POLITECNICO DI MILANO

School of Industrial and Information Engineering

Department of Aerospace Science and Technology

SATELLITE COMMUNICATION AND POSITIONING SYSTEMS

Starlink satellite downlink design

Author:
Niccolò BARDAZZI 10800456

16/01/2022
Academic Year 2021-2022

Abstract

Low earth orbit (LEO) satellite communication systems have attracted extensive attention due to their smaller pathloss, shorter delay and lower launch costs compared with their geostationary counterparts. In this way, a LEO constellation would drastically reduce the price per satellite with a big increment in performances. This brings to a much more market competitiveness due to a better technologies application. On the other hand, the number of satellites to be launched increases hence the overall system complexity grows exponentially.

Starlink's goal is to provide a global broadband coverage for high-speed internet access with performances comparable to 5G, especially for rural and remote areas. This user to Earth station connection Fig.1 is possible through 4 Earth-Space links: the uplink user-satellite, the downlink satellite-station, the uplink station-satellite and the downlink satellite-user. In this work it has been designed the downlink satellite-user through data collected from reports and engineering estimations which, in the end, lead to a very close sizing of the telecommunication subsystem. Of course this analysis can be easily extended to each satellite of the constellation with almost no changes.

Regarding the user ground terminal, the antenna takes around 15 minutes to be tracked by the satellite and to join the network. The system is fully autonomous, it means that once the link has been established, the antenna keeps steering the beam both mechanically and electronically. Every place on the Earth is fine for a link establishing, therefore this is an innovative way to provide internet and it is how it is going to work in the next future.

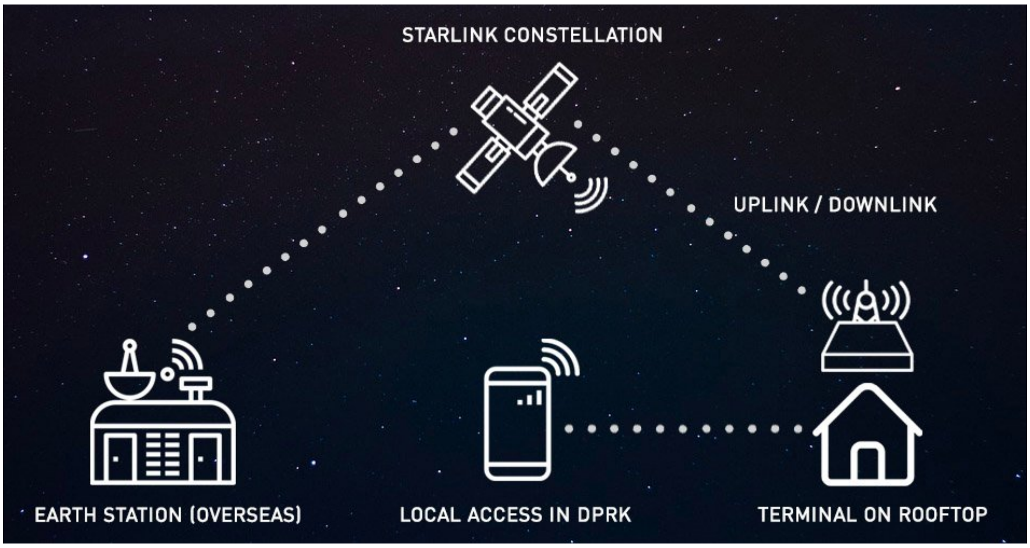

Figure 1: Starlink principle of working.

1 Introduction

1.1 Constellation overview

SpaceX' constellation, once fully deployed, will comprehend 4425 satellites distributed across several sets of orbits. The core constellation, which is still in phase beta, is composed of 1600 satellites evenly distributed in 32 orbital planes at 550 km, at an inclination of 53° [1]. The other 2825 satellites will follow in a secondary deployment, and will be distributed at 340 km and 1200 km altitudes (no further info are available after the 2020 change of plans). The whole constellation works in the Ku/Ka-band.

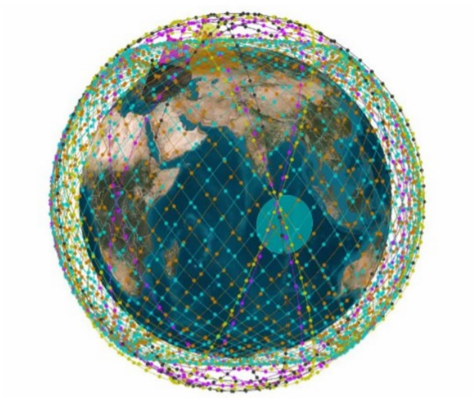

Figure 2: Starlink's constellation overview.

1.2 Satellite specifics

It has been selected a tracked Starlink's satellite (Starlink-61) for the exact knowledge of its keplerian elements which have been displayed in Tab.1.

Table 1: Starlink-61 keplerian elements [2].

Keplerian elements	Value
a_{mean}, km	6876.4
e	0.00055
i, °	52.986
ω, °	28.071
Ω, °	251.955

The requirements to be followed are:

- **R_0**: data rate prescribed to have a real impact on the market. At the moment R_0 is $\sim$100 Mbps, however with the imminent coming of 5G at least R = 1 Gbps is required [3].
- **BER**: Bit Error Rate needed to provide an efficient service. For Internet providers a reasonable estimate is 10^{-6}.
- **f**: carrier frequency chosen by SpaceX company which agrees with ITU-R Recommendations.
- **A**: availability of the link which has been estimated for a single satellite to be 99%.
- **RHCP**: polarization selected that SpaceX uses both for uplink and downlink while LHCP has been used for telemetry data [1]. The choice between these two only is due to Faraday rotation which in the linear polarization case would tilt the angle along a different direction leading to huge losses.

2 Transmitter side

The antenna is a phased array antenna, which works in the Ku-band. The company has the following allocation: 10.7–12.7 GHz, 14–14.5 GHz, for downlink and uplink user communications respectively, 17.8–18.55 GHz, 18.8–19.3 GHz for downlink gateway communications and 27.5–29.1 GHz, 29.5–30 GHz for uplink gateway communications [1] [4]. According to the ITU-R Recommendation(2020) all these ranges meet the requirements in the Regions 1-2-3 since the program has been intended for a global coverage. For the scope of the following project it has been selected the 12.7 GHz which is the one used for the downlink of user communications. Thus the transmitter gain can be computed in the following way:

$$G_{TX} = 10\log_{10}\left(\eta_{TX}\left(\frac{\pi D_{TX}}{\lambda}\right)^2\right) \quad (1)$$

where:

- $\eta_{TX} = 0.6$ is a common value
- λ is the wavelength in vacuum
- D_{TX} is the diameter of the transmitter, still unknown

Losses on the transmitter side are not known due to industrial secrets, however for the scope of the following project they can be neglected since they will be at least 2 orders of magnitude in the dB scale less than free-space losses.

3 Path attenuation

Since the number of satellites in the constellation is so high that when it will be fully operable, more than 20 satellites are expected to be present in the LoS of the most crowded place on Earth, the link can be taken as a zenithal downlink. Moreover, the working frequencies are really high, ensuring that the signal will bypass the atmosphere with a tiny curvature and really small ionospheric delay (< 0.36", $< 0.0025\,\mu$m according to ITU-R Recommendation 618).

Path attenuation is a sum of multiple factors including distance, pointing errors and propagating media. During the following work all the contributions have been taken into account with a particular attention on the atmospheric losses since are the ones that change in time.

3.1 Free-space losses

Assuming the altitude as a constant equal to the mean one (505.4 km), free space losses can be computed since they are only function of distance and frequency:

$$L_{FS} = 10\log_{10}\left(\frac{\lambda}{4\pi H}\right)^2 = -168.59\,\mathrm{dB} \quad (2)$$

where D is the user-satellite distance which has been taken coincident with the altitude.

3.2 Misalignment losses

Misalignment losses have been computed according to the following formula:

$$L_M = -12\left(\frac{e}{\theta}\right)^2 = -0.40\,\mathrm{dB} \quad (3)$$

where:

- e is the pointing error taken as $< \pm\, 1°$ (common value)
- θ is the half power beamwidth taken as 5.5° [5]

3.3 Atmospheric losses

The atmospheric losses have been recovered according to the link availability, frequency, latitude and longitude selections (as explained in section 1) with `p618PropagationLosses` MATLAB function [6] [7] of `Satellite Communications Toolbox`. The function uses the maps of ITU-R Recommendation P.1511, P.1510, P.836, P.840, P.837, P.435, P.839 which are respectively about topography (WGS-84 ellipsoid), annual mean surface temperature (ECMWF), water vapour content, clouds and fog, annual mean rainfall exceedance (ECMWF), refractivity and rain height (h(0°C)+0.36 km) to compute the atmospheric losses and the sky temperature (used later in subsection 4.4):

$$L_{atm} = -5.62\,\mathrm{dB} \quad (4)$$

Whether the availability of the system should be decreased or increased, it is possible to rely on Fig.3 which has been computed as explained previously for the whole outage range.

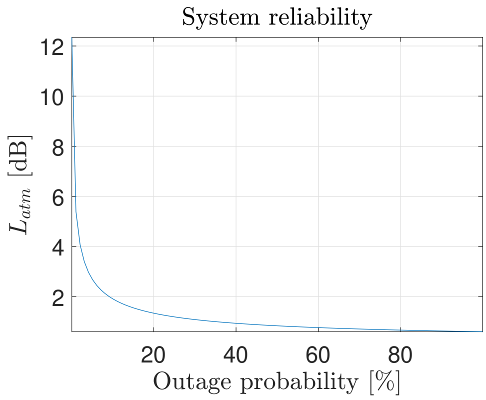

Figure 3: System reliability.

3.4 Total losses

Total losses have been easily recovered as the sum in dB of the previous losses:

$$L_{TOT} = L_{FS} + L_M + L_{atm} = -174.61\,\mathrm{dB}$$

4 Receiver side

4.1 Antenna dish

Starlink receiver is a phased array antenna therefore it enables to steer the beam mechanically (electric motors) and electronically, to reduce as much possible misalignment losses. Moreover, as shown in Fig.4, the antenna dish color is white to minimize also temperatures on the receiver side which would lead to a higher SNR.

Figure 4: Starlink antenna.

This dish has been designed for rainy and snowy countries too, indeed an other visible feature is its flatness which avoids the accumulation of elements like snow and water that would increment losses too. The plate diameter is 48 cm [5], therefore the gain has been recovered as:

$$G_{RX} = 10\log_{10}\left(\eta_{RX}\left(\frac{\pi D_{RX}}{\lambda}\right)^2\right) = 34.33\,\mathrm{dB} \tag{5}$$

with $\eta_{RX} = 0.567$ [5]

4.2 Low Noise Amplifier

In order to get the equivalent temperature of the system, firstly a LNA amplifier has to be chosen. This kind of device, with a very high gain makes all the other system components' temperatures negligible. In absence of data regarding the one that is actually used, Ampli-Tech APT22-18002600-1910-D22 amplifier has been chosen, Fig.5.

Figure 5: Low Noise Amplifier, Ampli-Tech APT22-18002600-1910-D22.

This is a broadband high gain LNA in the range 18-26.5 GHz with a gain of 38 dB and a noise figure (NF) of 1.9 dB.

4.3 Waveguide

Since the frequency range is very high, a waveguide has been supposed to be used instead of a transmission line. However, no available data are present regarding this component, therefore it has been used an estimate of its attenuation to take also into account its noise for the overall system noise, $A_{wg} = 0.8$.

4.4 System temperature

Starlink provider assures the nominal link conditions only in the case that the dish temperature falls in the range between -30°C and +40°C. In order to be conservative it has been taken 40°C = 313.15 K as the physical temperature for on ground components (T_{ph}), while $T_0 = 290\,\mathrm{K}$.
LNA: $T_{LNA} = (NF - 1)\,T_0 = 159.16\,\mathrm{K}$
Wave guide: $T_{wg} = (1 - A_{wg})\,T_{ph} = 62.63\,\mathrm{K}$
Sky: $T_{sky} = 200.29\,\mathrm{K}$ (from subsection 3.3)

At the end:

$$T_{sys} = 422.08\,\mathrm{K}$$

5 Modulation

According to SpaceX [5], Starlink network implement an adaptive the modulation scheme up to 64 QAM. In Fig.6 it has been shown, thanks to `berawgn` function of MATLAB [9], the BER as function of E_b/N_0 for the 4,8,16,32,64-QAM schemes.

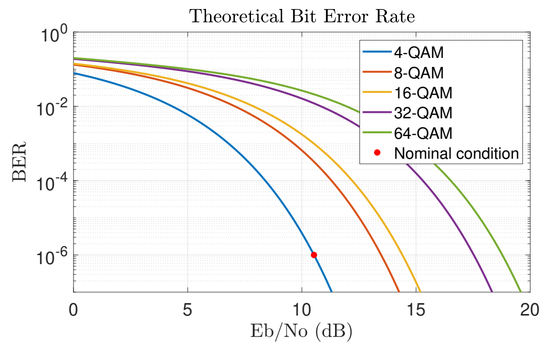

Figure 6: Starlink's Modulation schemes

The BER selection of 10^{-6} (section 1) with the 4-QAM modulation scheme and the safety margin of 2 dB drives the minimum requirement for $E_b/N_0 = 10.53 + 2 = 12.53$ dB. The safety margin should include also the fact that the access type is CDMA therefore the correct form is $E_b/(N_0+I_0)$. However to simplify the computations, I_0 has not been recovered, it has been preferred a bigger margin instead.

6 Link budget

6.1 Procedure

The link budget equation states that:

$$P_{RX} = EIRP + G_{RX} + L_{TOT} \tag{6}$$

where $EIRP$ ($= P_{TX}+G_{TX}$) and P_{RX} are unknown. Therefore it has been computed P_{RX} from the E_b/N_0 minimum requirement. Since the modulation scheme is 4-QAM, $M = 4$ and the data rate has been halved:

$$R = \frac{R_0}{2} \qquad M = 4$$

Now E_s/N_0 can be found as:

$$E_s/N_0 = E_b/N_0 \, \log_2(M) = 15.54\,\text{dB}$$

Hence:

$$SNR_{min} = E_s/N_0 \frac{R}{B} = 18.55\,\text{dB} \tag{7}$$

where R is the baud rate and B is the bandwidth whose value must be at least 500 MHz for that rate.

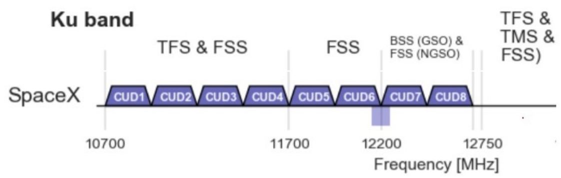

Figure 7: SpaceX frequency allocations.

With SNR_{min} the receiver power can be computed through:

$$SNR_{min} = \frac{P_{RX}}{kT_{sys}B} \tag{8}$$

where k is the Boltzmann's constant ($1.38\,10^{-23}$ m^2·kg·s^{-2}·K^{-1}).

6.2 Results

Link budget equation results are in the end:

$$\begin{aligned} P_{RX} &= -99.82\,\text{dBW} \\ EIRP &= 41.16\,\text{dBW} \end{aligned} \tag{9}$$

In order to provide an estimate also of the transmitting antenna' size, according to the dimension of the satellite, it has been supposed a power transmitted of 20 W (this kind of data is covered by industrial secrets), hence the diameter of the patch array would be 25 cm which is a very close number with respect to the real one, estimated by looking at the pictures of the satellite.

The nominal conditions have been reconstructed in Table 2.

Table 2: Starlink-61 minimum requirements.

Link characteristic	
Availability	99%
f, GHz	12.7
R_0, Gbps	1
B, MHz	500
T_{sys}, K	<422.08
L_{TOT}, dB	-174.61
BER	10^{-6}
SNR_{min}, dB	18.55
E_s/N_0, dB	15.54
EIRP, dBW	41.16
D_{TX}, m	0.25
C/N, dB	29.60
Modulation	up to 64-QAM
Polarization	RHCP
Access type	CDMA

7 Conclusions

Starlink is the most ambitious private project in space with a cost estimated of ~ 50 billions of euro. This work proves the feasibility of one of its 4 links required for the delivery of 1 Gbps to every place on Earth. Nevertheless the constellation is still in beta phase, the downlink requirements can be easily satisfied, therefore eventual SpaceX problems are expected to be more related to the network deployment and connections.

References

[1] *DEL PORTILLO, Inigo; CAMERON, Bruce G.; CRAWLEY, Edward F. A technical comparison of three low earth orbit satellite constellation systems to provide global broadband. Acta Astronautica, 2019, 159: 123-135.*

[2] In-The-Sky.org *Starlink-61* `https://in-the-sky.org/spacecraft.php?id=44249` Accessed: 2021-09-20

[3] eoPortal Directory, *Starlink Satellite Constellation of SpaceX* `https://directory.eoportal.org/web/eoportal/satellite-missions/s/starlink` Accessed: 2021-09-20

[4] *Aguilar, Alexa, et al. "Tradespace exploration of the next generation communication satellites." AIAA Scitech 2019 Forum. 2019*

[5] *SpaceX* `https://apps.fcc.gov/els/GetAtt.html?id=259301` Accessed: 2021-09-27

[6] MATLAB, *MATLAB Help Center* `https://www.mathworks.com/help/satcom/ref/p618config.html` Accessed: 2021-09-20

[7] MATLAB, *MATLAB Help Center* `https://www.mathworks.com/help/satcom/ref/p618propagationlosses.html#mw_07a62782-40a6-4717-8bcf-f25ab58eb260` Accessed: 2021-09-20

[8] *Arstechnica* `https://arstechnica.com/information-technology/2021/06/starlink-dish-overheats-in-arizona-sun-knocking-user-offline-for-7-hours/` Accessed: 2021-09-27

[9] MATLAB, *MATLAB Help Center* `https://www.mathworks.com/help/comm/ref/berawgn.html` Accessed 2021-10-4