8. Let it Snow—Atmospheric Impairments

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Atmospheric Phenomena

- **Absorption**: A reduction in the amplitude (field strength) of a radiowave caused by an irreversible conversion of energy from the radiowave to matter in the propagation path.

- **Scattering**: A process in which the energy of a radiowave is dispersed in direction due to interaction with inhomogeneities in the propagation medium.

- **Refraction**: A change in the direction of propagation of a radiowave resulting from the spatial variation of refractive index of the medium.

- **Diffraction**: A change in the direction of propagation of a radiowave resulting from the presence of an obstacle, a restricted aperture, or other object in the medium.

- **Multipath**: The propagation condition that results in a transmitted radiowave reaching the receiving antenna by two or more propagation paths. Multipath can result from refractive index irregularities in the troposphere or ionosphere, or from structural and terrain scattering on the Earth’s surface.

- **Scintillation**: Rapid fluctuations of the amplitude and the phase of a radiowave caused by small-scale irregularities in the transmission path (or paths) with time.

- **Fading/Shadowing**: The variation of the amplitude (field strength) of a radiowave caused by changes in the transmission path (or paths) with time.
Origin of Propagation Impairments

- Major Effects coming from
  - the troposphere, extending from the ground to an altitude of 15 km
  - Major effects close to the ground
  - The ionosphere, situated between 70 and 1000 km
    - Major effect at 400km
- Strongly different on different frequency bands
- Not fully predictable
ITU-R gives recommendations about how to compute the atmospheric attenuation in link budget and system design, and provides map of (average) values for different regions of the world

- Atmospheric gases attenuation in dB (ITU-R P.676 Annex 2)
- Rain attenuation in dB (ITU-R P.618)
- Clouds attenuation in dB (ITU-R P. 840)
- Scintillation in dB (ITU-R P.618-8)

The Recommendations rely on a set of publicly available data

- Rain intensity in dB (ITU digital maps)
- Wet term of refraction co-index (ITU digital maps)
- Rain height (ITU digital maps)
- Total Columnar content (ITU digital maps)
- Water vapor content (ITU digital maps)
- Temperature (ITU digital maps)
• **The attenuation is strongly dependent on the carrier frequency**
  - It can be predicted via physical models as a function of the *rain rate* \( r \) in mm/h and of the *path* \( l_e \) traveled by the radio wave in the rain:

\[
L_{rain} = \gamma_r l_e = a r^b l_e \text{ (dB)}
\]

- \( \gamma_r \text{ (dB/km)} \) depends on the rain rate as \( \gamma_r = a r^b \) (\( a \) and \( b \) temperature- and frequency-dependent coefficients)
- \( l_e \) is the equivalent path length (km) in the rain, depending on the satellite elevation \( \theta \), the height of the rain zone \( h_r \), etc. *(the formulas are too cumbersome)*
Example: overall values of $\gamma_r$

- As shown in this particular but typical case, the attenuation beyond $Ka$ band is problematic
- Some form of countermeasures are needed (diversity) to increase availability of the link
- The relevance of the countermeasures strongly depend on the climatic zone ($cdf$ of rain rate)
- Leads to an attenuation $L_{\text{rain}}$ that is substantially negligible below 3 GHz
Rain intensity $r$ (mm/h) exceeded for 0.01% of an average year – The corresponding attenuation $L_{\text{rain}} = a r^b I_e$ becomes an additional margin in the link budget to secure 0.01% availability.
In practice, a worst-case approach is taken: the value of $r$ is taken as the worst-case $x\%$ of the (average) year to grant a $(100-x)\%$ availability of the link.
• Idea: Re-routing the traffic to an Earth station which is experiencing less attenuation.

• Diversity gain calculated using empirical formulas specified in the ITU-R P.618 recommendation as a function of site distance $d$.

Gateway with an elevation angle of 30 degrees suffers 15 dB of attenuation for a given availability. When there is a second gateway separated by 10 km, for the same availability, there will be 6.2 dB reduction in the attenuation.
It’s not over: *Depolarization* caused by rain

- It is produced from a differential attenuation and phase shift caused by non-spherical, possibly inclined (due to wind) raindrops
  - Particularly relevant when polarization diversity is used to increase spectral efficiency

\[
I_1 \triangleq 10 \log \left( \frac{|E_{11}|^2}{|E_{21}|^2} \right)
\]

\[
I_2 \triangleq 10 \log \left( \frac{|E_{22}|^2}{|E_{12}|^2} \right)
\]
In general, negligible for “reasonable” frequencies and “reasonable” elevation angles.

Circular polarization can be considered equivalent to 45-degree linear.
Different Gas Components of the atmosphere give different unit attenuation coefficients (dB/km)

Notice the notorious absorption peak @ 60 GHz
The total attenuation is computed according to the path traveled into the atmosphere (depending on the elevation $\theta$).

In practice, we take the Zenith attenuation $A_\theta = \frac{A_0}{\sin(\theta)}$.

Again, negligible for “low” frequencies, considerable for Q band (33-50 GHz) or V band (40-75 GHz).
- **Fog**
  - Is made of water *droplets*, not water vapor
  - Attenuation negligible at all frequencies < 100 GHz

- **Clouds**
  - Water droplets again, not water vapor
  - Are characterized by water content \((g/m^3)\). The total attenuation is the product of unit attenuation \((dB/(g/m^3))\) times the total content of the "water column" above the Earth station \((kg/m^2)\), divided of course by \(\sin(\theta)\) (elevation angle)
  - The result is a substantially smaller attenuation than for rain, but in general on longer time periods.
Attenuation significant only beyond Ku-band

![Graph showing cloud attenuation vs. frequency and elevation angle]

- Frequency (GHz) range: 10 to 110
- Elevation Angle (degrees)
- Cloud Attenuation (dB)
- Lines represent different values (5, 7, 10, 20, 30 dB)
The Ionosphere: Plasma gas

- The ionosphere is a region of ionized gas or plasma that extends from about 15 km to more than 400 km altitude.

- It is ionized by solar radiation in the ultraviolet and x-ray frequency range and contains free electrons and positive ions (actually, less than < 1% molecules, mainly oxygen and nitrogen, are ionized)

- The free electrons affect electromagnetic wave propagation for satellite communications – it is not just propagation in the vacuum any longer

- The effect is weak, but not negligible

- The main property of the ionosphere that affects propagation is the electron concentration as a function of the altitude
The main effects of this is i) Scintillation, and ii) Additional propagation delay.
Ionospheric Scintillation

- Rapid fluctuations of the amplitude and phase of the radiowave, caused by electron density irregularities in the ionosphere
- Strongest at UHF (30-300 MHz), strikes up to 7 GHz
- Is a source of fading/shadowing on the received signals - can be modeled with a Rayleigh/Nakgami distribution with Doppler spread 0.1-1 Hz and duration (up to) 30 minutes
The presence of electrons increases the refraction index of the ionosphere so that the wave is *retarded* wrt propagation in the vacuum (thicker medium...)

In terrestrial radio communication, this effect can be used to *bend* the path of the wave that “bounces back” on the ionosphere and propagate well beyond the horizon – this was used for long time in the HF band to realize intercontinental radio communications.

In GNSS, the distance from the satellite to the receiver (the *range*) $r$ is evaluated by measuring the “flight time” $\tau$ of the radio signal from the satellite to the user receiver as $r = c\tau$, i.e., assuming propagation in the vacuum. If the ionosphere introduces an additional (unknown) delay, then the measurement is *biased* and not accurate, and the positioning will result not accurate as well.

**Therefore**, especially for GNSS (and we are anticipating topics we will deal with later on in the course), we need to be able to estimate and possibly correct the ionospheric delay: ionospheric bulletins (Space Weather Centers)!
The refraction index of the ionosphere depends on the frequency $f$ of the wave, and on the local electron content $n_e(r)$, where $r$ is a generic point along the wave propagation path. The expression is found to be ($n_e$ in electrons/cm$^3$ and $f$ in Hz).

$$n(r) = 1 + \frac{40.3 \, n_e(r)}{f^2}$$

The flight time from the satellite to the Earth is

$$\tau = \int_{\text{EARTH}}^{\text{SAT}} \frac{ds}{v(r)} = \frac{1}{c} \int_{\text{SAT}}^{\text{EARTH}} n(r) ds = \frac{1}{c} \int_{\text{SAT}}^{\text{EARTH}} \left(1 + \frac{40.3 \, n_e(r)}{f^2}\right) ds = \frac{r}{c} + \frac{40.3}{f^2} \frac{1}{c} \int_{\text{SAT}}^{\text{EARTH}} n_e(r) ds$$

We see that $r/c$ is the vacuum-propagation delay, so that the ionospheric (additional) delay $\tau_{\text{iono}}$ is...

$$\tau_{\text{iono}} = \frac{40.3}{f^2} \frac{1}{c} \int_{\text{SAT}}^{\text{EARTH}} n_e(r) ds = \frac{40.3}{c \cdot f^2} N_T$$
Iono delay values

\[ \tau_{\text{iono}} = \frac{40.3}{c \cdot f^2} N_T \]

- \( N_T \) is the Total Electron Count (TEC) along the radio path and it is the parameter that actually determines how large the iono delay is.
- The equation is also formulated as

\[ \tau_{\text{iono}} = \frac{1.345}{f^2} N_T \cdot 10^{-25} \]

- with \( N_T \) expressed now in electrons /m\(^2\) and frequency in GHz.
- Usual values of TEC are \( 10^{16} - 10^{18} \) /m\(^2\)
Mean Values of VTEC (Vertical $N_t$) across the Years

![Graph showing mean values of VTEC across the years.](image)

- Location: 54.4°N; 13.4°E
- Time: 11:00–14:00 LT

VTEC count ($10^{16}$ Units) vs. Year (1996–2010)
• The nominal delay for a GALILEO satellite @ 24,000 km altitude is 80 ms – this delay (smaller than 1 μs) may appear negligible but...
• It actually represent a *bias* in the sat-to-Earth range with values above – not negligible at all if we wish to get to an accuracy of about 1 m !!!
We can now get back to Link Budget with impairments...
Adverse Propagation Conditions

5 dBs SNIR variation range

User Terminal SNIR evolution

Fading attenuation during a storm event

Atmospheric Attenuation at 20 GHz (99.7%)
Adaptive/Variable Coding and Modulation (ACM/VCM)

**MOD**

- **Bit-rate Control, MODCOD Selection**
  - Highly protected MODCOD, Lower bit rate, Lower required \( \text{C/N+I} \)
  - Low-Protected MODCOD
  - Feedback Channel -> ACM
  - No Feedback -> VCM
  - DEM \( \text{C/N+I} \) Measurement

**Frame Multiplexing**

**Low-Protected MODCOD**

**Highly protected MODCOD, Lower bit rate, Lower required \( \text{C/N+I} \)**

**Feedback channel**

**Feedback**

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