# Link Considerations

Prof. Otto Koudelka

Institute of Communication Networks and Satellite Communications, TU Graz
koudelka@tugraz.at



# PERFORMANCE

- characteristics of
  - TX station
  - RX station
- Propagation effects
- noise, interference
- characteristics of satellite



# NOISE

- Noise power

$$N = N_0 B = kTB$$

k…Boltzman constant
T…System noise temperature
B…System bandwidth



# INVERSE SQUARE LAW

- Carrier power
- $A_{eff}$... effective antenna aperture
- R...distance
- $G_T$...transmit antenna gain

$$C = \frac{P_T}{4\pi R^2} G_T A_{eff}$$



# ANTENNA GAIN

$$A_{eff} = \frac{G\lambda^2}{4\pi} = \eta A$$

$$G = \eta \frac{4\pi}{\lambda^2} \frac{D^2 \pi}{4} = \eta \frac{\pi^2 D^2}{\lambda^2}$$



# CARRIER POWER

$$C = \frac{P_T G_T}{4\pi R^2} \left( \frac{G_R \lambda^2}{4\pi} \right)$$

$$EIRP = P_T G_T$$

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

free-space loss

## CARRIER/NOISE RATIO

$$C = \frac{C}{N} N = \frac{C}{N} k T_s B$$

$$\frac{C}{N} = \frac{P_T G_T}{(4\pi R/\lambda)^2} \left( \frac{G_R}{T_s} \right) \frac{1}{kB}$$



## FIGURE OF MERIT

- G/T
- important characteristic for
  - satellite
  - ground station



## LINK BUDGET CALCULATION

- figures may vary widely
  - EIRP high
  - free-space loss very high
  - receive carrier power very low
- logarithmic representation advantageous



## LOGARITHMIC REPRESENTATION

- Signal-to-noise ratio [dB]

$$\frac{C}{N} = 10\log(P_T) + 10\log(G_T) - 20\log\left(4\pi R/\lambda\right) + 10\log(G_R) - 10\log(T_s) - 10\log(k) - 10\log(B)$$

$$\frac{C}{N} = EIRP_{[dBW]} - L_{s[dB]} + (G/T)_{[dB/K]} - k_{[dBJ/K]} - B_{[dBHz]}$$



## $E_b/N_o$

- energy per bit / noise density
- r...rate of information (not necessarily channel rate)

$$\frac{E_b}{N_o} = \frac{C}{N} \frac{B}{r}$$



## $C/N_o$

- carrier power / noise density

$$\frac{C}{N_o} = EIRP_{[dBW]} - L_{s[dB]} + (G/T)_{[dB/K]} - k_{[dBJ/K]}$$

## C/T

- also used in link budgets
- in [dBW/K]
- leaves out *k = -228.6 dB(J/K) and* bandwidth
- at the end of calculation B and k taken into account

$$\frac{C}{T} = EIRP_{[dBW]} - L_{s[dB]} + (G/T)_{[dB/K]}$$



## EXAMPLE 1

- Antenna gain
  - f = 14.0 GHz
  - antenna diameter: 0.8 m
  - antenna efficiency: 60%

$$G = 10\log\left(\eta\frac{\pi^2 D^2}{\lambda^2}\right) = 10\log\left(0.6\frac{\pi^2 0.8^2}{\left(\frac{3E8}{14E9}\right)^2}\right) = 39.16dB$$



## EXAMPLE 2

- Antenna gain
  - f = 30 GHz
  - antenna diameter: 0.8 m
  - antenna efficiency: 60%

$$G = 10\log\left(\eta\frac{\pi^2 D^2}{\lambda^2}\right) = 10\log\left(0.6\frac{\pi^2 0.8^2}{\left(\frac{3E8}{30E9}\right)^2}\right) = 45.8dB$$



## EXAMPLE 3

- EIRP
  - f = 14.0 GHz
  - antenna diameter: 2.4 m
  - antenna efficiency: 60%
  - transmit power: 16 W

$$G = 10\log\left(\eta\frac{\pi^2 D^2}{\lambda^2}\right) = 10\log\left(0.6\frac{\pi^2 2.4^2}{\left(\frac{3E8}{14E9}\right)^2}\right) = 48.7dB$$



## EXAMPLE 4

$$EIRP = 10\log(16) + 48.7 = 60.7dBW$$

- corresponds to 1,174,897.5 W



## EXAMPLE 5

- free-space loss, GEO satellite
- f = 14 GHz

$$L_{fs} = 10\log\left(\frac{4\pi R}{\lambda}\right)^2 = 20\log\left(\frac{4\pi R}{\lambda}\right) = 20\log\left(\frac{4\pi 39E6}{0.0214}\right) =$$

= 207.2 dB

## EXAMPLE 6

- free-space loss, GEO satellite
- f = 12 GHz

$$L_{fs} = 10\log\left(\frac{4\pi R}{\lambda}\right)^2 = 20\log\left(\frac{4\pi R}{\lambda}\right) = 20\log\left(\frac{4\pi 39E6}{0.025}\right) =$$

= 205.8 dB

ERASMUS-IP Satellite Communications Systems

## EXAMPLE 7

- free-space loss
- f = 30 GHz

$$L_{fs} = 10\log\left(\frac{4\pi R}{\lambda}\right)^2 = 20\log\left(\frac{4\pi R}{\lambda}\right) = 20\log\left(\frac{4\pi 39E6}{0.01}\right) =$$

= 213.8 dB

ERASMUS-IP Satellite Communications Systems

## ANTENNA GAIN VERSUS FREE-SPACE LOSS

- 2.4 m antenna, different frequencies
- 14 GHz: G = 48.7 dB
- 30 GHz: G = 55.3 dB
- difference: + 6.6 dB

- difference in free-space loss: - 6.6 dB !

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## EXAMPLE 8

- free-space loss, LEO satellite, 800 km distance
- f = 2.2 GHz

$$L_{fs} = 10\log\left(\frac{4\pi R}{\lambda}\right)^2 = 20\log\left(\frac{4\pi R}{\lambda}\right) = 20\log\left(\frac{4\pi 8E5}{0.136}\right) =$$

= 157.3 dB

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## ADDITIONAL LOSSES

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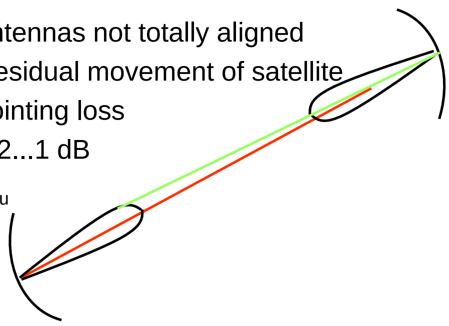
## POINTING LOSS

- antennas not totally aligned
- Residual movement of satellite
- pointing loss
- 0.2...1 dB
- $L_{pu}$



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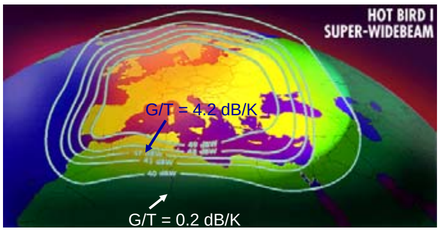
## CONTOUR LOSS

- satellite antenna gain reduces at outer zones with respect to beam center






## OUTPUT LOSSES

- HPA connected to feed via waveguide
- resulting in additional loss
- design should be such that output losses are minimum
- $L_{out}$



## ATMOSPHERIC ATTENUATION

- gaseous absorption in atmosphere
- attenuation by hydrometeors
- depending on rain rate, drop size, frequency
- $L_{atu}$



## PROPAGATION EFFECTS

- Influence by troposphere
  - region up to 15 km
  - absorption
  - depolarization
- Influence by ionosphere
  - much less significant at microwave frequencies



## PRECIPITATION

- Occurrence of precipitation defined by percentage of time during which a given intensity is exceeded
- Rain rate in mm/h
- Different climatic zones
- Measurements necessary for each zone



## PRECIPITATION

- rain drop size important
- hail produces very significant attenuation
- wet snow
- dry snow less critical

# EUROPE AFRICA

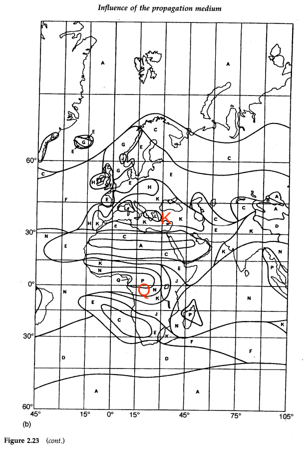
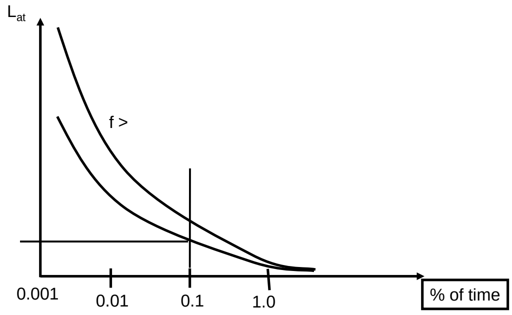



Figure 2.23 (cont.)



# CUMULATIVE STATISTICS






# AVAILABILITY

- Percentage of time in which defined QoS is met
- e.g. bit error rate of $10^{-6}$ for 99.9 %
- Outage: percentage of time in which attenuation is too high to meet QoS
- e.g. 0.1 % = 8.76 hours /year
- 0.01 % = 53 minutes /year



# AVAILABILITY

- directly related to precipitation time statistics



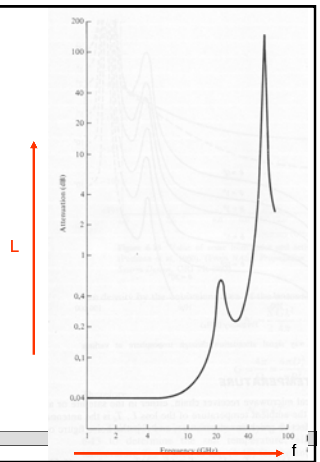
# CLEAR SKY ATTENUATION

- Depends on
  - frequency
  - elevation angle
  - atmosphere
    - pressure
    - temperature
    - water vapour content



OXYGEN
WATER
VAPOUR
ABSORPTION

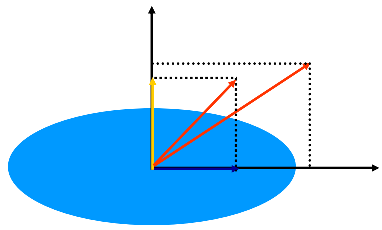
at zenith



# OTHER EFFECTS



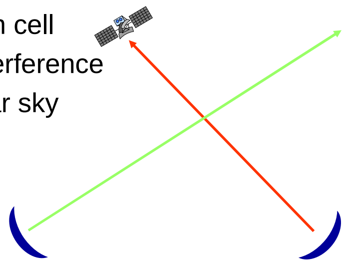
# DEPOLARIZATION





# SCATTERING

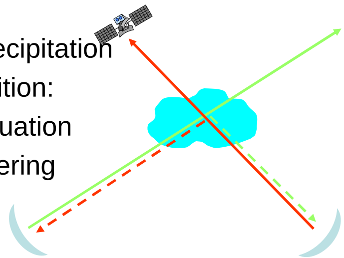
- on rain cell
- no interference in clear sky





# SCATTERING

- in precipitation condition:
- attenuation
- scattering



- interference



# SCINTILLATIONS

- Variation of refraction index of atmosphere (troposphere and atmosphere)
- Refraction index of troposphere
  - decreases with altitude
  - independent of frequency



# SCINTILLATION

- several dB fluctuation at Ka-band
- fast in comparison with tropospheric attenuation

# SATELLITE ANTENNA NOISE TEMP.

- Noise from earth
- Noise captured from outer space
- Oceans radiate more noise than land masses
- Conservative figure: 290 K



# UPLINK EXAMPLE (1)

- f = 14.0 GHz
- $G_T$= 48.7 dB
- P = 16 W = 12 dBW
- Output back-off: 3 dB
- R = 39,000,000 m
- G/T = 4.2 dB/K
- B = 2.048 MHz



# UPLINK EXAMPLE (2)

- Output loss $L_{out}$ = 1 dB
- Atmospheric loss $L_{atu}$ = 0.6 dB
- Contour loss $L_{cu}$ = 2 dB
- Pointing loss $L_{pu}$ = 0.4 dB



# UPLINK

$$\frac{C}{T} = EIRP - BO - L_{out} - L_{fsu} - L_{pu} - L_{cu} - L_{atu} + (G/T)$$

$$\frac{C}{T} = 60.7 - 3 - 1 - 207.2 - 0.4 - 2 - 0.6 + 4.2 = -149.3 dBW/K$$

$$\frac{C}{N} = \frac{C}{T} - 10\log(k) - 10\log(B)$$

$$\frac{C}{N} = -149.3 - (-228.6) - 63.1 = 16{,}17 dB$$



# POWER FLUX DENSITY

- At transponder input

$$\Phi = \frac{EIRP_{eff}}{A} = \frac{EIRP_{eff}}{4\pi r^2}$$

$$EIRP_{eff} = \frac{P_{out} G_T}{L_{out} L_{pu} L_{cu} L_{atu}}$$

$$EIRP_{eff} = P_{max} - BO + G_T - L_{out} - L_{cu} - L_{pu} - L_{atu}$$

in dB



# “SPREADING LOSS”

$$L_{spr} = 10\log(4\pi r^2)$$ in $dBm^2$

$$L_{spr} = 10\log(4\pi\, 39000000^2) = 162.8 dB\, m^2$$

# INPUT FLUX DENSITY

- in dBW/m²

$$\Phi = P_{\max} - BO + G_T - L_{out} - L_{cu} - L_{pu} - L_{atu} - L_{spr}$$



# TRANSPONDER FLUX DENSITY

- Key parameter of transponder
- IPFD… input power flux density for saturation
- can be set by telemetry to adjust the sensitivity of transponder
- e.g. $\Phi_{sat}$ = - 96 dBW/m²



# INPUT BACK-OFF

- Difference of actual received flux density and IPFD
- $B_{in} = \Phi_{sat} - \Phi$

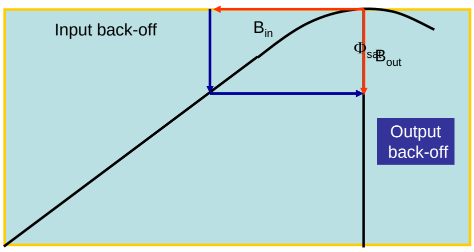


# BACK-OFF

- usually the max. EIRP of ground station is given
- back-off in dB from max. EIRP
- EIRP = $EIRP_{max}$ - BO
- max. EIRP may drive HPA into saturation
  - not possible for multi-carrier operation
  - also degradation depending on modulation scheme



# POWER TRANSFER CURVE




In linear region difference between output and input backoff: e.g. 4.5 dB



# IPFD EXAMPLE

$$L_{spr} = 10\log(4\pi\, 39000000^2) = 162.8dB\, m^2$$

$$\Phi = P_{\max} - BO + G_T - L_{out} - L_{cu} - L_{pu} - L_{atu} - L_{spr}$$

$$\Phi = 12 - 3 + 48.7 - 1 - 2 - 0.4 - 0.6 - 162.8$$

$$\Phi = -109.1dBW / m^2$$

## INPUT/OUTPUT BACKOFF EXAMPLE

$\Phi_{sat} = -96\ \text{dBW/m}^2$

- $B_{in} = \Phi_{sat} - \Phi = -96 - (-109.1) = 13.1$ dB
- $B_{out} = 13.1 - 4.5 = 8.6$ dB



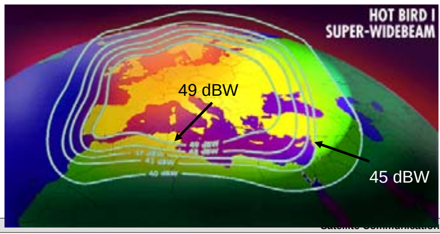
## SATELLITE EIRP

- Maximum EIRP of transponder: specified $EIRP_{sat}$
- EIRP due to drive level:
  $EIRP = EIRP_{sat} - B_{out}$
- Example:
- $EIRP_{sat} = 49$ dBW
  $EIRP = 49 - 8.6 = 40.4$ dBW



## DOWNLINK CONTOUR

- EIRP towards earth station reduced
- $EIRP_e = EIRP - L_{cd}$






## FURTHER LOSSES

- Downlink free-space loss
- Pointing loss of earth station antenna
- Propagation loss on downlink
- Input loss at receiver

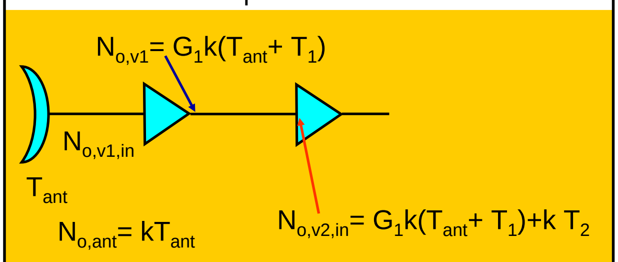


## FIGURE OF MERIT OF GROUND STATION



## RECEIVER NOISE TEMPERATURE

- cascaded amplifiers and antenna



## SYSTEM NOISE TEMPERATURE

- referred to input of first stage

$$N_{o,v1,in} = k(T_{ant} + T_1 + T_2/G_1)$$

$$T_{sys} = T_{ant} + T_1 + T_2/G_1$$ Friis formula

$$T = (F - 1)T_o$$

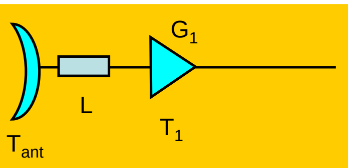


## LOSSY SYSTEMS

- lossy lines (e.g. coaxial cables, waveguides)
- L = input power / output power = 1/G
- $T_e = T_{source}$ (L - 1)
- if network (resistor) at $T_o$ : L = F, $T_L$=(L-1).290



## RECEIVER WITH LOSSY LINES




$$T_{sys} = T_{ant} + T_L + L\,T_1$$

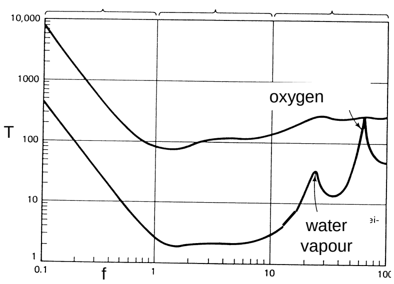


## EARTH STATION ANTENNA

- noise from sky
- noise from earth
- above 2 GHz: dominant contribution from non-ionized region of atmosphere
- depends on elevation angle
- Typ. Figure for Ku-band antenna: 70 K



## ANTENNA NOISE






## INCREASE IN NOISE TEMPERATURE

- Atmosphere: “lossy line”
- $T_m$ … medium temperature, 280 K
- to be added to overall noise temperature

$$T_{at} = \left(1 - \frac{1}{L_{at}}\right) T_m$$

## ATMOSPHERIC ATTENUATION

- specific attenuation $\alpha$ in [dB/km]
- l… path length in
- $R_p$…rain rate

$$\alpha = a R_p^b$$

$$L_{at} = \alpha l$$



## OVERALL NOISE TEMPERATURE

- Clear sky:

$$T_{sys} = T_{ant} + T_L + L T_1$$

- Precipitation:

$$T_{sys} = T_{ant} + (1 - \frac{1}{L_{atd}}) T_m + T_L + L T_1$$



## PROPAGATION MEASUREMENTS

- Beacon receivers
- Radiometers
- Radar
- Rain gauge



## BEACON RECEIVER

- Precise constant-level beacon carrier from satellite used
- Narrow-band PLL receiver with high dynamic range > 30 dB
- Any decrease in signal level due to atmospheric attenuation
- Calibration of receiver in regular intervals by hot and cold load



## BEACON RECEIVER

- Environment must be stable
  - air-conditioned receiver, constant temperature
  - antenna heating to avoid water and snow on surface
- Measurement intervals: 60, 10, 1 s (even sub-second)



## RADIOMETER

- passive
- measurement of background temperature
- higher attenuation -> higher loss -> higher noise temperature
- calibration against beacon receiver

## EXAMPLE

- $L_{atd}$ = 4 dB = 10 $^{0.4}$ = 2.5
- $T_{at}$ = (1 - 1/2.5) 280 = 168 K



## VARIATIONS

- can reach up to 1 dB/s at Ka-band
- slower at Ku-band
- any fade countermeasure technique must be able to cope with fluctuations



## DOWNLINK



## C/T DOWNLINK

$$\left(\frac{C}{T}\right)_d = EIRP - L_{cd} - L_{fsd} - L_{pd} - L_{atd} - L_{in} + (G/T)_e$$

$EIRP_e$…EIRP satellite
$L_{cd}$…downlink contour loss
$L_{fsd}$…downlink free-space loss
$L_{pd}$…pointing loss (downlink)
$L_{in}$…input loss
$G/T_e$…ground station figure of merit



## EXAMPLE

- EIRP = 40.4 dBW
- Downlink contour: 3 dB
- Pointing loss: 0.3 dB
- LNB noise temperature: 80 K
- Antenna temperature: 70 K
- Input loss: 0.1 dB
- Atmospheric attenuation: 2.5 dB



## EXAMPLE

- Receive frequency: 12.5 GHz
- Antenna size: 2.4 m
- Antenna efficiency: 60 %

$$G_R = 10\log\left(\eta\frac{\pi^2 D^2}{\lambda^2}\right) = 10\log\left(0.6\frac{\pi^2 2.4^2}{\left(\frac{3E8}{12.5E9}\right)^2}\right) = 47.7dB$$

## G/T Earth Station

- calculate system noise temperature

$$T_{sys} = T_{ant} + (1 - \frac{1}{L_{atd}})T_m + T_L + L\,T_1$$

$$T_{sys} = 70 + (1 - \frac{1}{10^{0.25}})280 + (1.02 - 1)290 + 1.02.80$$

$$T_{sys} = 281.16\,K$$

$$G/T_e = 47.7 - 10\log(281.16) = 23.2 dB/K$$



## C/T DOWNLINK

$$\left(\frac{C}{T}\right)_d = EIRP - L_{cd} - L_{fsd} - L_{pd} - L_{atd} - L_{in} + (G/T)_e$$

$$L_s = 20\log\left(\frac{4\pi R}{\lambda}\right) = 20\log\left(\frac{4\pi 39E6}{0.024}\right) = 206.2dB$$

$$\left(\frac{C}{T}\right)_d = 40.4 - 3 - 206.2 - 0.3 - 2.5 + 23.2 - 0.1 = -148.5dBW/K$$



## OVERALL C/T

- Composed of uplink and downlink

$$\frac{C}{T} = \frac{1}{(C/T)_u^{-1} + (C/T)_d^{-1}}$$



## EXAMPLE

- Overall C/T

$$\frac{C}{T} = 10\log\left(\frac{1}{10^{-(-149.3/10)} + 10^{-(-148.5/10)}}\right)$$

$$\frac{C}{T} = -151.9 dBW/K$$



## C/N

- Bandwidth = 2.048 MHz
- C/N = -151.9 -(-228.6) – 63.1 = 13.6 dB
- Assuming Eb/No minimum of 6.2 dB and 1 dB implementation loss
- additional 6.4 dB margin



## INTERMODULATION NOISE

- Intermodulation noise generated in non-linear transponder

$$\left(\frac{C}{N}\right)^{-1} = \left(\frac{C}{N}\right)_u^{-1} + \left(\frac{C}{N}\right)_d^{-1} + \left(\frac{C}{N_i}\right)^{-1}$$

## INTERMODULATION

- Number of carriers
- modulation characteristics
- amplitude & phase characteristics of transponder



## INTERFERENCE

- Co-channel
- Adjacent channel
- Interference models provided by satellite operator

$$\left(\frac{C}{N}\right)^{-1} = \left(\frac{C}{N}\right)_u^{-1} + \left(\frac{C}{N}\right)_d^{-1} + \left(\frac{C}{N_i}\right)^{-1} + \left(\frac{C}{I}\right)^{-1}$$