Estimation of the Starlink Global Satellite System Capacity

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Abstract: In this paper, the capacity of the Starlink global satellite system is considered and evaluated. We will evaluate using the link budget. The code gain due to the addition of error-correcting coding has been added to the calculation of the link budget. At high frequencies, the orbit height is limited to 340 km. Most of the satellites are planned to be located at this altitude. For lower frequencies, higher orbits can be used: 550 km and 1110 km. To date, the spectral efficiency of possible variations of Starlink is limited to 4.5 bits/Hz. At the time of this writing, there are approximately 3300 Starlink satellites in orbit, which theoretically provides a capacity of about 20 Tbps due to the reduced level of modulation and the use of only one polarization. At the end of the first stage of launching satellites into orbit, the system capacity will be 88.5 Tbps over most of the studied frequency band and it will increase as more satellites are launched into low-earth orbit. Working in the future in dual polarizations with 64QAM and with a planned 11 943 satellites, SpaceX will be able to provide Internet access anywhere in the world with high bandwidth and spectral efficiency.

1 INTRODUCTION

Capacity is one of the most important characteristics of any transmission system. The use of multiposition modulation methods makes it possible to provide high transmission rates by increasing the number of signal levels, but it is limited by the system capacity [1]. But increasing the number of signal levels leads to a decrease in the noise immunity of the signal, so there is a need to develop other ways to increase the capacity, which can cause less signal-to-noise loss. Increasing the capacity and spectral efficiency makes it possible to reduce the cost of using the allocated frequency band. However, with the growth of the transmission system capacity and the data transmission rate, the total cost of the system components increases and the probability of errors during data transmission increases. The optimal ratio between the values of these parameters is one of the most important factors for operators and equipment manufacturers.

Today, one of the world's largest operators and manufacturers of equipment for telecommunications services is SpaceX, which develops a network of Starlink satellites [2], through which it provides fast broadband Internet access services.

Initially, SpaceX planned to launch 4,425 satellites with Ka- and Ku-band transmitters (from 12 to 18 GHz and from 26.5 to 40 GHz, respectively) with a service life of 5-7 years into low Earth orbit in 83 orbital planes in the altitude range from 1110 up to 1325 kilometers. It is this placement, according to the company, should have eliminated the main drawback of satellite Internet - large delays in signal transmission [3-5]. In 2017, it became known that the SpaceX satellite constellation will consist of 11 943 satellites. In addition to the initial 4425 devices at altitudes of 550 and 1110 km, the constellation is planned to include 7518 satellites in lower orbits - from 335 to 346 kilometers. By design, all devices will be built in peer-to-peer connections. Each satellite in the network will be an independent unit, simultaneously performing the functions of both a client, that is, a network member, and a server that controls its segments. This should expand communication channels and increase access speed in densely populated areas - a significantly lower location of satellites will reduce the signal delay to 25 ms [6,7]. For comparison, in cellular networks of the 4G standard, the delay is on average from 7-8 ms, but it can be more depending on the load on the network and the distance of the cell towers. At the moment, SpaceX has launched 3449 Starlink satellites into orbit during 65 Falcon 9 launches, of which approximately 3300 are operating normally.

The capacity [8,9] of the Starlink satellite will be 20 Gbit/s when operating in two polarizations and with 64QAM (Quadrature Amplitude Modulation) [10]. In this case, the rate of the error-correcting code reaches 0.95, and the spectral efficiency is 7.45 dB. This value is approximately 2 times higher than in other satellite methods of broadband Internet access. But as of today, the network can only use one polarization. To work with 64QAM modulation, it is necessary to have a signal-to-noise ratio of more than 17 dB. However, this parameter at the UT-1 terminal is between 11 and 12.5 dB, which corresponds to 16-32APSK (amplitude and phase shift keying) and has a spectral efficiency of 4.5 bit/Hz maximum.

The spectral efficiency of possible Starlink options is presented in Table 1 [11].

Table 1: Starlink spectral efficiency.

Modulation	Code rate	Spectral efficiency, bit/s/Hz	Spectral efficiency, dB
QPSK	0,5	0,989	-0,05
8PSK	0,75	2,228	3,48
8PSK	0,833	2,479	3,94
16APSK	0,666	2,637	4,21
16APSK	0,75	2,967	4,72
32APSK	0,9	4,453	6,49
64QAM	0,772	4,5234	6,55
64QAM	0,873	5,1152	7,09
64QAM	0,948	5,5547	7,45

2 LINK BUDGET

The characteristics of the system will be estimated using the link energy budget [10,12].

Power received at the user terminal

$$P_{rx} = P_{tx} + G_{tx} + G_{rx} - L_{tx} - L_{rx} - L_{atm} - L_p. \quad (1)$$

In this equation, P_{tx} is the power of the transmitter, G_{tx} and G_{rx} are the gains of the transmitter and receiver, respectively, L_{tx} and L_{rx} are the losses at the transmitter and receiver, L_{atm} is atmospheric losses, and L_p is the path loss introduced by the separation between the transmitter and receiver.

P_{tx} is the power of the transmitter is dependent on dynamic resource allocation η_a and satellite mass m.

Transmitter gain (G_{tx}) is dependent on the antenna technology (antennas diameter d, wavelength λ):

- Parabolic: $G_{tx} = 20 \cdot \log_{10}\left(\frac{\eta_a \pi d}{\lambda}\right)$;
- Phased Array: $G_{tx} = 20 \cdot \log_{10}\left(\frac{4\eta_a \pi \sqrt[3]{m^2}}{\lambda}\right)$.

Receiver gain on noise (G_{rx}) based on user terminal type:

- Parabolic: G_{rx} = 5.24 dB;
- Phased Array: G_{rx} = 10.8 dB.

Atmospheric losses L_{atm} is dependent on frequency band and atmospheric pressure P_{atm}, the averages are as follows:

- X-band L_{atm}= 0.61 dB/km;
- Ku/Ka-band L_{atm}= 0.97 dB/km;
- V-band L_{atm}= 7.42 dB/km.

Matlab's internal gaspl function for atmospheric losses simulation was used. The simulation results are presented in Figure 1.

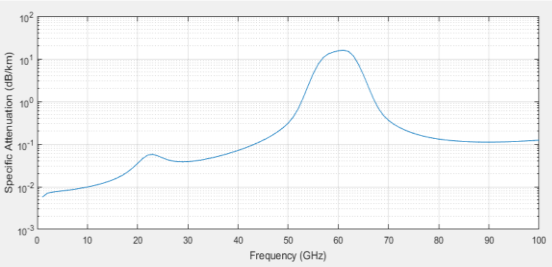

Figure 1: Atmospheric losses simulation.

We observe a burst of parameter L_{atm} at 60 GHz in fig. 1. To reduce the influence of atmospheric losses, it is desirable to use the frequency range up to 53 GHz, which corresponds to the frequency plan proposed by SpaceX (Table 2). For uplink transmission they use 14-52.4 GHz frequencies and for downlink transmission they use 10.7-42.5 GHz frequencies. Also in Table 2 the proposed modulation types are shown. The modulation type can be changed from BPSK to 64QAM.

Table 2: Starlink frequency allocation and modulation type [10].

Characterictic	Uplink	Downlink
Frequency (GHz)	14.0-14.5 27.5-29.1 29.5-30.0 47.2-52.4	10.7-12.7 17.8-18.6 18.8-19.3 37.5-42.5
Modulation type	BPSK, MQAM	OQPSK, MQAM

Free-Space Path Loss in Decibels (L_p)

$$L_p = 20 \cdot \log_{10}\left(\frac{4\pi d}{\lambda}\right)$$

The following initial data were taken for calculations (Table 3).

Table 3: Link budget simulation parameters.

Parameter	Value	Parameter	Value
η_a	1	d	5 m
m	400 kg	P_{atm}	101.3 kPa
L_{tx}	0.5 dB	L_{rx}	0.5 dB

The results of modelling of Free-Space Path loss and atmospheric losses depending on the orbit altitude are shown in Figure 2.

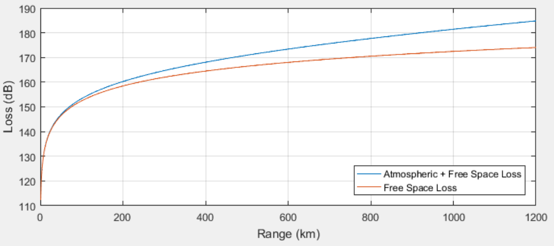

Figure 2: Free-Space Path loss and atmospheric losses.

Free-Space Path Loss is the main contributor to power loss (Figure 2). At altitudes calculated for Starlink satellites, this value is 160-175 dB. The total losses from Free-Space Path Loss and atmospheric losses are 165-185 dB.

The results of modelling and calculating the dependence of power received at the user terminal on the height of the satellite orbit for various frequencies (from 10 to 50 GHz) are shown in Figure 3.

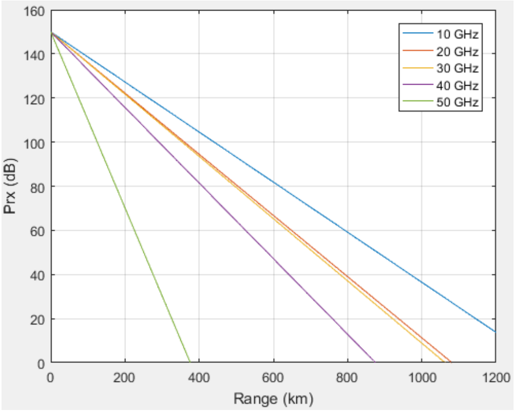

Figure 3: Link budget without ECC.

From Figure 3 it can be seen that the highest value of the signal power is 150 dB. As the signal passes through the atmosphere, it gradually attenuates. Attenuation also occurs on transmitting and receiving devices. The degree of attenuation depends on many parameters and it limits the height of the satellites orbit.

It is customary to use an error-correcting code to increase the noise immunity of systems. In this case, we use an error-correcting code to increase the link budget. We add CG to (1) - coding gain due to error-correcting code (ECC), its code rate options are shown in Table 1.

$$P_{rx} = P_{tx} + G_{tx} + G_{rx} - L_{tx} - L_{rx} - L_{atm} - L_{path} + \mathrm{CG} \tag{2}$$

The results of modelling and calculating the dependence of power received at the user terminal on the height of the satellite orbit for different frequencies (from 10 to 50 GHz), taking into account the use of an error-correcting code with a coding gain of 10 dB, are shown in Figure 4.

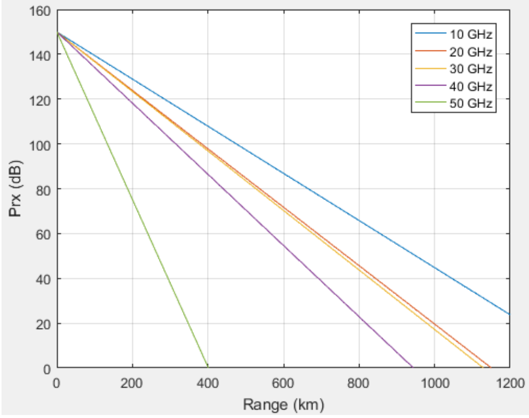

Figure 4: Link budget with ECC.

To ensure the minimum error probability, it is necessary to have a margin of the signal-to-noise ratio at the reception, which depends on the modulation type.

From Figure 4 it can be seen that at high frequencies the orbit height is limited to 340 km. Most of the satellites are planned to be located at this altitude. For lower frequencies, higher orbits 550 km and 1110 km can be used.

3 SYSTEM CAPACITY

System capacity is very important parameter. In accordance with Shannon's theorem, this is the maximum information transfer rate in the system.

The communication system is subject to noise, with Johnson noise contributing the most power to the bands of interest. Johnson noise power spectral density

$$N_0 = k \cdot T,$$

where $k = 1.3806 \cdot 10^{-23}$ – Boltzmann's constant; T – temperature.

Signal-to-noise ratio

$$\mathrm{SNR} = \frac{P_{rx}}{P_n} = \frac{P_{rx}}{k \cdot T \cdot \mathrm{BW}},$$

where P_n – noise power; BW – bandwidth.

We take power of signal P_{rx} from (2), bandwidth is based on the Starlink frequency plan (Table 2).

The information rate DR is calculated using the Shannon-Hartley:

$$\mathrm{DR} = \mathrm{BW} \cdot \log_2(1 + \mathrm{SNR}).$$

The data rate per satellite is 10 Gbps by using only one polarization.

The capacity of the system as a whole [13] is calculated as the product of the information rate per satellite and the number of satellites n_{sat}:

$$C_{ch} = \mathrm{DR} \cdot n_{sat}$$

In [14], it was shown that the capacity of the system has an optimum, that is, it is necessary to solve the problem of optimizing this parameter. An increase in the modulation level leads to an increase in capacity, however, when a certain level is reached, a further increase of capacity slows down significantly or even a decreasing is observed.

Dependence of system capacity on frequency band is situated in Figure 5.

System capacity is 88.5 Tbps over most of the studied frequency band and it will increase as more satellites are launched into low-earth orbit.

At the time of this writing, there are approximately 3300 Starlink satellites in orbit, which theoretically provides a capacity of about 33 Tbps. However, binary and quaternary modulation methods are used. The capacity of the constellation of satellites is 20 Tbps, which is about 4.5 times less than the declared capacity at the end of the first stage of launching satellites into orbit.

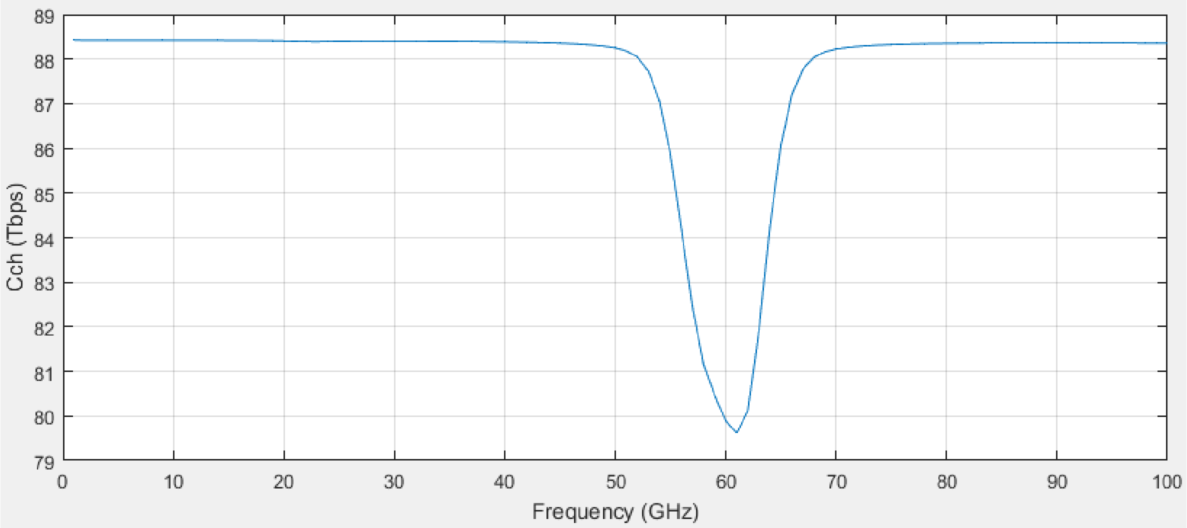

Figure 5: System capacity.

4 CONCLUSIONS

At the time of this writing, there are approximately 3300 Starlink satellites in orbit, which theoretically provides a capacity of about 33 Tbps. To ensure the minimum error probability, it is necessary to have a margin of the signal-to-noise ratio at the reception, which depends on the modulation type. However, binary and quaternary modulation methods are used. At high frequencies, the orbit height is limited to 340 km. That's why, the capacity of the constellation of satellites reaches 20 Tbps only, which is about 4.5 times less than the declared capacity at the end of the first stage of launching satellites into orbit.

Working in dual polarization with 64QAM modulation and with a planned 11943 satellites, SpaceX will be able to provide Internet access anywhere in the world with high capacity and spectral efficiency.

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