ELEC-H415 - Communication channels

Analysis of a LEO satellite communication link

1. Objectives

Satellite communications have regained interest over the last few years, notably due to new large Low Earth Orbit (LEO) satellite constellations (e.g. Starlink), providing high data-rate internet everywhere on the globe, especially in remote regions. LEO satellites are much closer to the Earth than typical geostationary satellites, and they orbit around the Earth at a very high speed (28000 km/h!). A lot of them are needed to cover the entire globe (over 5000 Starlink satellites are currently active). These systems are currently operating in the Ku-band (10-12 GHz), but the trend is to occupy higher frequency bands. The aim of this project is to analyze the downlink communication of a next-generation LEO satellite connected to a ground station at 26 GHz.

2. Scenario

You are asked to model the downlink channel from a LEO satellite towards a ground station, under the following assumptions:

- Carrier frequency: 26 GHz.
- Bandwidth: 40 MHz.
- Transmitter EIRP: 40 dBW (10 kW).
- Receiver noise figure: 2 dB
- Receiver antenna temperature: 275 K
- Satellite orbit altitude: 500 km
- Satellite revolution period: 5668 s
- Rain rate exceeded for 0.01% of the time: 30 mm/h.

From a geometry point-of-view:

- The LEO satellite orbit is circular, and it passes through the zenith.
- Simulations will be done in a vertical plane where the satellite is traveling from 0° elevation to 90° (zenith), then to 180°.

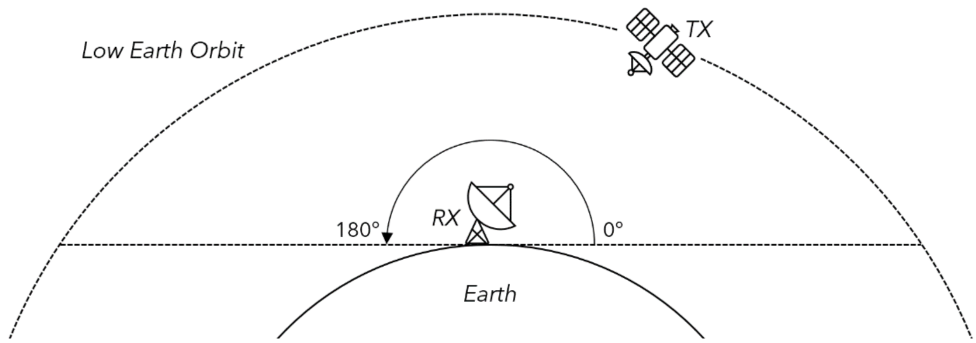

Figure 1 - Schematic of the satellite scenario

Assumptions:

- The transmitted waves are horizontally polarized, and they match the polarization of the receive antenna.

- Atmospheric attenuations are neglected unless for Bonus 1.1, where rain attenuation is considered.

Ray tracing hypotheses:
- For every position of the satellite, only the largest multipath component reaching the receiver is considered, the others are ignored.
- Only the rays arriving at the receiver with an angle between 0° and 180° are considered, such that the rays reflected off the ground are ignored.
- The relative permittivity of the building walls is 4.
- We only consider the Line-of-Sight (LOS), single reflections off buildings, and diffraction.

3. Results

The expected results are split into three different parts, each one implementing additional complexity to the link analysis.

- **Part 1**: Let's first consider that the ground station is equipped with a single lossless isotropic antenna ($G(\theta) = 1$), and that no obstacle is present around the receiver (only the LOS is incident).
  During one satellite pass, evaluate the following metrics, as a function of the satellite elevation:
    - Free space path loss
    - Received power (*)
    - Signal-to-noise ratio
    - Channel capacity (*)
    - Theoretical maximal total transmitted data during one satellite pass (*).

- **Part 2**: Let's consider now that the ground station is equipped with a horizontal Uniform Linear Array (ULA), which can have two types of elementary unit:
    - An isotropic antenna with $U(\theta) = U_0$
    - A patch antenna (microstrip) with $U(\theta) = U_0 \sin^2 \theta$

  The antennas in the array are spaced by a distance λ/2. When doing beamforming, it is assumed that the ULA is always perfectly pointing to the satellite position.

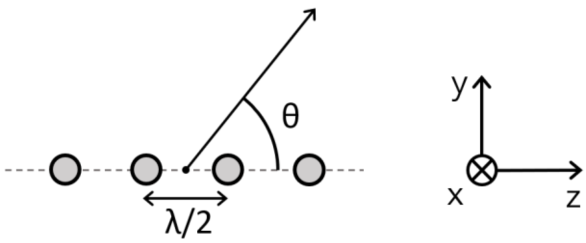

Figure 2 - Uniform Linear Array configuration

  Compute the array gain for both types of elementary units, and for 4, 8 and 16 array elements. For every ULA, draw the gain patterns (from 0° to 180°) for the following pointing angles: 90°, 45°, 30° and 0°. Discuss.
  Compute again the metrics of Part 1 marked with a (*). Discuss.

- **Part 3**: Consider that two buildings are next to the ground station, as depicted in Fig 3. What is the largest MPC received by the ground station for every elevation angle of the satellite? Does it change depending on the type of antenna? Considering only the strongest MPC, evaluate again the metrics of Part 1 marked with a (*) for the three types of antennas of Parts 1 and 2. Discuss.

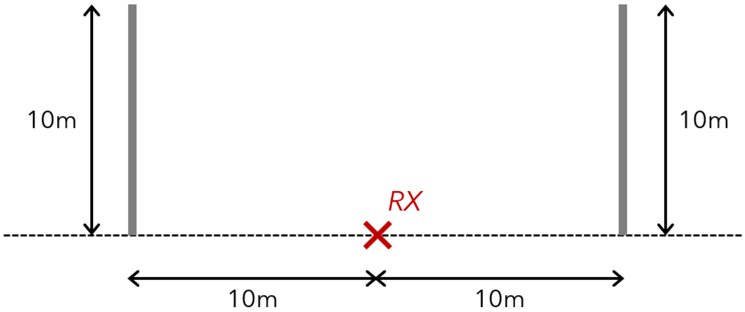

Figure 3 - Geometry of the scene

BONUS

- **Bonus 1.1**: Add rain attenuation for 1%, 0.1%, 0.01% and 0.001% annual exceedance. Plot the attenuation caused by rain as a function of the elevation angle and evaluate the same metrics from Part 1. How does rain impair the link? (See Appendix)
- **Bonus 1.2**: In practice, the bitrate cannot be adapted in real time to the SNR during the satellite pass. Evaluate the total data transmitted during one pass if a constant bitrate during the whole pass is used. Find the optimal bitrate to maximize the amount of data that could be transmitted in that way. From which elevation angle onwards will the satellite start transmitting data in this case? What happens if rain occurs?

- **Bonus 2.1**: Evaluate the optimal number of antennas in the linear array given a pointing error from 0.2° to 2°.

- **Bonus 3.1**: Would it be possible to establish NLOS communication at a sufficient bitrate? If not, what could we change to make it possible?

4. Report

Your report should contain 4 items:

- The theoretical foundations you used to develop your software and to obtain results. Please do not copy/paste the course notes. If something is already explained in the course notes, just make reference to it in your report. Any re-writing of the course content will be considered as a flaw.
- Validation of your calculation on some basic cases.
- Results.
- Analyses and physical interpretations of results.

The report (PDF file) has to be posted on the ULB Virtual University by Sunday May 26th.

Appendix – Rain attenuation

Signals are subject to different sources of attenuation when propagating through the atmosphere. The largest contribution comes from rain, which can significantly impair the signal reception, particularly at such high frequency bands. The International Telecommunication Union (ITU) provides recommendations on how to estimate rain attenuation on a statistical basis. The following formulas have been simplified, such that they approach the ITU recommendation results for elevation angles E ≥ 20°. For smaller elevation angles (E < 20°), consider the rain attenuation constant and equal to the one computed at 20° elevation.

Rain attenuation is depending on the rain rate and on the slant path length (there is also a frequency dependency that is not explicitly shown here). The rain rate is associated with a percent of time specification, such that we first evaluate the rain attenuation for a rain rate $R_{0.01}$ which is exceeded for 0.01% of the time, and then we can infer other percentages based on that reference value. The rain attenuation L_r for an exceedance percentage of 0.01% is given by the following expression:

$$L_r(0.01) = \gamma d_s$$

The slant-path distance d_S can be found by looking at the geometry shown in Fig 4, which gives

$$d_s\ [\text{km}] = \frac{h_R}{\sin E}$$

where the rain height $h_R = 2.4$ km and E is the elevation angle.
The specific attenuation γ is given by

$$\gamma = kR_{0.01}^{\alpha}$$

with the following coefficients

$$k = 0.15 + 0.003\cos^2 E \qquad\qquad \alpha = \frac{0.15 + 0.007\cos^2 E}{k}$$

The rain attenuation for any other percentage of exceedance p can then be computed with the following expression:

$$L_r(p) = L_r(0.01)\left(\frac{p}{0.01}\right)^{-0.65-0.03\ln(p)+0.05\ln(L_r(0.01))}$$

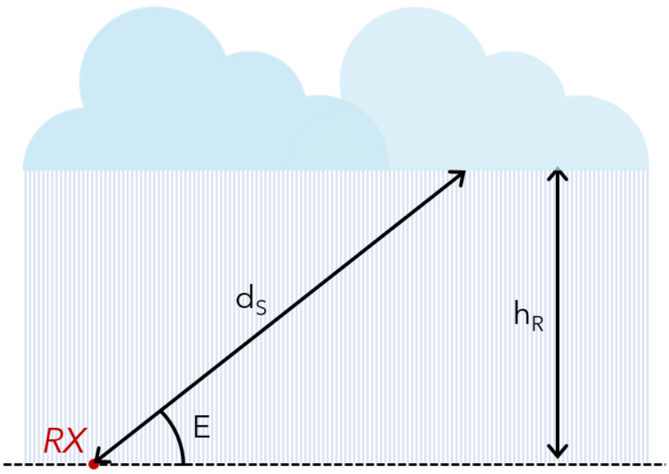

Figure 4 - Slant-path length