theta_{3dB} \approx 70 \cdot \frac{\lambda}{D}$$

$$G_{\max} = \eta\left(\frac{70\pi}{\theta_{3dB}}\right)^2 = \frac{48360 \cdot \eta}{\theta_{3dB}^{\ 2}}$$

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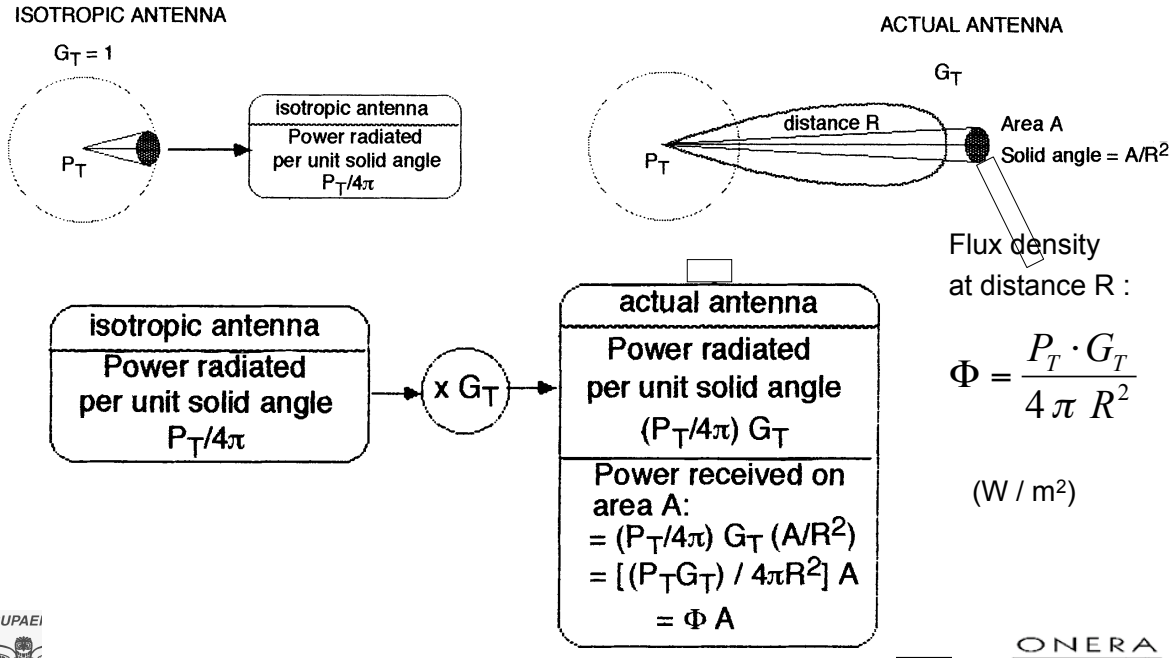
## TRANSMITTED POWER IN A GIVEN DIRECTION




Flux density at distance R :

$$\Phi = \frac{P_T \cdot G_T}{4\,\pi\ R^2}$$

(W / m²)

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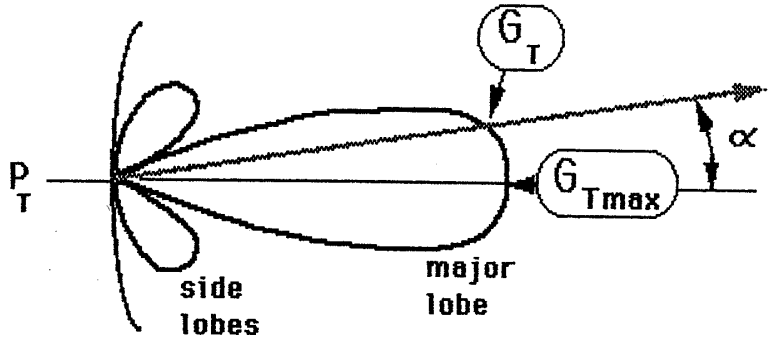
## RADIATED POWER : EIRP




❒ Effective Isotropically Radiated Power in the considered direction α

$$EIRP = P_T \cdot G_T$$

➢ where : $P_T$ : power fed to the antenna
$G_T(\alpha)$ : antenna gain at angle α

➢ Maximum EIRP is at boresight (α = 0) : **Max (EIRP) = $P_T.G_{Tmax}$**

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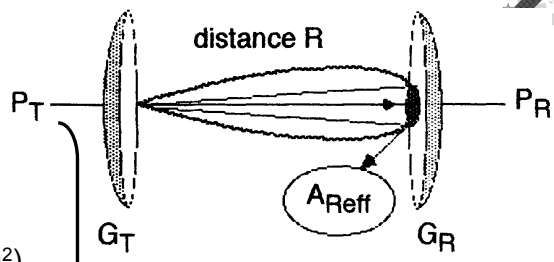
## CARRIER POWER BUDGET: SINGLE LINK




Effective Isotropically Radiated Power :

$$EIRP = P_T \cdot G_T$$

Tx Flux density @ distance R : $\Phi = \dfrac{P_T \cdot G_T}{4\pi R^2}$ (W/m²)

Rx Flux density : $\Phi = \dfrac{P_R}{A_{Reff}}$ (W)

Rx antenna gain : $G_R = \dfrac{4\pi \cdot A_{Reff}}{\lambda^2} \Leftrightarrow A_{Reff} = \dfrac{\lambda^2}{4\pi} \cdot G_R$

$$P_R = \frac{P_T \cdot G_T}{4\pi R^2} \cdot \frac{\lambda^2}{4\pi} \cdot G_R$$

$$\boxed{P_R = \frac{EIRP \cdot G_R}{L_{FS}}}$$

Free space attenuation : $L_{FS} = \left(\dfrac{4\pi R}{\lambda}\right)^2$ (dB)

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## POWER BUDGET : FREE SPACE LOSS

$$L_{FS} = \left(\frac{4\pi R}{\lambda}\right)^2$$

$$E_{sat} = Arctg\left(\frac{\cos(\varphi) - \dfrac{R_0}{R_0 + R_{sat}}}{\sqrt{1 - \cos(\varphi)^2}}\right)$$

$$R = (R_{sat} - H_{st}) \times \sqrt{1 + 2 \cdot \frac{R_0}{R_{sat} - H_{st}} \cdot \left[1 + \frac{R_0}{R_{sat} - H_{st}}\right] \cdot [1 - \cos(\varphi)]}$$

where $\cos\phi = \cos L_{st} \times \cos L_{sat} \times \cos |G_{st} - G_{sat}| + \sin L_{st} \times \sin L_{sat}$

with

| | | |
|---|---|---|
| $lat_{st}$, $G_{st}$, $H_{st}$ : | latitude, longitude & altitude of the Earth station | |
| $G_{sat}$, $R_{sat}$ : | longitude & altitude of the satellite | (35786 km) |
| $R_0$ : | Earth radius | (6378 km) |

GEO sat. : $\cos(\varphi) = \cos(L_{st}) \cdot \cos|G_{st} - G_{sat}|$

$$d_{sat} \approx R_{sat} \times \sqrt{1 + 0.42 \cdot [1 - \cos(\varphi)]}$$

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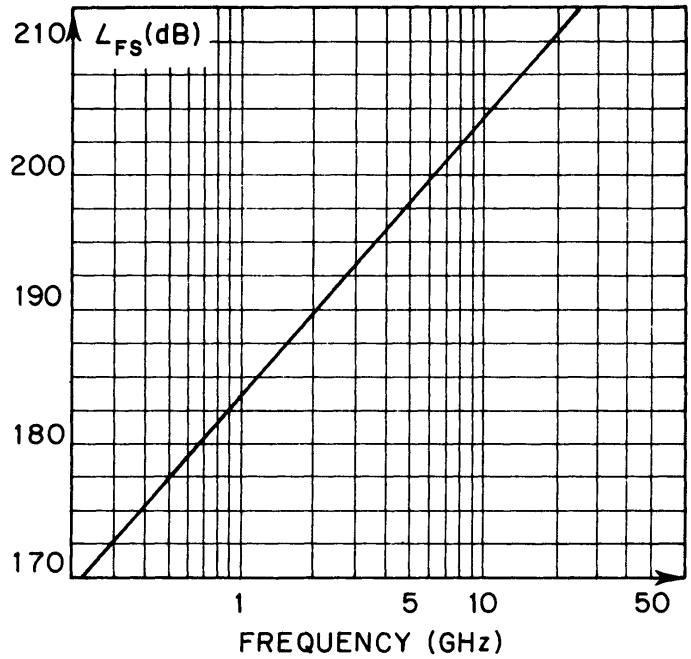
## POWER BUDGET : FREE SPACE LOSS

$$L_{FS} = \left( \frac{4\pi\ R}{\lambda} \right)^2$$

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## POWER BUDGET : PROPAGATION LOSS

- **PROPAGATION ISSUES**
  - **Ionospheric effects : important for frequencies lower than 5 GHz**
  - **Tropospheric effects : dominant for frequencies higher than 10 GHz**

- **ATTENUATION EFFECTS**
  - **Gas attenuation : dry air (oxygen) and water vapour**
  - **Hydrometeor attenuation : clouds, rain and melting layer**
  - **Scintillation : clear sky conditions, with clouds, during rain**

- **INFLUENCE ON SATELLITE LINK**
  - **Strong impairments : $A_{tot} = A_{gaz} \cdot A_{rain}$**
  - **Lower availability when frequency increases**

$$P_R = \frac{EIRP \cdot G_R}{L_{FS} \cdot A_{tot}}$$

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# RAIN ATTENUATION

❒ **ATTENUATION THROUGH A PRECIPITATION OF LENGTH L :**

**where $\gamma(x)$ : specific attenuation [dB/km]**

$$A = \int_0^L \gamma(x) \cdot dx$$

❒ **SPECIFIC ATTENUATION :** $\gamma = k R^{\alpha}$ **see Rec. ITU-R P.838**

**where k and $\alpha$ : coefficients, frequency and polarisation dependent**

❒ **TOTAL SLANT PATH ATTENUATION**

**in most of the statistical models : see Rec. ITU-R P.618**

$$A = \frac{\gamma \cdot L}{\sin E_{sat}}$$

**$L_{001} = f(L_{ES}, E_{sat}, h_r, R_{001}, F, \gamma_{001})$**

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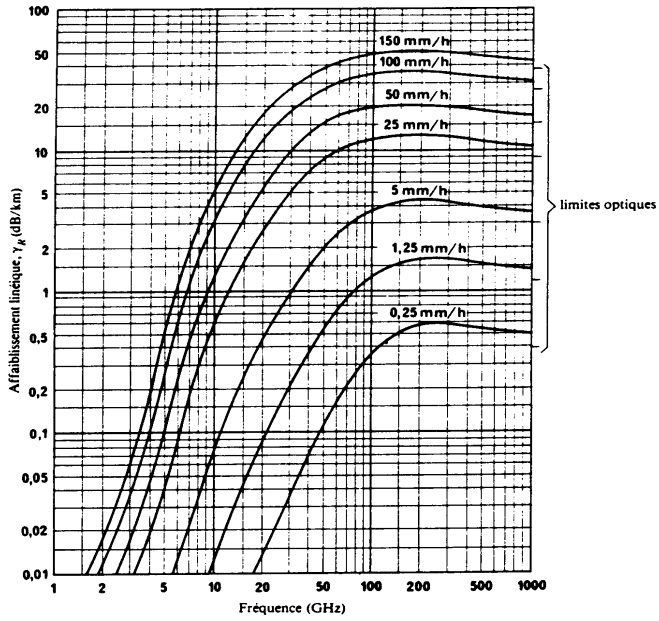
# RAIN ATTENUATION




❒ **RAIN SPECIFIC ATTENUATION**

**Rec. ITU-R P.838**

➢ $\gamma = k R^{\alpha}$ **[dB/km]**

➢ **with $(k,\alpha) = f(F,\tau, E_{sat})$**

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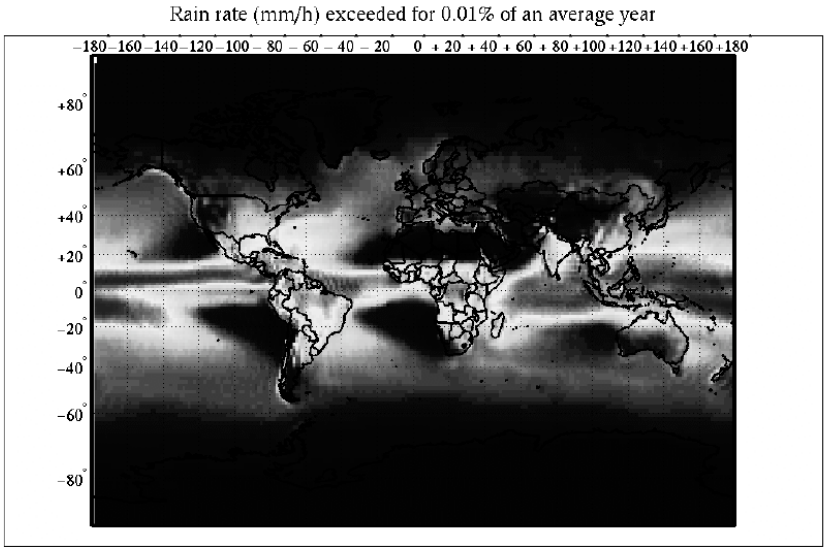
# RAIN ATTENUATION

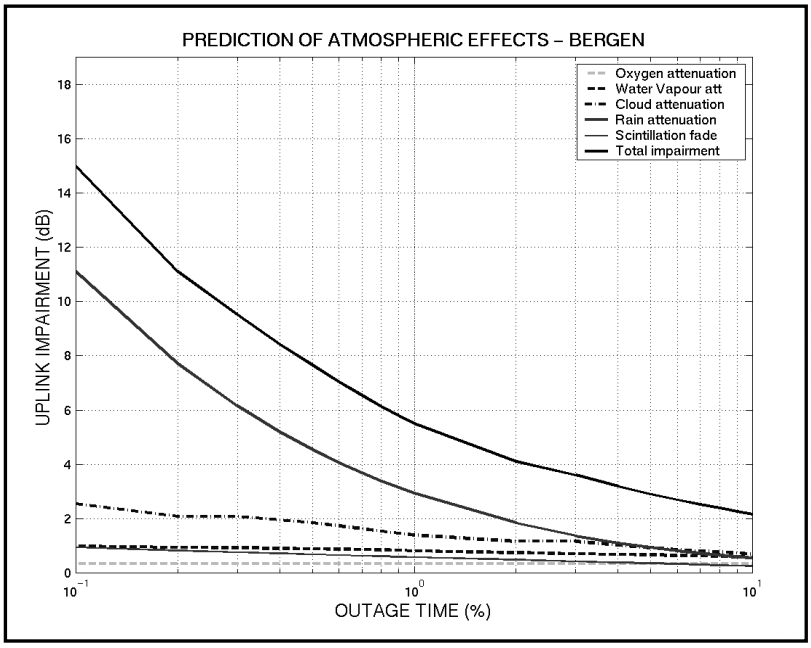


❒ **CLIMATIC DEPENDENCE**

- ➢ Attenuation ➚ when RR ➚
- ➢ Map of rain rate exceeded for 0.01 % of an average year
- ➢ Rec. ITU-R P.837

# TOTAL ATTENUATION

Predictions performed with Rec. ITU-R P.618




**Total impairment @ 30 GHz**

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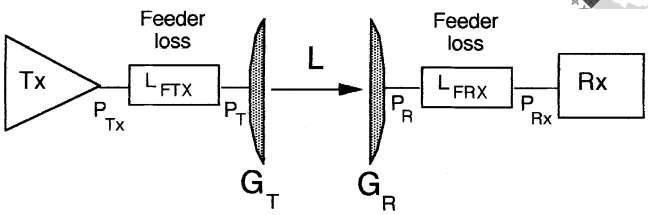
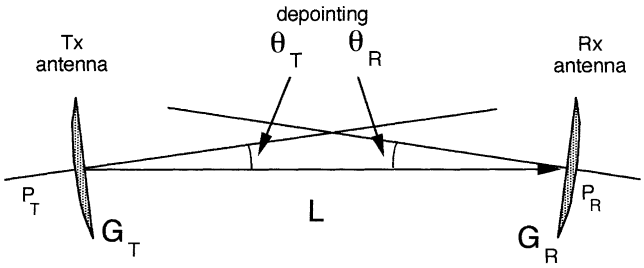
# POWER BUDGET : IMPLEMENTATION LOSSES

- **FEEDER LOSSES :**
  - **EIRP = $P_T.G_T = (P_{Tx}.G_T) / L_{FTx}$**




- **ANTENNA MISPOINTING**
  - **Antenna gains in the Tx-Rx direction :**
    - **$G_T = G_{Tmax} / L_T$**
      **where $L_T$ (dB) = 12 . $(\alpha_T / \theta_{3dB})^2$**
    - **$G_R = G_{Rmax} / L_R$**
      **where $L_R$ (dB) = 12 . $(\alpha_R / \theta_{3dB})^2$**




- **POLARIZATION MISMATCH**

**Losses caused by possible polarization mismatch between Tx & Rx antennas**

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# ORIGIN OF NOISE

## ❒ DEFINITION OF NOISE

➢ **All unwanted contributions of energy at the input of the receiver which tend to corrupt the useful signal**

## ❒ ORIGIN OF NOISE

➢ **Radiation from radiating bodies located within the antenna lobe i.e. :**

- for satellite antennas : the Earth
- for Earth station antennas : - galactic & cosmic sources,
  - atmospheric phenomena
  - ground in sidelobes radiation pattern

➢ **Noise generated within the receiver components**

➢ **Interference from other transmitters**

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# NOISE CHARACTERISATION

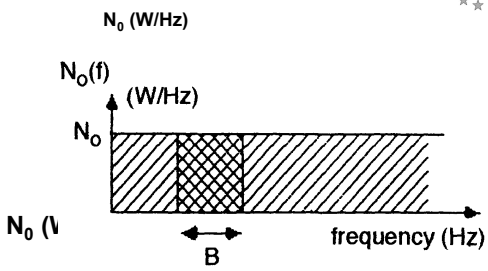
## ❒ NOISE POWER SPECTRAL DENSITY :

➢ **$N_0(f)$ : amount of noise power per unit of bandwidth**

➢ **If $N_0(f) = C^{te} = N_0$ ⇨ White Noise**

➢ **given N = Noise power (W) measured in bandwidth B (Hz) :**

$$N_0 = \frac{N}{B}$$

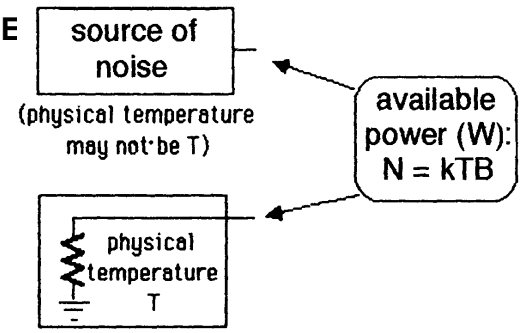



## ❒ NOISE TEMPERATURE T OF A NOISE SOURCE

$$N_0 = kT$$

➢ **where T : t° of a passive system (e.g. resistor) which would generate the <u>same</u> amount of noise as the considered source of noise**

➢ **k : Boltzman constant = 1.379 . $10^{-23}$ W/K.Hz**
**= - 228.7 dBW/K.Hz**

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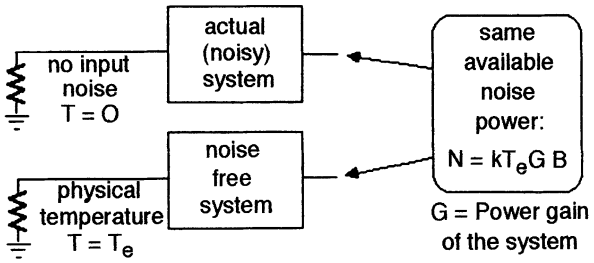
# EFFECTIVE INPUT NOISE TEMPERATURE – NOISE FIGURE

## ❒ EFFECTIVE NOISE TEMPERATURE OF A SYSTEM : Te (K)

➢ $T_e$ : noise t° of a source at the input of the system (considered as noise-free) that produces the same contribution to the system output noise as the internal noise of the actual system itself




## ❒ NOISE FIGURE : F

➢ Ratio of the total system noise power to that part of the system output noise power generated by an input source at the reference t° : $T_0$ = 290 **K**

$$F_{dB} = 10\ LOG\left(F\right) = 10\ LOG\left(1 + \frac{T_e}{T_0}\right) \quad \Leftrightarrow \quad T_e = \left(F - 1\right)\cdot T_0$$

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# SYSTEM NOISE TEMPERATURE

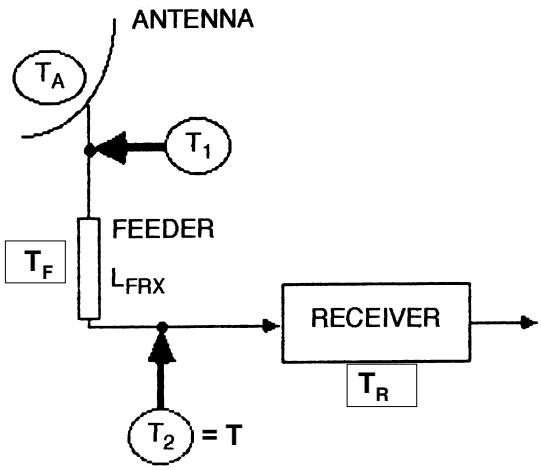
## ❒ CONTRIBUTIONS TO SYSTEM NOISE TEMPERATURE

➢ **Noise from the antenna**
➢ **Noise generated from feeder losses**
➢ **Noise generated within the receiver**

## ❒ SYSTEM NOISE T° CALCULATION AT THE INPUT OF THE RECEIVER

$$\frac{T_1}{L_{FRX}} = \boxed{T_2 = \frac{T_A}{L_{FRX}} + T_F\left(1 - \frac{1}{L_{FRX}}\right) + T_R}$$

➣ T : system noise t°
➣ $T_A$ : antenna noise t°
➣ $T_F$ : t° of feeder (room t°)
➣ $T_R$ : receiver effective input noise t°
➣ $L_{FRX}$ : feeder loss

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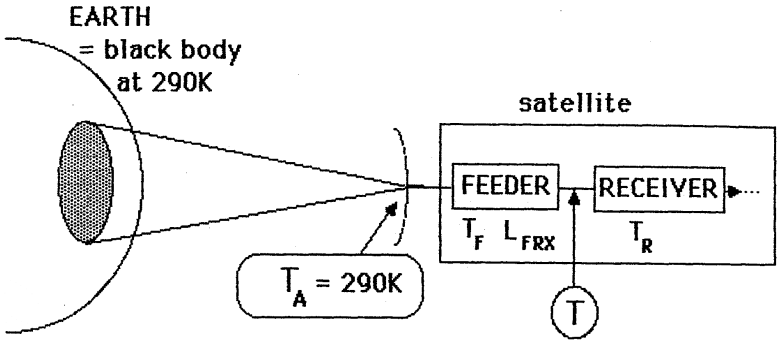
# SATELLITE ANTENNA NOISE TEMPERATURE




**$T_A$ : averaged contribution of Earth noise t° (about 290 K)**
**+ surrounding background (galactic) t° (a few K)**

- **With spot beam antenna, Earth is viewed within the entire antenna pattern & $T_A \approx 290$ K**
- **Noise t° T at receiver input :**

$$T = \frac{T_A}{L_{FRX}} + T_F\left(1 - \frac{1}{L_{FRX}}\right) + T_R$$

- **With $T_A$ = 290 K & assuming $T_F \approx 290$ K (ambient) :**

$$T \approx T_F + T_R \approx 290 + T_R$$

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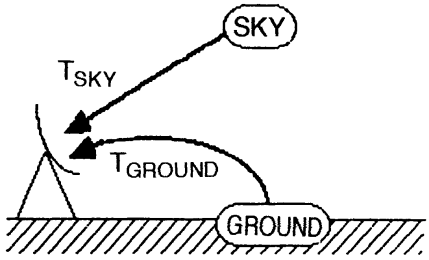
# EARTH STATION ANTENNA NOISE TEMPERATURE

- **CLEAR SKY CONDITIONS**

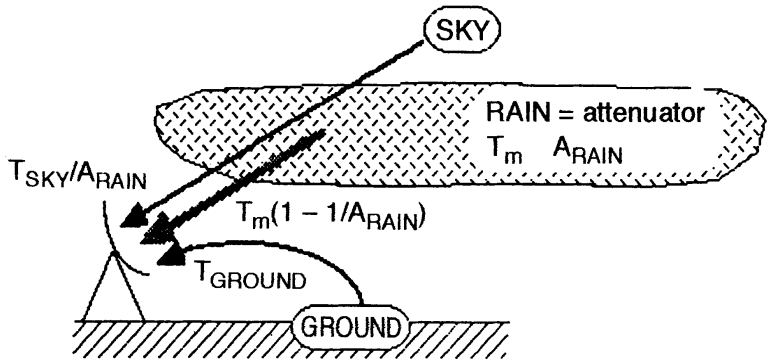
$$T_A = T_{SKY} + T_{GROUND}$$




- **RAIN CONDITIONS**
  - **Brightness t° of clouds or rain**

$$T_B = T_M\left(1 - \tau^{\frac{1}{\cos\vartheta}}\right) = T_M \times \sigma_e$$

with $\tau$ : transmission coefficient
and $\sigma_e$ : medium emissivity




  - **Antenna t° due to clouds or rain**

with : $T_M = 1.12\ T_{amb}(K) - 50$

$$T_A = \frac{T_{SKY}}{A_p} + T_M\left(1 - \frac{1}{A_p}\right) + T_{GROUND}$$

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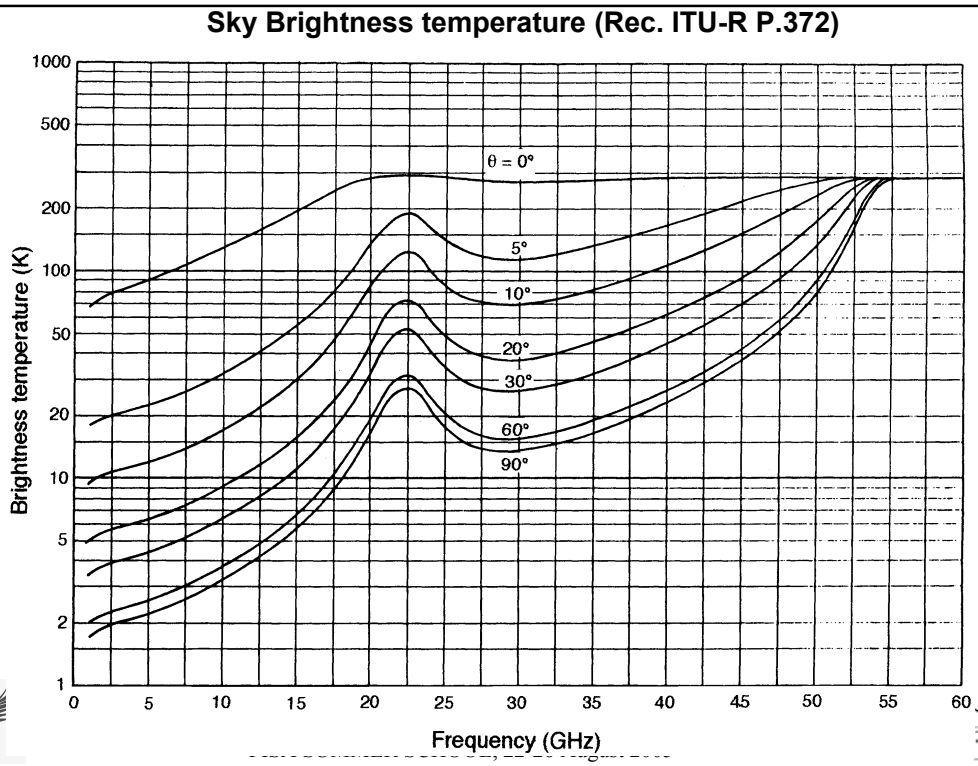
# CLEAR SKY NOISE TEMPERATURE

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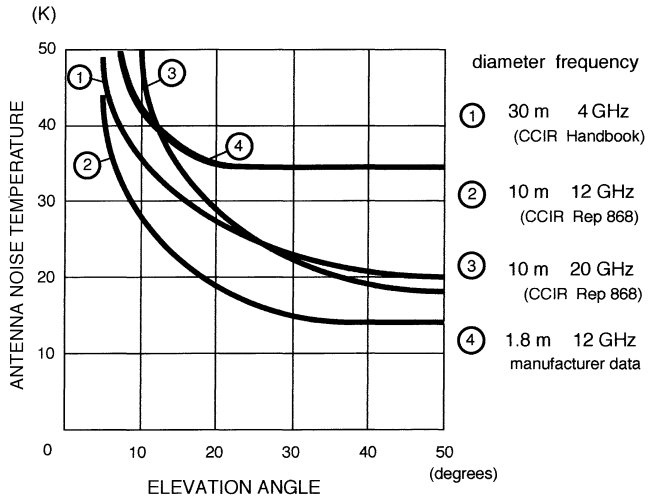
# GROUND CONTRIBUTION TO ANTENNA NOISE TEMPERATURE

- **DEPENDS ON :**
  - Type of antenna (mounting, diameter)
  - Elevation angle of antenna
  - Sidelobes radiation pattern
  - Frequency

- **PRACTICAL VALUES**
  - ≈ 10 - 30 K @ elevation angle ≈ 10 °

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## CONTENT OF THE PRESENTATION

- LINK ANALYSIS and PERFORMANCES OBJECTIVES
- CARRIER POWER BUDGET and PROPAGATION IMPAIRMENTS
- NOISE POWER BUDGET and SYSTEM NOISE TEMPERATURE
- LINK PERFORMANCE
- FADE MITIGATION TECHNIQUES (FMT)
- FMT IMPLEMENTATION
- SYSTEM PERFORMANCE & CONCLUSION

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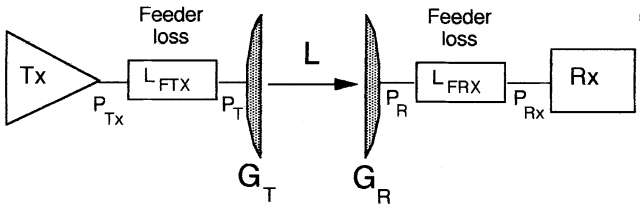
## CARRIER POWER-TO-NOISE POWER SPECTRAL DENSITY RATIO

- SINGLE LINK CONFIGURATION




**C : Carrier power at receiver input (W)** $C = P_{RX} = (P_T\, G_T)\, .\, G/L$

where $G = G_{Rmax} / L_{FRX}\, L_R$($L_R$ : antenna off-axis fall-out)

**$N_0$ : Noise power spectral density (W/Hz)** $N_0 = k\, T$

where T : SYSTEM NOISE TEMPERATURE (K)

**EIRP (W)** **Rx Figure of merit ($K^{-1}$)**

$$C / N_0 = (P_T\, G_T)(1/L)(G/T)(1/k)$$

**Path Loss**

FIGURE OF MERIT G/T ($K^{-1}$) characterizes the effectiveness of the receiving end

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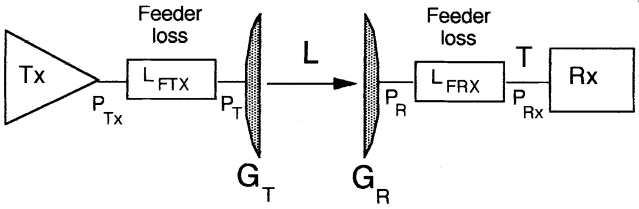
## CARRIER-TO-NOISE POWER RATIO AT RECEIVER INPUT

- **SINGLE LINK CONFIGURATION**




***$C = P_{RX} = (P_T\, G_T)\ .\ G/L$***

***$N_0 = k\, T$***

***where T = System Noise Temperature (at receiver input)***

$$C / N_0 = (P_T\ G_T)(1/L)(G/T)(1/k)$$

$$\frac{C}{N} = \frac{C}{N_0} \cdot 1/B_N$$

where $B_N$ : receiver noise effective Bandwidth (Hz)

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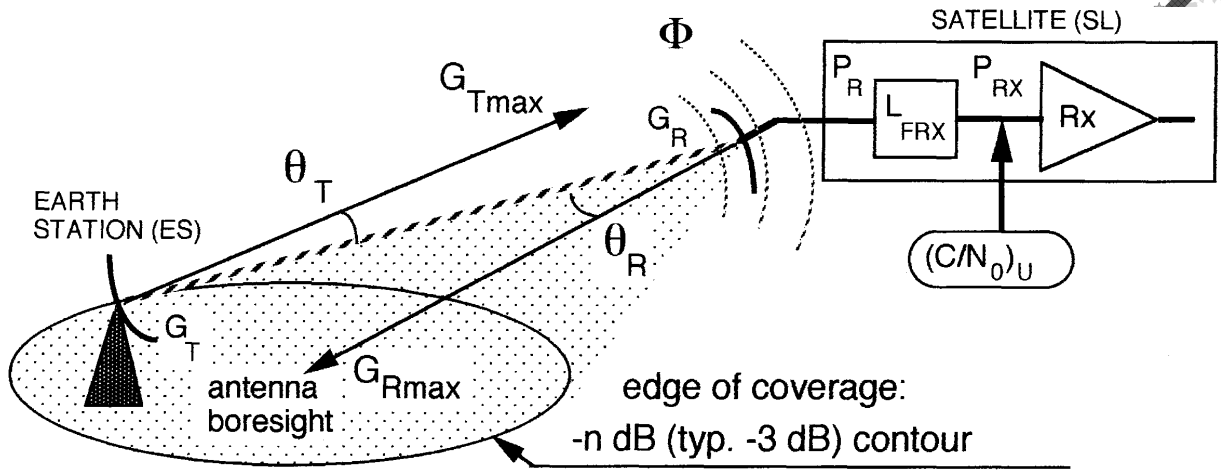
## UPLINK $C/N_0$




$$(C/N_0)_U = (EIRP)_{ES}(1/L)_U(G/T)_{SL}(1/k)$$

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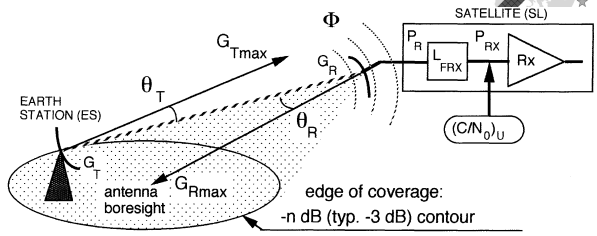
## UPLINK $C/N_0$




- $EIRP_{ES} = (P_T\, G_T)_{ES} = (P_{Tx}/L_{FTX})_{ES} \cdot (G_{Tmax}/L_T)_{ES}$
  - $L_T = 12\,(\alpha_T / \theta_{3dB})^2$
    where $\alpha_T$ : ES depointing angle
    (depends on type of tracking if any)
- $(G/T)_{SL} = (G_{Rmax}/L_R)_{SL} \cdot (1/L_{FRX})_{SL} \cdot (1/T)_{SL}$
  - where $L_R$ : usually 3dB for Earth stations
    $T$ : satellite system noise temperature ≈ 290 + $T_R$ (K)

$$(C/N_0)_U = (EIRP)_{ES}\,(1/L)_U\,(G/T)_{SL}\,(1/k)$$

  - $(G/T)_{SL}$ depends on Earth station line-of-sight direction

- **Power flux density (W/m²)**
  - $\Phi = EIRP_{ES} / 4\pi R^2$
  - ® $C_U = P_{Rx} = \Phi \cdot A_{reff}\,(1/L_{FRX}) = \Phi\,(G_R\lambda^2/4\pi)\,(1/L_{FRX})_{SL} = \Phi\,(G_{Rmax}/L_R)\,(1/L_{FRX})_{SL}\,(\lambda^2/4\pi)$

$$\Rightarrow\ (C/N_0)_U = \Phi\,(G/T)_{SL}\,(\lambda^2/4\pi)\,(1/k)$$

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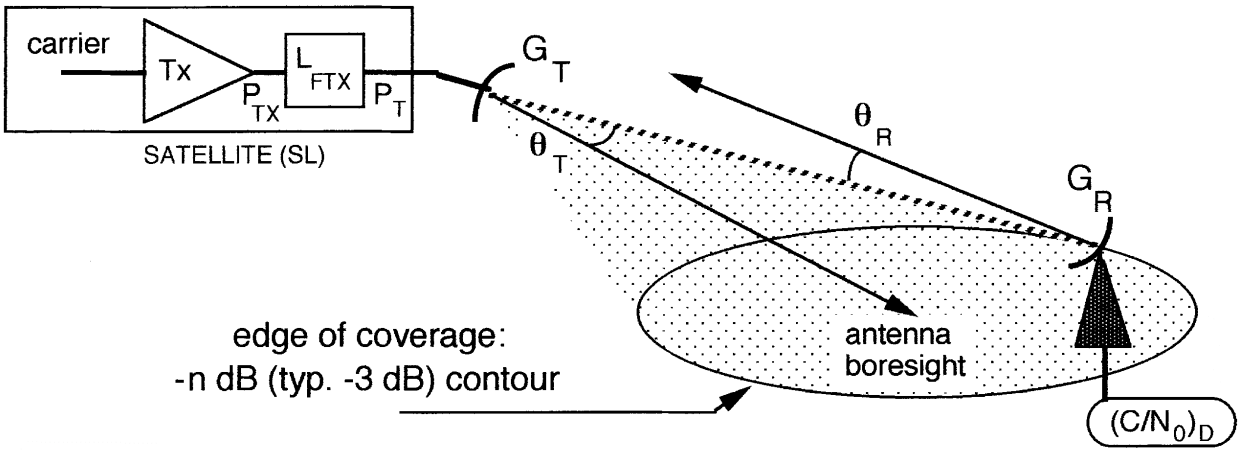
## DOWNLINK $C/N_0$




$$(C/N_0)_D = (EIRP)_{SL}\,(1/L)_D\,(G/T)_{ES}\,(1/k)$$

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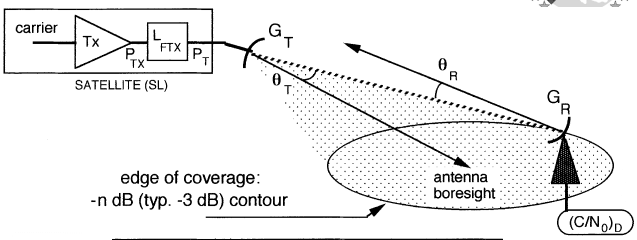
## DOWNLINK $C/N_0$




- **$(C/N_0)_D$ computation assumes that a noise-less carrier is generated by the satellite**

- **$EIRP_{SL} = (P_T\, G_T)_{SL} = (P_{Tx}/L_{FTX})_{SL} \cdot (G_{Tmax}/L_T)_{SL}$**

$$(C/N_0)_D = (EIRP)_{SL}\,(1/L)_D\,(G/T)_{ES}\,(1/k)$$

  - where $L_T$ : usually 3dB for Earth stations located at edge of coverage

- **$(G/T)_{ES} = (G_{Rmax}/L_R)_{ES} \cdot (1/L_{FRX})_{ES} \cdot (1/T)_{ES}$**
  - **$L_T = 12\,(\alpha_R / \theta_{3dB})^2$**

    where $\alpha_R$ : ES depointing angle (depends on type of tracking if any)

    and T : Earth station system noise temperature (K),
    it includes antenna noise $T_A$
    which varies with elevation angle and rain intensity

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## INFLUENCE OF PROPAGATION ON LINK BUDGET

- **UPLINK**

$$C/N_{0,U} = EIRP_{ES} - L_{FS,U} - A_U + G/T_{SL} - k_{dB}$$

  - **$C/N_{0,U} = (C/N_{0,U})^{ClearSky} - A_U$**

- **DOWNLINK**

$$C/N_{0,D} = EIRP_{SL} - L_{FS,D} - A_D + G/T_{ES} - k_{dB}$$

Transparent repeater

  - **$C/N_{0,D} = (C/N_{0,D})^{ClearSky} - A_D - \Delta(G/T_{ES})_{Ad} - \Delta(EIRP_{SL})_{Au}$**

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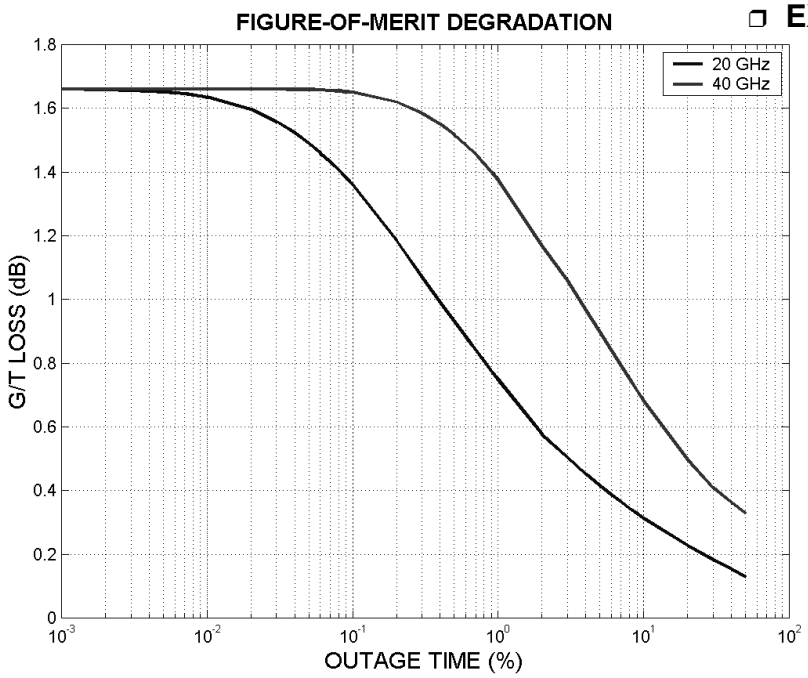
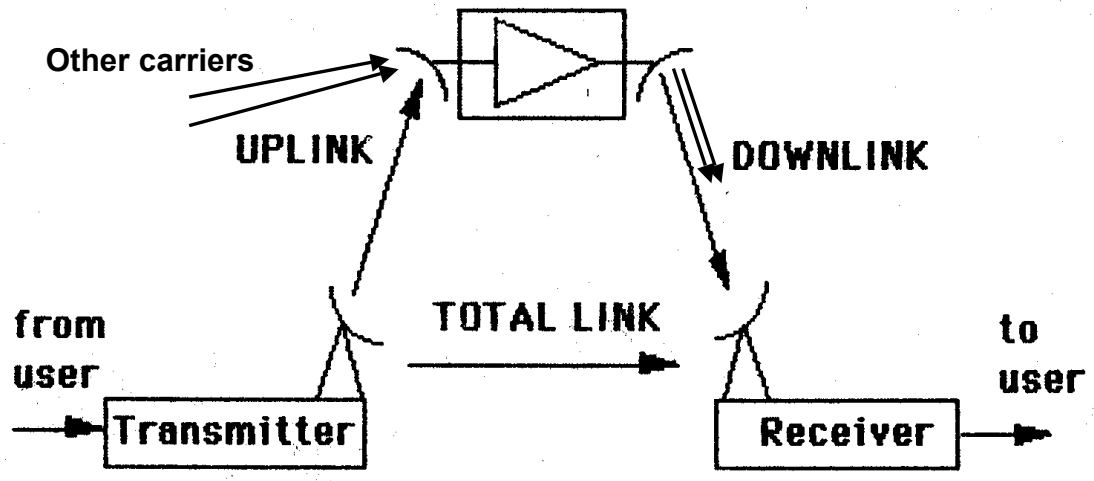
## EFFECT OF ATMOSPHERE ON G/T




❒ **EXAMPLE**

- **Earth station figure of merit degradation for an Earth station located in Milan (Italy)**
- **$E_{sat}$ = 38°**
- **Rec. ITU-R P.618**

## OVERALL STATION-TO-STATION LINK

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# OPERATING POINT

- **LINEAR OPERATION**

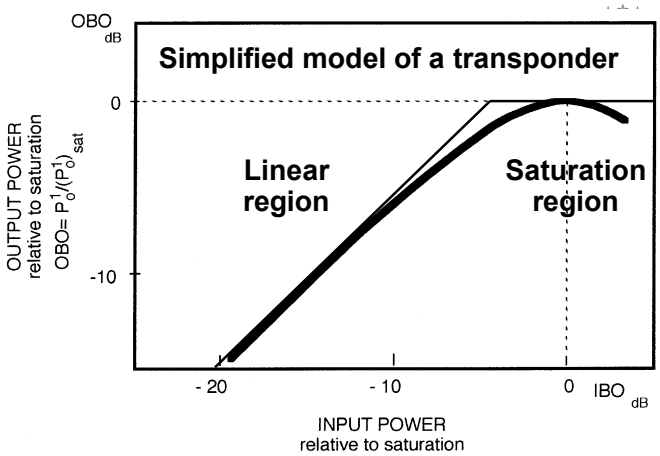
  $P_T < (P_T)_{max}$ - $(N_0)_{IM} = 0$

  - Constant repeater power gain
  - Satellite transmit output power shared between :
    - amplified carriers
    - amplified input noise

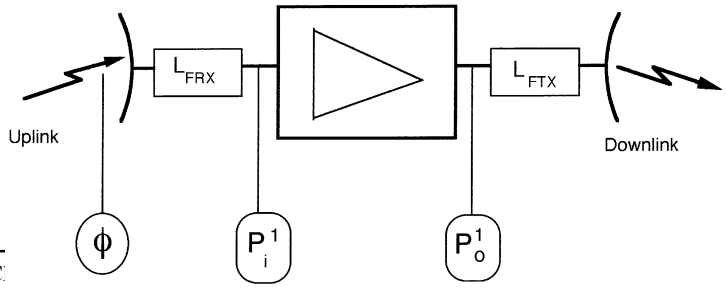
- **SATURATION REGION OPERATION**

  - Limited available power from sat. repeater
  - Output power shared between :
    - amplified carries
    - amplified input noise
    - intermodulation products

    ⇒ Power gain value dependent on operating point




$IBO = P^1_i/(P^1_i)_{sat} = (\phi)_{SL} / (\phi_{sat})_{SL}$

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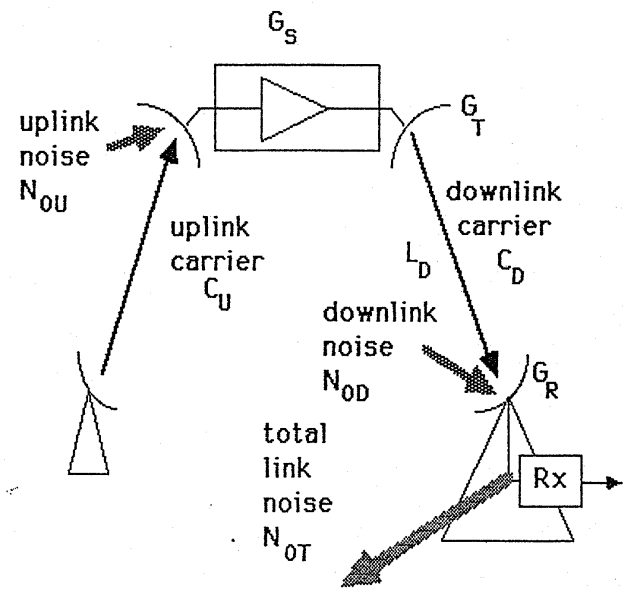
# OVERALL LINK BUDGET with LINEAR OPERATION - 1/2




Total link noise

**Total link noise**
**=**
**Uplink retransmitted noise**
**+ downlink noise**

- Uplink : $(C/N_0)_U = C_U / N_{0U}$
- Downlink : $(C/N_0)_D = C_D / N_{0D}$
- Overall link : $(C/N_0)_T = C_D / N_{0T}$

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## OVERALL LINK BUDGET with LINEAR OPERATION - 2/2

① $C_D = C_U . G_S . G_T . (1/L_D) . G_R = G . C_U$

where $G = G_S . G_T . G_R / L_D$ represents the total power gain from satellite repeater input receiver to Earth station input receiver

② **Noise at receiver input = uplink retransmitted noise + downlink noise :**

$$N_{0T} = N_{0U} . G_S . G_T . (1/L_D) . G_R + N_{0D}$$
$$= G . N_{0U} + N_{0D}$$

③ $(C/N_0)_T^{-1} = N_{0T} / C_D$

$$= (G . N_{0U} + N_{0D}) / C_D = N_{0U} / C_U + N_{0D} / C_D$$

$$\boxed{(C/N_0)_T^{-1} = (C/N_0)_U^{-1} + (C/N_0)_D^{-1}}$$

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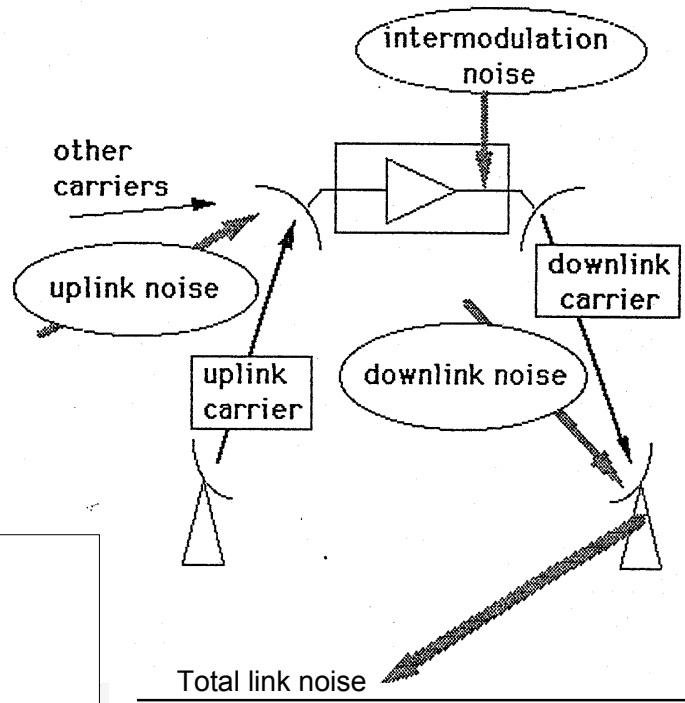
## MULTICARRIER OPERATION - 1/5




**Total link noise**
**=**
**Uplink retransmitted noise**
**+ intermodulation noise**
**+ downlink noise**

- **Uplink :** $(C/N_0)_U = C_U / N_{0U}$
- **Intermodulation :** $(C/N_0)_{IM}$
- **Downlink :** $(C/N_0)_D = C_D / N_{0D}$
- **Overall link :** $(C/N_0)_T = C_D / N_{0T}$

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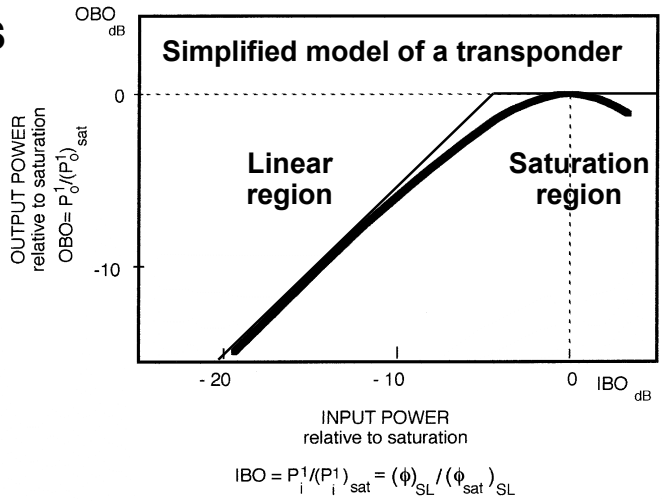
# INTERMODULATION PRODUCTS

- **INTERMODULATION PRODUCTS**
  If several carriers at frequencies $f_1, f_2, \ldots, f_n$ are fed to a non-linear device operated in the saturation region, one finds at the output of the transponder the input carriers plus a number of so-called "intermodulation products".




- **FREQUENCY $f_{IM}$** of each of these "intermodulation products" is a linear combination of the input frequencies :
  - ➢ $f_{IM} = m_1 f_1 + m_2 f_2 + m_3 f_3 + \ldots + m_n f_n$

    *where $m_i$ is a positive or negative integer*

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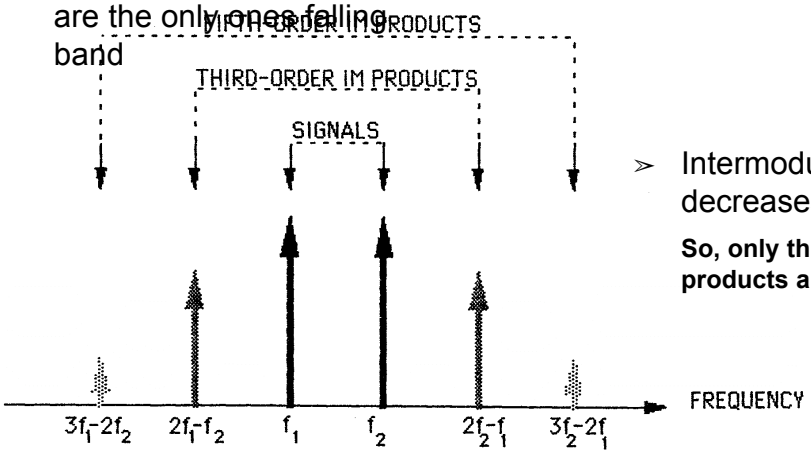
# MULTICARRIER OPERATION : INTERMODULATION PRODUCTS

- **The order M of any intermodulation product is defined as :**
  $M = |m_1| + |m_2| + |m_3| + \ldots + |m_n|$

➢ When the center frequency of the amplifier is large compared to its bandwidth, odd-order intermodulation products with : $\Sigma\, m_i = 3, 5..$ are the only ones falling within the useful frequency band




➢ Intermodulation product power decreases with the order of the product.

**So, only third & fifth order intermodulation products are of concern**

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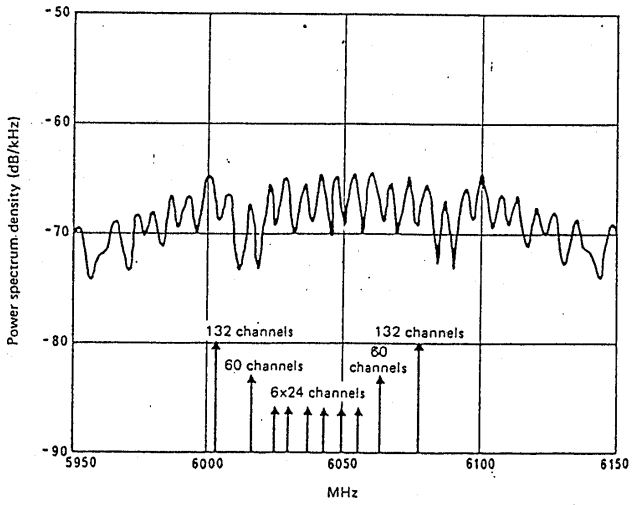
## MULTICARRIER OPERATION : INTERMODULATION NOISE - 4/5

- Intermodulation products may appear at :
  - Tx ES non-linear power amplifier output
  - satellite repeater output

- 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

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




**Ex. : intermodulation noise spectrum for a typical TWTA with 10 carriers :**
- six central carriers
- two 64-channel carriers
- two 132-channel carriers

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## MULTICARRIER OPERATION : OVERALL LINK BUDGET - 5/5

- **TOTAL NOISE @ receiver input =**

  uplink retransmitted noise
  + intermodulation noise
  + downlink noise

- **Assuming the SAME POWER LEVEL for all incoming carriers @ repeater input :**

$$(C/N_0)_T^{-1} = (C/N_0)_U^{-1} + (C/N_0)_D^{-1} + (C/N_0)_{IM}^{-1}$$

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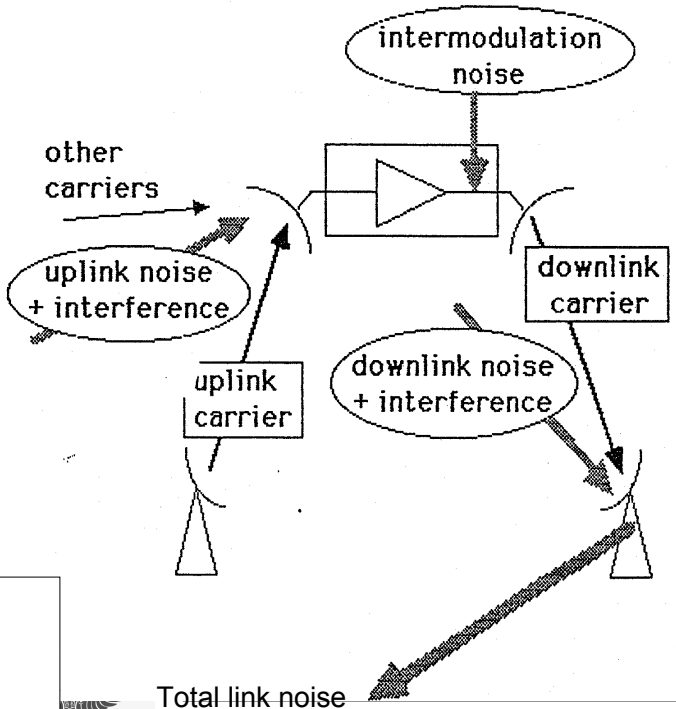
## MULTICARRIER OPERATION WITH INTERFERENCE




**Total link noise**
**=**
**Uplink retransmitted noise**
**+ intermodulation noise**
**+ interference**
**+ downlink noise**

- **Uplink : $(C/N_0)_U = C_U / N_{0U}$**
- **Intermodulation : $(C/N_0)_{IM}$**
- **Interference : $(C/N_0)_I$**
- **Downlink : $(C/N_0)_D = C_D / N_{0D}$**
- **Overall link : $(C/N_0)_T = C_D / N_{0T}$**

Total link noise

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## OVERALL LINK BUDGET with INTERMOD & INTERFERENCE

- **SOURCES OF INTERFERENCE**
  - Within the considered satellite system
  - Satellite systems ↔ satellite systems
  - Satellite systems ↔ terrestrial microwave systems

- **Interfering signals are considered as noise with Power noise density $(N_0)_I$**
  **This noise adds tot he total noise of the system :**

$$(C/N_0)_T^{-1} = (C/N_0)_U^{-1} + (C/N_0)_D^{-1} + (C/N_0)_{IM}^{-1} + (C/N_0)_I^{-1}$$

where $(C/N_0)_I$ represents the Carrier-to-Interference Ratio
and includes uplink and downlink contributions

$$(C/N_0)_I^{-1} = (C/N_0)_{I,U}^{-1} + (C/N_0)_{I,D}^{-1}$$

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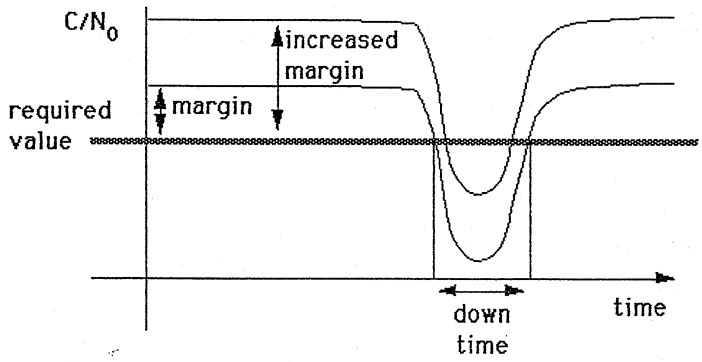
## LINK AVAILABILITY ADJUSTMENT: STATIC MARGIN

- **STATIC LINK POWER MARGIN**
  - Difference between required and provided C/No
  - Allows reduction in provided C/No without affecting link performance




  - Larger margin value provides higher link availability as (C/N0)T will fall below the required value during a shorter time interval

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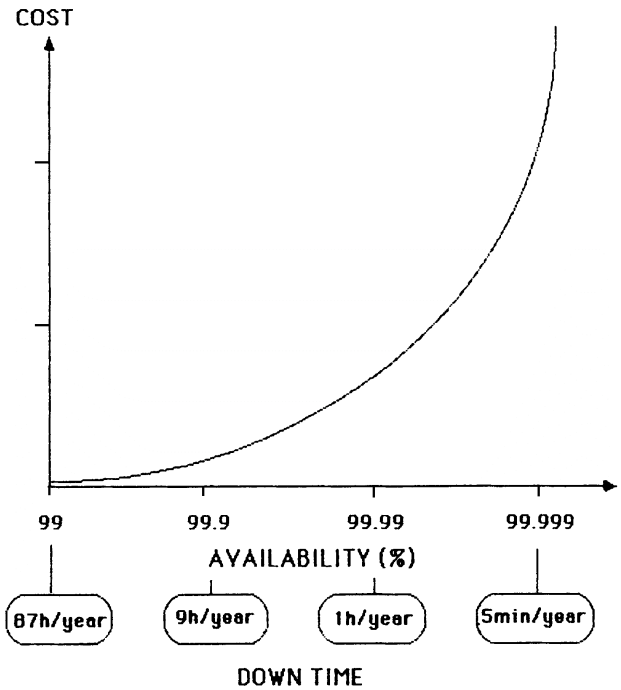
## LINK AVAILABILITY

- **System cost increases rapidly with system availability**
  - Customer should not ask for tight specifications, unless strictly needed

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- ❒ **FADE MITIGATION TECHNIQUES (FMT)**
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- ❒ **SYSTEM PERFORMANCE & CONCLUSION**

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## FRAMEWORK RELATED TO BROADBAND SATCOM SYSTEMS

### ❒ TREND TO HIGHER FREQUENCY BANDS

- ➢ Conventional bands (L, S, C) overcrowded & Ku-band almost saturated
- ➢ Increasing use of data rate-hungry multimedia applications
- ➢ Competition with terrestrial networks : need for larger bandwidths

### ❒ HIGH FREQUENCY BAND ADVANTAGES

- ☺ Wide bandwidths : 1 GHz at Ka-band, 3 GHz at Q/V-band, 2 GHz at EHF band
- ☺ Technology : reduced antenna and RF component size,
- ☺ Narrow spot beams and high EIRP

### ❒ HIGH FREQUENCY BAND LIMITATIONS

- ☹ Current technology not mature enough ⇨ high development costs
- ☹ Pointing accuracy more critical at equivalent antenna diameter
- ☹ Propagation issue : influence of tropospheric effects

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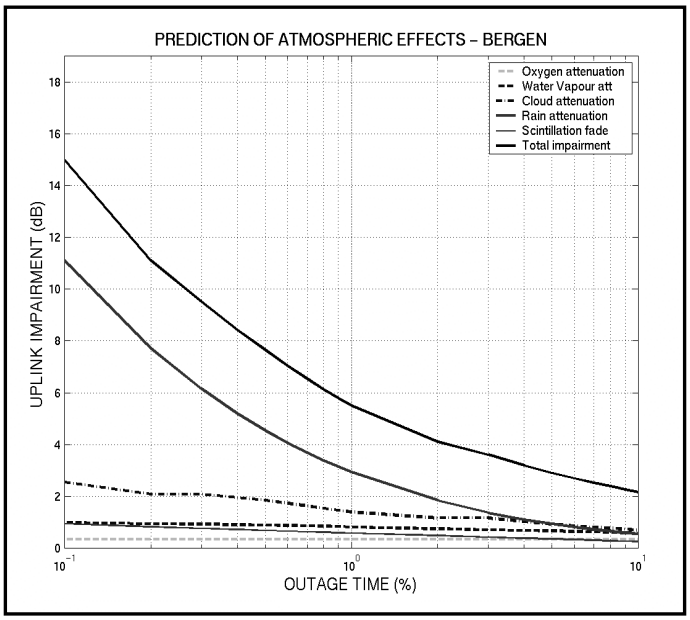
# PROPAGATION IMPAIRMENTS AT HIGH FREQUENCIES

- **TOTAL IMPAIRMENT @ 30 GHz**
  - Predictions obtained with Recommendation ITU-R P.618

- **HOW TO PROVIDE SUFFICIENT AVAILABILITY ?**
  - Large static margins not applicable (technology limitations and cost efficiency)
  - **Fade Mitigation Techniques (FMT)**

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# BASICS OF FMT : OBJECTIVES

$$\frac{C}{N_0} = \frac{E_S}{N_0} \times R_S \qquad \frac{E_S}{N_0} \geq \left(\frac{E_s}{N_0}\right)_{req}$$

f(cod, mod)

- **POWER CONTROL : aims at keeping constant link $C/N_0$**
  - Up-Link Power Control, End-to-End PC, Down-Link PC, On-Board Beam Shaping

- **ADAPTIVE WAVEFORM : aims at adapting the required $C/N_0$ @ constant BER**
  - Adaptive Coding or Modulation : allows the required $E_S/N_0$ to be adjusted
  - Data Rate Adaptation : aims at adjusting the data rate

- **DIVERSITY : aims at re-routing connection in the network**
  - Site Diversity, Satellite Diversity, Frequency Diversity

- **LAYER 2 : aims at re-transmitting lost information**
  - Automatic Repeat reQuest, Time Diversity

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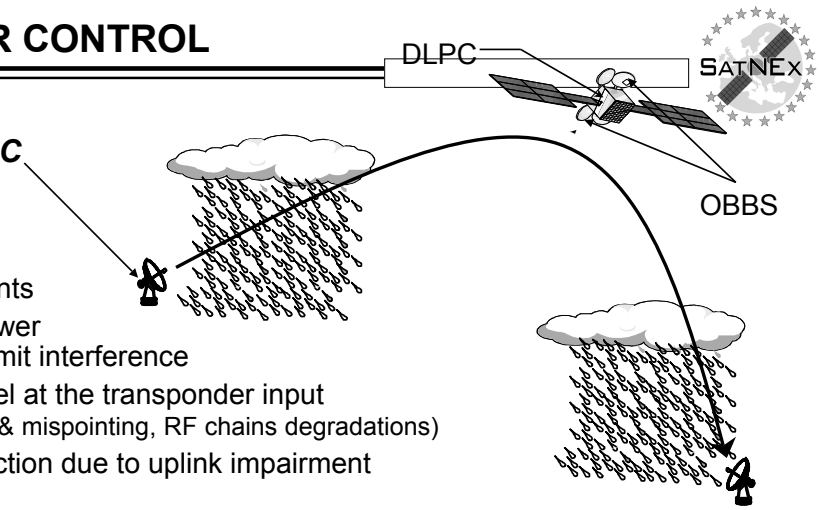
## BASICS OF FMT : POWER CONTROL




*ex : ULPC*

- **UPLINK (ULPC)**
  - compensates for uplink propagation impairments
  - allows operating at low power in clear sky cond. to limit interference
  - constant carrier power level at the transponder input (satellite antenna gain roll-off & mispointing, RF chains degradations)
  - avoids satellite EIRP reduction due to uplink impairment

- **EEPC (transparent repeater operated far from saturation)**
  - maintains a constant margin on the overall link budget
  - mitigates downlink impairments if sufficient repeater margin keeping reasonable non-linear effects (intermodulation noise & capture effects)

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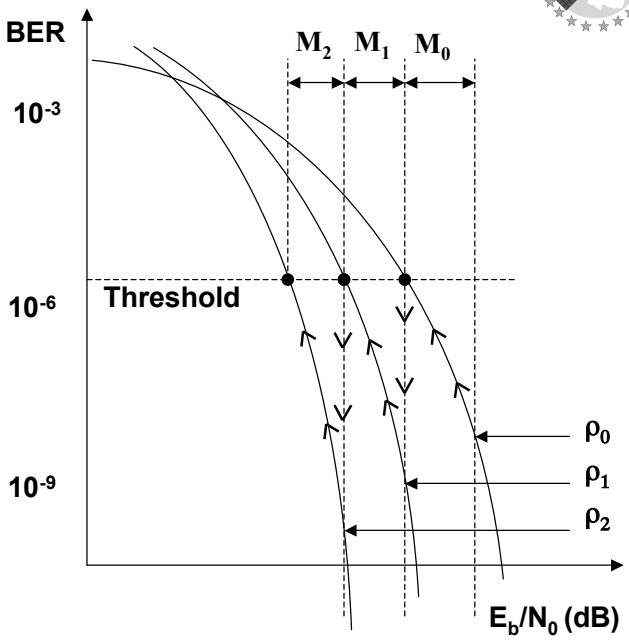
## BASICS OF FMT : ADAPTIVE WAVEFORM

- **AC, AM : Adaptive Coding or Modulation**




**OPERATION MODE** :

Perf. objective : BER = $C^{te}$

- Constant bandwidth & variable info data rate ($R_b$) (Additional mitigation due to DR adjustment)
- Variable bandwidth & constant info data rate ($R_b$)

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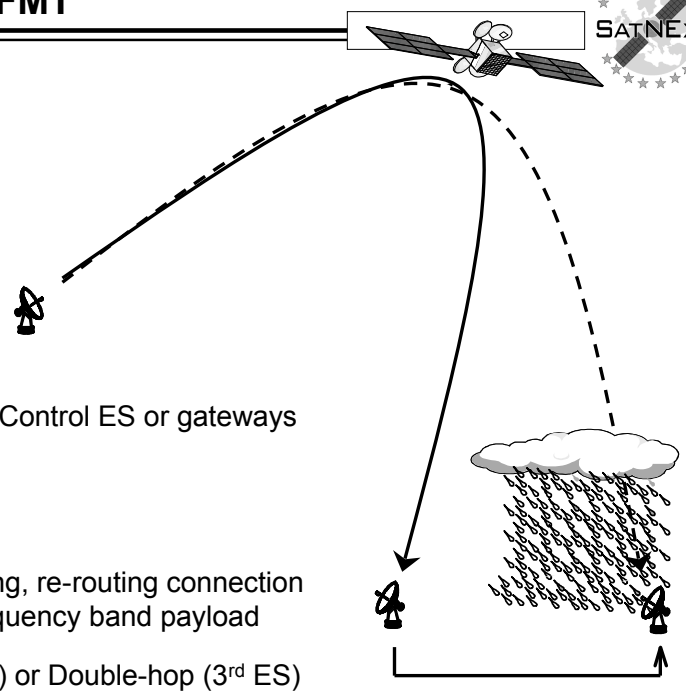
## BASICS OF FMT : DIVERSITY FMT



- **SITE DIVERSITY (SD)**
  - **Principle** :
    2 ES inter-connected
    by a terrestrial link
  - **Limitations** :
    uncorrelated fades
    => convective cells
  - ➙ Low percentages of time - Control ES or gateways

- **FREQUENCY DIVERSITY (FD)**
  - **Objective :** in presence of fading, re-routing connection through a lower frequency band payload
  - **Config. :** Cross-strapping (OBP) or Double-hop (3rd ES)

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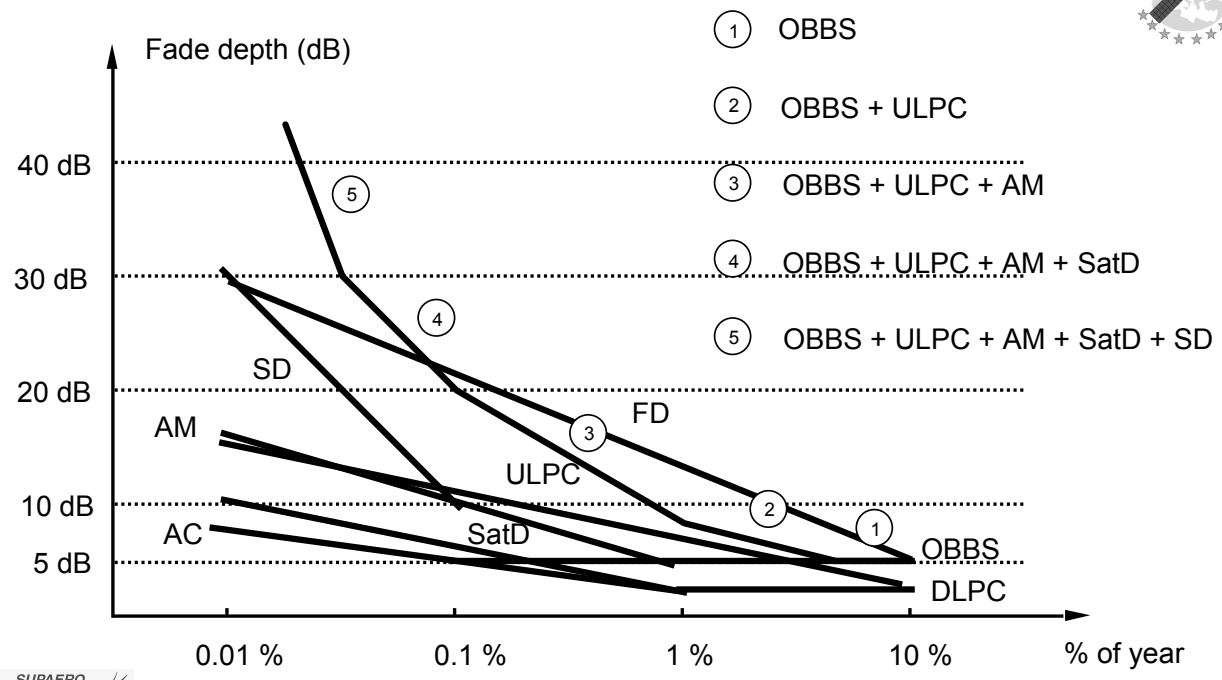
## BASICS OF FMT : JOINT FMT

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# CONTENT OF THE PRESENTATION

- LINK ANALYSIS and PERFORMANCES OBJECTIVES
- CARRIER POWER BUDGET and PROPAGATION IMPAIRMENTS
- NOISE POWER BUDGET and SYSTEM NOISE TEMPERATURE
- LINK PERFORMANCE
- FADE MITIGATION TECHNIQUES (FMT)
- FMT IMPLEMENTATION
- SYSTEM PERFORMANCE & CONCLUSION

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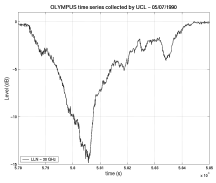
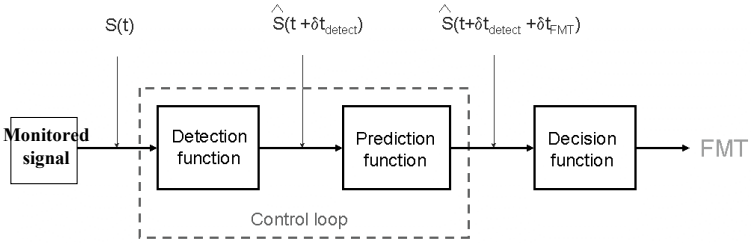
# FMT IMPLEMENTATION : CONTROL LOOP



## DETECTION OF THE CHANNEL BEHAVIOUR

- Purpose : real-time estimate of current fade level
- Real-time estimate of overall SNIR




## SHORT-TERM PREDICTION

- Purpose : compensation of the system reaction time
- Filtering of fast varying component, frequency scaling, real -time short-term prediction

## DECISION FUNCTION

- Purpose : to authorise & trigger a given mitigation
- Introduction of local margins to compensate control loop inaccuracies

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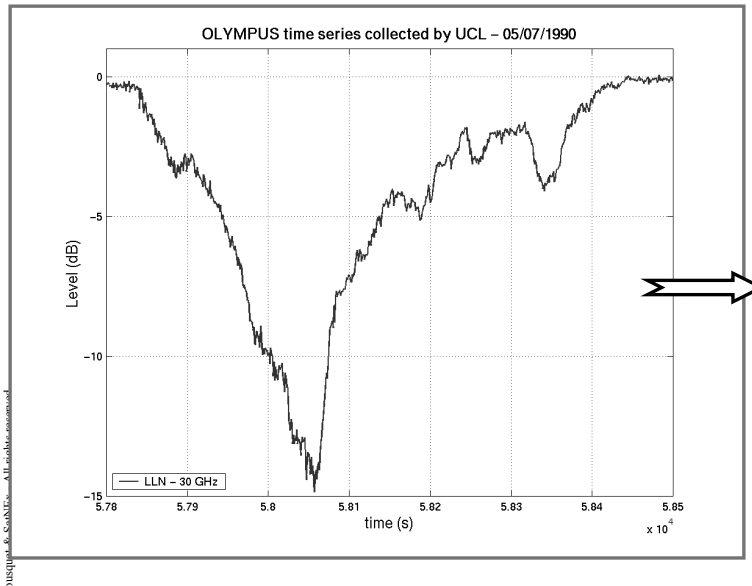
# FMT IMPLEMENTATION : POWER VARIATIONS




✈ **Slow variations : attenuation**

✈ **Fast fluctuations : scintillation**

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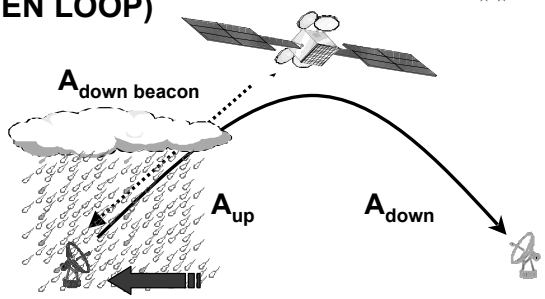
# FMT IMPLEMENTATION : FADE AND SNIR ESTIMATION

❒ **INFORMATION EXTERNAL TO THE LINK (OPEN LOOP)**

- ➢ **Meteorological measurements**
  - ➵ Rainfall rate : Rain-gauge
  - ➵ Brightness temperature : Radiometer
  - ➵ Reflectivity profiles : Radar
  - ➵ Satellite imagery
- ➢ **Beacon measurement**




$F_{scaling}(A_{down\ beacon}) \approx A_{up}$

ρ **INFORMATION INTERNAL TO THE LINK**

- ➢ **BER measurements**
- ➢ **Power measurements**
  - ➵ Measurement of the average amplitude of the received symbols
  - ➵ Estimation of the Signal to Noise + Interf. Ratio (SNORE)
- ➢ **Affected by interference contributions**

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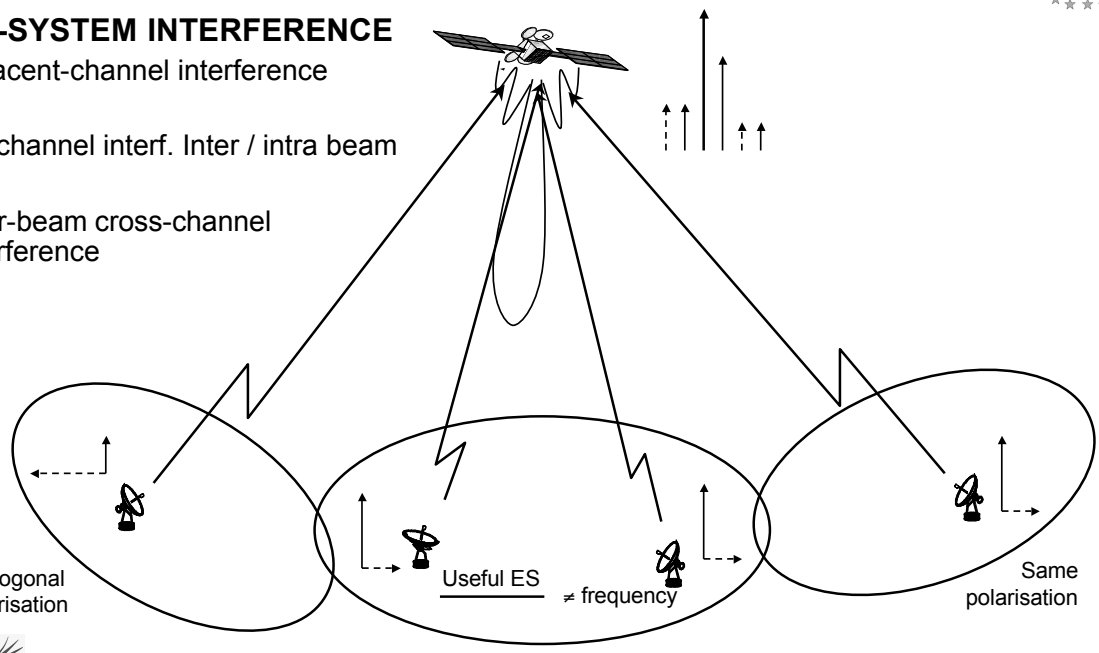
## FMT IMPLEMENTATION : INTERFERENCE CONTRIBUTIONS

- **INTRA-SYSTEM INTERFERENCE**
  - Adjacent-channel interference
  - Co-channel interf. Inter / intra beam
  - Inter-beam cross-channel interference

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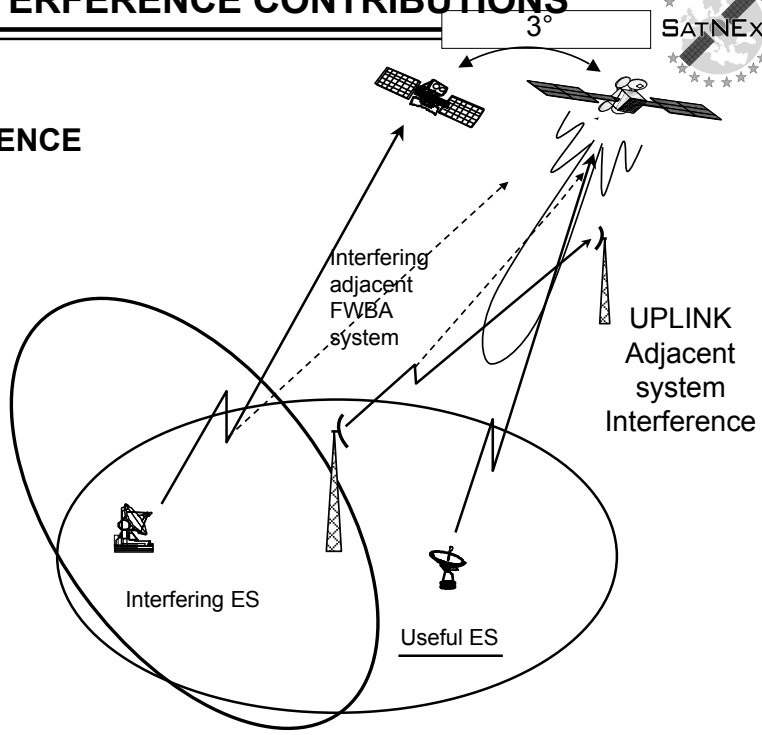
## FMT IMPLEMENTATION : INTERFERENCE CONTRIBUTIONS

- **INTER-SYSTEM INTERFERENCE**
  - Adjacent satcom system interference
  - Other system interference

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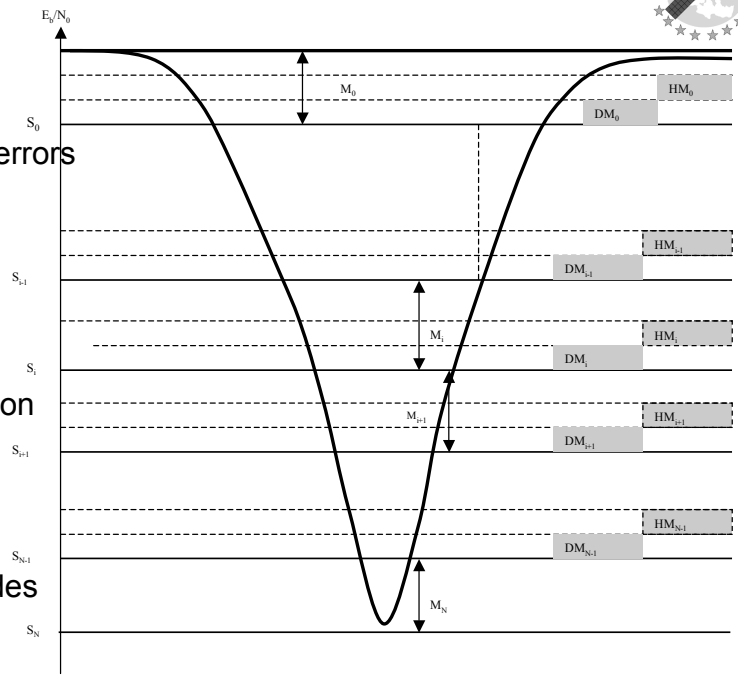
## FMT IMPLEMENTATION: TRIGGERING MARGINS

- **DETECTION MARGIN**
  - Takes into account estimation errors due to attenuation varying more rapidly than expected
  - Avoids triggering due to fast fluctuations
  - Copes with errors due to frequency scaling implementation
- **HYSTERESIS MARGIN**
  - Avoids repeated switches between consecutive FMT modes

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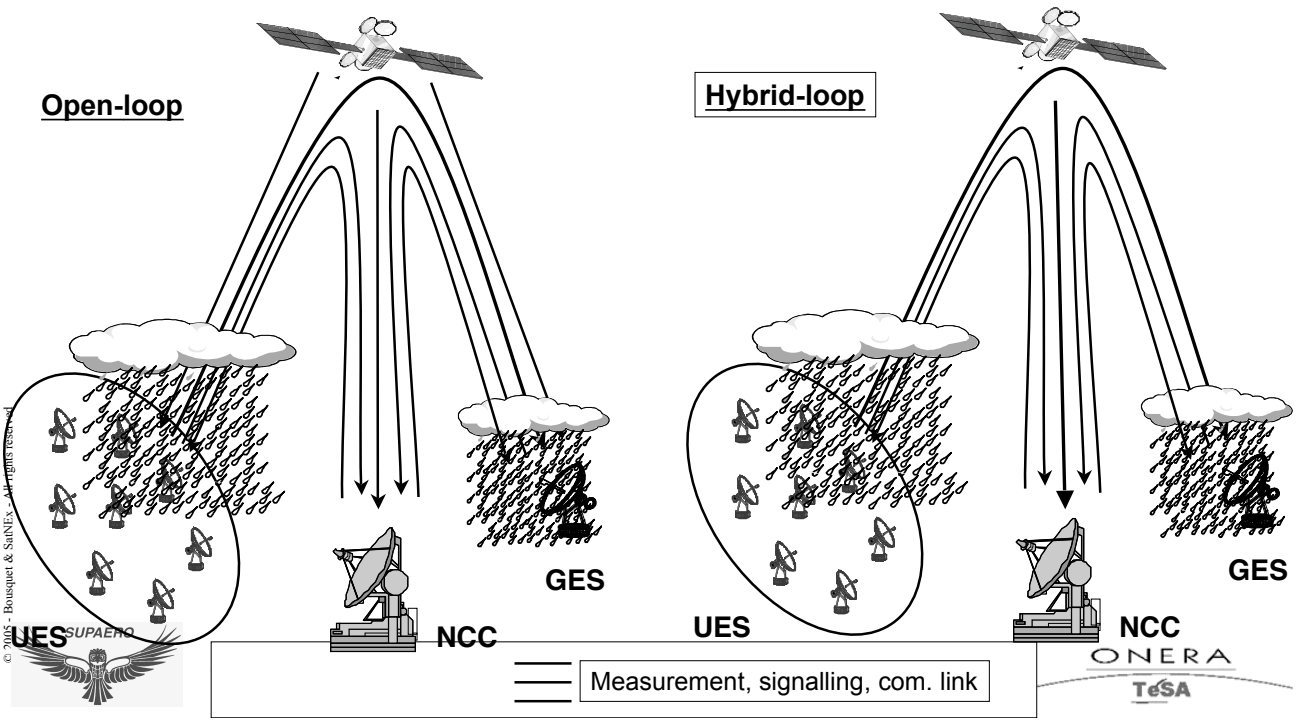
## FMT CONTROL LOOP ARCHITECTURE :

## CENTRALIZED D&D SCHEMES FOR BENT-PIPE SYSTEM

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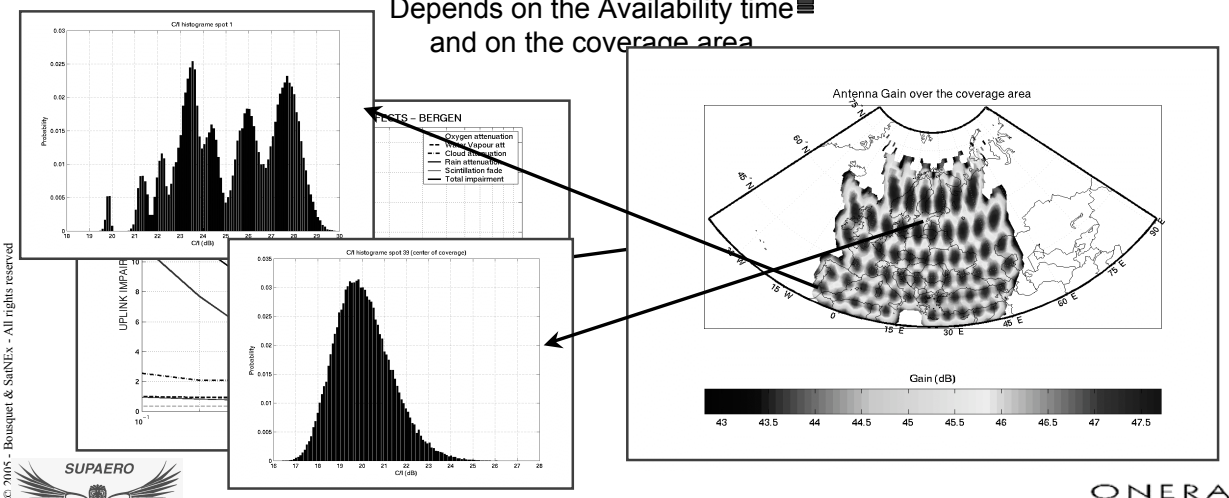
## LINK BUDGET within SYSTEM DESIGN: TRADITIONAL APPROACH

- DESIGN WITH STATIC PHYSICAL LAYER AND STATIC MARGINS

$$\frac{C}{N_0}\left(Lfs, Gsat_{minimum}, Att_{worst\ case}, Int_{max}\right) \geq \frac{C}{No} Required$$

Depends on the Availability time and on the coverage area

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## LINK BUDGET IN FMT SYSTEM DESIGN: NEW APPROACH

❒ **TAKES INTO ACCOUNT LINK BUDGET SITUATION AT EACH POINT (X,Y) OF THE COVERAGE**.

$$\frac{C}{N_0}\left(\underbrace{Lfs(x,y),Gsat(x,y)}_{\textbf{Position dependent}},\underbrace{Att(x,y,t),Int(x,y,t)}_{\textbf{Position \& Time dependent}}\right)$$

Atmospheric attenuation is modeled using CDF given in ITU-R P 618 recommendation
Interference in modeled from antenna pattern and considering a uniform distribution of users and traffic

$$\frac{C}{N_0}\left(Lfs(x,y,f),EIRP(x,y,t),Att(x,y,t,f),Int(x,y,t)\right)$$

**Power Control** **Site Diversity** **Frequency Diversity**

$$\frac{C}{N_0} \geq \frac{C}{N_0}\mathrm{Required}(\textbf{mod}, \textbf{coding})$$

**Adaptive Coding and Modulation**

It assigns to each point the best possible modulation and coding in terms of spectral efficiency

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## LINK BUDGET with FMT SYSTEM DESIGN: NEW APPROACH

❒ **CAPACITY**

- With a fixed available bandwidth : capacity is linked to the spectral efficiency of the waveform and code used

$$\frac{C}{N_0} \geq \frac{C}{N_0}\mathrm{Required}(\mathrm{mod},\mathrm{cod})$$

Spectral efficiency $\Gamma$

- If Adaptive Coding and Modulation is used, the mean capacity of the system can be calculated by integration and averaging

$$\Gamma_{max}(x,y,Att,f) \equiv maximum\ efficiency\ that\ meets\ condition$$

$$\Gamma(x,y,f) = \int_0^1 \Gamma_{\max}(x,y,Att(x,y),f)\, p_{\mathrm{Att}(x,y)}(Att(x,y))\, dp_{Att(x,y)}$$

$$\Gamma_{systeme}(f) = \frac{1}{Nb}\sum_{n=1}^{Nb}\frac{1}{S(B_n)}\iint_{(x,y)\in B_n}\Gamma(x,y,f)\,dxdy$$

❑ **AVAILABILITY: Time when service meets the required quality**

$$\frac{C}{N_0}(t) \geq \mathrm{Minimum}\ \frac{C}{N_0}\mathrm{Required}$$

❑ **COVERAGE: Area where service is available**

$$\frac{C}{N_0}(x,y,t=avail) \geq Minimum\ \frac{C}{N_0}\mathrm{Required}$$

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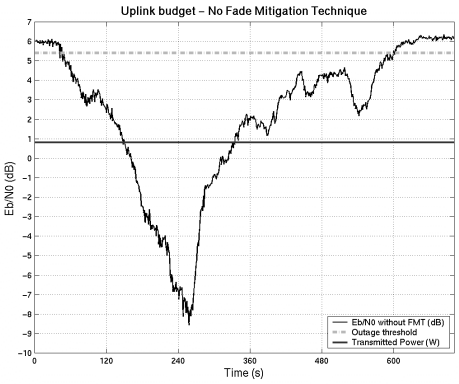
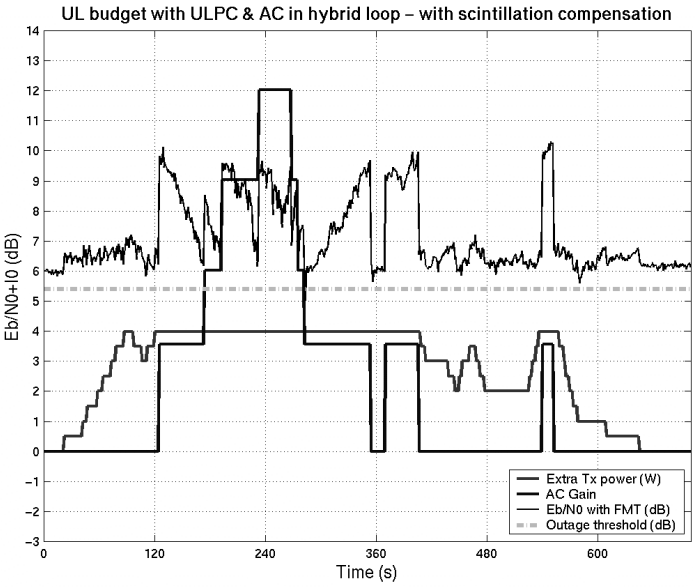
# EVENT-BASED ANALYSIS WITH FMT

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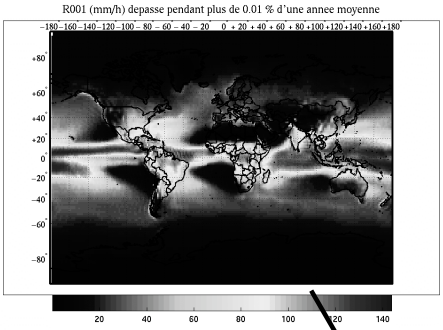
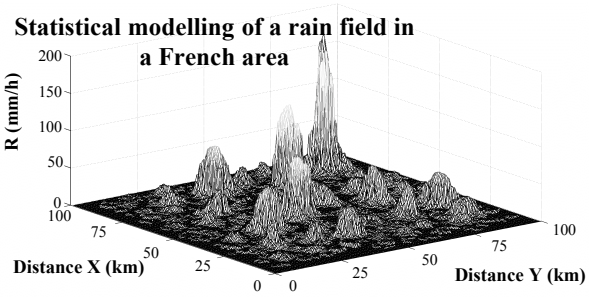
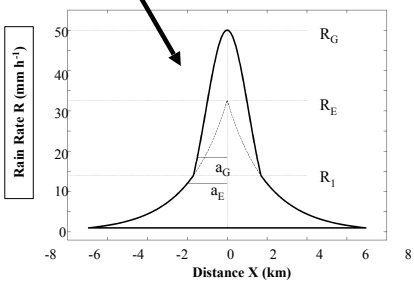
# ADVANCED CHANNEL MODELS :

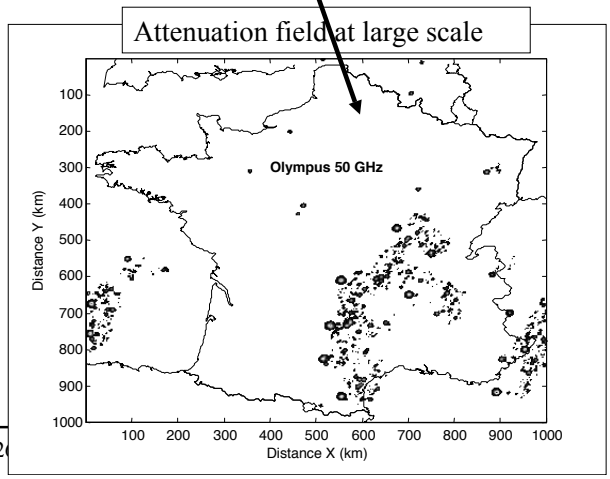
# SPATIAL VARIATIONS




**HYCELL model :**

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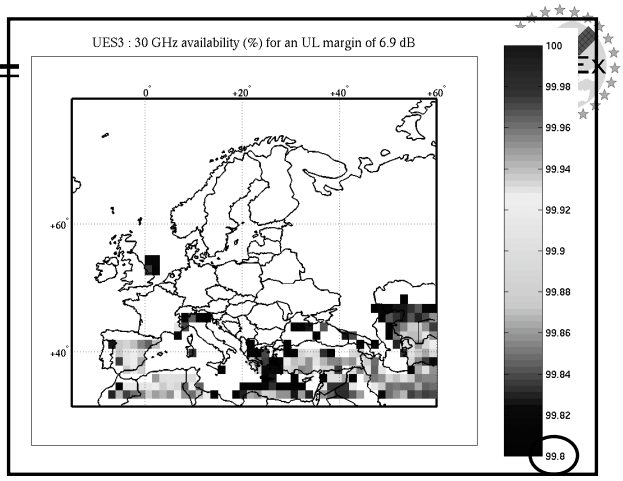
# Ex: LINK AVAILABILITY WITH ULPC




## ❒ APPLICATION DOMAIN

- Possible whatever the type of service : real time or not, reliable or not, ...

## ❒ DEFINITION OF ULPC

- Output power : from 600 mW to 2 W
  ⇨ ULPC dynamic range ≈ 6 dB

| Frequency | 29.75 GHz | 29.75 GHz | Coding rate | 2/3 | 2/3 | Uplink information data |
|---|---|---|---|---|---|---|
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |

**Required availability = 99.8 %**

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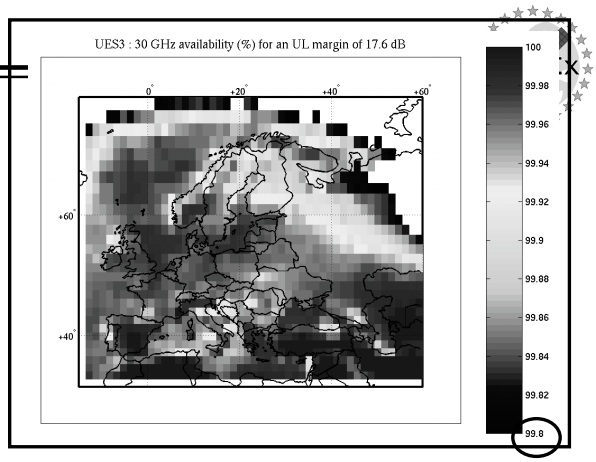
# LINK AVAILABILITY WITH ULPC & AC




## ❒ DEFINITION OF JOINT FMT

- ULPC : from 800 mW to 2 W
- AC : Constant Tx DR : **$R_c$ = 3019 kbit/s**
- DRA : DR / 2 and DR / 4
- FMT dynamic range : **16.0 dB**

| Frequency | 29.75 GHz | 29.75 GHz | 29.75 GHz | 29.75 GHz | Coding rate | **3/4** | **1/2** | **1/3** | **1/3** | Uplink in |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |

**Required availability = 99.8 %**

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# CONCLUSION

- **LINK PERFORMANCE**
  - Conditions QoS and other system performance
  - Strong fades occurs for significant time percentages as frequency increases (Ka, Q/V…)
  - Static link margins are used for conventional systems
- **FMTs allows mitigation of strong fades**
  - Power control, ACM, diversity…
  - FMT techniques are complementary
- **FMT implementation**
  - Several functions: estimation, prediction, decision
  - Open, closed, hybrid detection schemes
  - Centralized and distributed architectures
  - Decision/Hysteresis margins
- **New Link budget design approach with ACM**
  - No longer defined for worst case location
  - Matched to each station-to station link
  - Significant increase in system capacity (clear sky), availability & coverage (rain conditions)

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