Fly Your Satellite! 4

RedPill PocketQube

J2050 – New Epoch Technologies

University of Padova – Italy

Link and Data Budget Analysis Report

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0.2	30.09.2024	12-15	Updated data budget
0.3	24.11.2024	4-16	Updated link and data budget philosophy

Contents

Link Budget

This report aims at characterizing the LoRa link performance to identify the requirements necessary to establish a successful bidirectional communication link between the space and ground segment. The analysis is performed considering modules operating at 436 MHz, assuming an intermediate frequency based on the available UHF radio frequencies for amateur satellite use. The orbit considered for this analysis is a 550 km LEO orbit, as it is the worst case among the orbits selected during mission analysis.

Hardware configuration

The space and ground segment hardware configurations are considered symmetrical with both devices based on LoRa1268F30 module with Semtech SX1268 transceiver. LoRa1278F30 module can also be considered as a drop-in replacement, offering comparable performance although at higher power consumption. This module incorporates a switching circuit for RX/TX operations and a LNA providing up to +32 dBm output power.

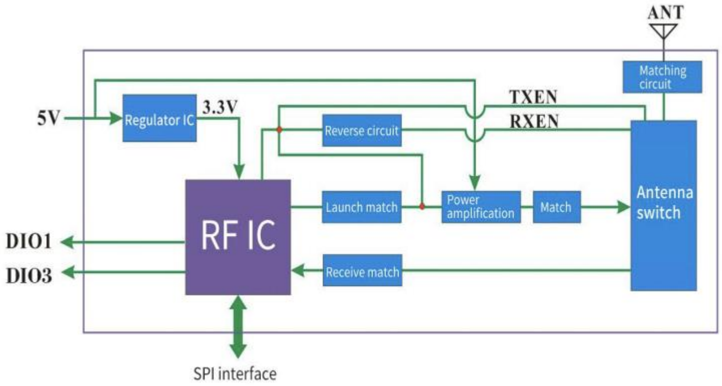

Figure 1: LoRa1268F30 module architecture

The antenna configuration on the space segment is a half wavelength dipole with linear polarization. Radiation patterns are reported in the figures below.

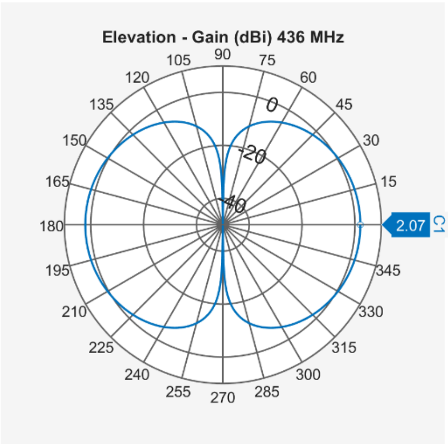

Figure 3: Elevation gain pattern

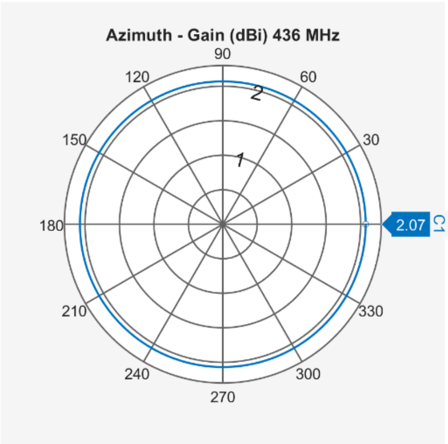

Figure 2: Azimuth gain pattern

For the ground segment, a directional Yagi antenna with 12 dB gain with circular polarization pattern is considered.

LoRa parameters configuration

LoRa is a technology developed by Semtech. It uses a proprietary Chirp Spread Spectrum (CSS) modulation, which is more resilient than others to interference and jamming. The LoRa technology has several parameters that must be configured in the transceivers, such as the transmitted power, Bandwidth (BW), Spreading Factor (SF), and Coding Rate (CR).

In the LoRa modulation the BW is configurable and this parameter determines the maximum shift in the central frequency that the modules are able to compensate, and the noise power. The shift that the modules compensate can be up to 25% of the BW[1]. The maximum considered orbital speed is 7.6613 km/s which leads to a doppler shift of 11.14 kHz. Hence, a minimum BW of 44.56 kHz is needed. Additionally, the bandwidth should be the smallest value possible to reduce the noise power and transmission time. Considering that the typical values are 125 kHz, 250 kHz and 500 kHz, the optimal BW is 125 kHz.

The SF parameter is directly correlated to the sensitivity of the transceiver, specifically to the required signal to noise ratio (SNR) at the receiver side. The minimum SF required will be determined from the link analysis. From SX1268 and SX1278 datasheets we can extract the following table[2].

SF	5	6	7	8	9	10	11	12
SNR	-2.5	-5	-7.5	-10	-12.5	-15	-17.5	-20

Table 1: SNR limit at SF value

Finally, the CR parameter does not have a direct link on the link performance, but it represents the number of redundant bits for Forward Error Correction (FEC). This coding rate is represented by a ratio in which the numerator corresponds to the data bits and the denominator represents the redundant bits. For example, if CR is 4/8, for every 4 bits of useful information, the coder generates a total of 8 bits of data, of which 4 bits are redundant. This allows for single bit error correction. Therefore, CR only has an influence on the data budget and not on the link budget. Since reliability is critical in this type of link and no additional software implementation of error correcting codes is currently planned the highest redundancy will be chosen, which corresponds to the coding rate of CR = 4/8.

Link budget computation

In the following section, the link budget computation for the nominal and favorable conditions are calculated with the following assumptions:

1. Worst-case conditions are considered in the computation of variable losses, such as antenna pointing and polarization mismatch.
2. Performance of design components are derived by applying a variable margin on their expected performance. This means, the expected performance is decreased by the

[1] SX1268 datasheet, page 19
[2] SX1268 datasheet, page 37

selected margin form the design values. The selected margins, in accordance with the development level of the devices, are reported in the table below.

Performance item	Margin [%]	
	Favorable conditions	Nominal conditions
GS antenna gain	5	10
PQ antenna gain	30	30
GS TX power	5	10
PQ TX power	5	10

Table 2: Selected margins on performance items

It must be noted that the margin is applied directly on the design value without considering logarithmic notations: this means that by applying a 10% margin on the design GS antenna gain of 12 dB, the nominal GS antenna gain considered is 10.8 dB.

Losses

The losses that will be considered are related to distance, atmospheric attenuation, antenna polarization mismatch, pointing and an additional parameter for unforeseen losses.

Free Space Path Losses (L_{FSP}) can be calculated as a function of frequency and distance

$$L_{FSP} = 20\log(d) + 20\log(f) + 20\log\left(\frac{4\pi}{c}\right)$$

Where the frequency is 436 MHz and the distance is calculated for each elevation angle. The resulting loss for each elevation angle is reported table 3.

Elevation [°]	10	20	30	40	50	60	70	80	90
Distance [km]	1815.1	1293.6	992.8	812.1	698.9	626.9	852.2	557.8	550.0
FSPL [dB]	150.4	147.5	145.2	143.4	142.1	141.2	140.5	140.2	140.0

Table 3: Free space path losses

For atmospheric attenuation, the ITU recommendation ITU-R P.676-13[3] about attenuation by atmospheric gases and related effects will be considered. An approximated specific attenuation at sea level for the nominal case of 5×10^{-3} dB/km has been extracted for 436 MHz. Assuming an atmospheric thickness of 100 km, the equivalent atmospheric thickness for each elevation angle has been computed together with the relative loss. Please note that the sea level specific attenuation value has been used across all the atmospheric thickness, leading to an overestimation of the actual atmospheric losses in favor of safety.

Elevation [°]	10	20	30	450	50	60	70	80	90
Atmosphere thickness [km]	477.4	277.1	195.6	153.9	129.8	115.2	106.3	101.5	100.0
Atmospheric losses [dB]	2.4	1.4	1.0	0.8	0.6	0.6	0.5	0.5	0.5

Table 4: Atmospheric losses

[3] ITU-R P.676-13, page 5

Polarization losses can be calculated knowing that the space segment has linear polarization while the ground segment has circular polarization. The equation to compute polarization loss as function of the angle between the electric fields is

$$L_{pol} = (cos\varphi)^2$$

Where the maximum out of phase angle between the electromagnetic waves is 45°. Thus, the maximum polarization losses are 3 dB.

Pointing losses are the result of mismatch between the main radiation lobes of the antenna pair. The GS is equipped with a dual axis tracking system to follow the satellite during its path. Its tracking performance is however not yet assessed, so a conservative value of 2 dB is used for the GS pointing losses.

Noise

The noise power is needed to define the SNR and subsequently verify the link margin. It must be computed for both uplink and downlink case. A theoretical approach can be used to compute noise power using the noise temperature parameter.

For the uplink case, a noise temperature of 290K can be considered[4]. This value is often over-conservative, but it is better to overestimate and study the worst-case scenario. Noise power can therefore be obtained with the formula

$$P_N = K_B T_N BW$$

Giving a result of -123.0 dBm.

For the downlink case, the different noise sources must be considered with the formula

$$T_A = T_{SKY} + T_{GROUND}$$

Where T_{SKY} is equal to 20K and T_{GROUND} can be estimated as 2320K[5] for a median business area such as the location where the GS will be located. Therefore, the total equivalent noise temperature is 2340K giving a noise power of -113.9 dBm.

However, it must be noted that these results are only theoretical and do not consider additional noise sources such as line noise and electrical noise present in the transceiver module. While the uplink cannot be further studied as the space radiation environment is not easily simulated on ground, for the downlink case we can use the readings available at our currently operative GS. It must be noted that the J2050 GS currently deployed is not representative of the final configuration, as it employs a vertical polarized omnidirectional antenna and SX1278 transceiver module. The detected noise floor at our GS is currently fluctuating between -108 dBm and -102 dBm. This is in accordance with the theoretical value of -113.9 dBm, as there are additional noise sources not considered in the previous evaluation. Such noise levels are not

[4] E. G. Njoku and E. K. Smith, "Microwave antenna temperature of the Earth from geostationary orbit," Radio Sci., vol. 20, no. 3, pp. 591–599, May 1985

[5] Same as above

representative of the final GS configuration: the use of a directional antenna with circular polarization will affect the noise readings greatly, however such change can not be determined *a priori*. It is expected that at low elevation angles the noise power may increase, as the main lobe of the directional antenna will increase the gain relative to terrestrial noise sources, while at higher elevations the directionality of the antenna will help rejecting terrestrial noise. Such tests are currently planned and depend on the availability of the final GS hardware. Moreover, better EM shielding for the ground hardware will be present to mitigate further interferences not happening at the antenna.

For this report, the currently available median noise readings will be used for the downlink case leading to a noise power of -107 dBm. No margin is applied as the value is obtained directly from an experimental reading. The uplink case will consider the previously computed theoretical of -123 dBm.

Results

In this section, results for various scenarios will be presented. Knowing the LoRa parameters, data rate can be calculated using the formula

$$C = SF \frac{CR}{2^{SF}} BW$$

To simplify satellite operations, the same values will be used in each operating mode and scenario. This is because to receive a LoRa packet its parameters must be known beforehand and selecting a single configuration will allow multiple GS in the TinyGS network to listen to the satellite, without needing to update the link parameters on the fly. Based on the results below, an optimal SF value of 10 has been chosen resulting in a data rate of 610 bps. This value allows successful communication in the active downlink scenario considered at nominal conditions for elevation equal or higher than 20°. Such SF value can be modified via software configuration if the obtained link margin is not considered satisfactory, at the expense of lower data rate.

While the study has been performed for elevation angles from 10° to 90°, the final tables display results for the minimum accepted elevation of 20°, as lower elevations are considered below the threshold needed to consider the satellite as passing above the GS.

Scenario 1: downlink 15° pointing

In this scenario, the downlink best case will be considered. The spacecraft is pointing the GS with 15° accuracy, leading to a PQ antenna pointing loss of 0 dB from the radiation patterns provided above. Transmission power is in LORA_HIGH mode at +30 dBm.

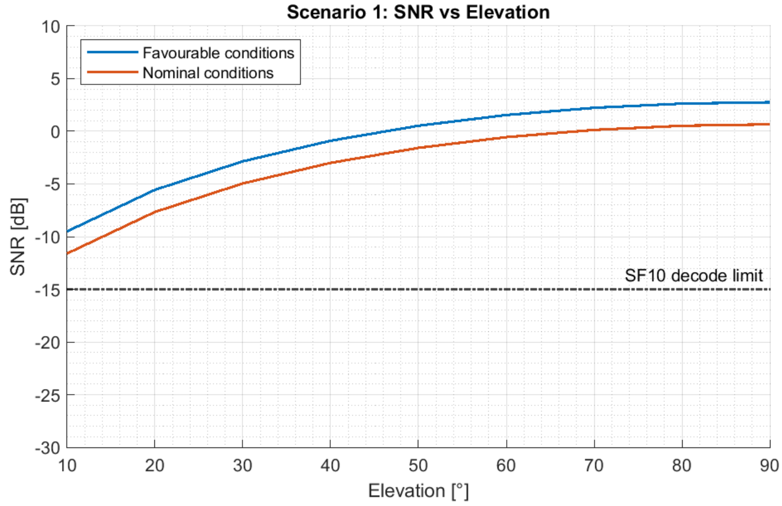

Figure 4: Scenario 1 SNR to elevation

Conditions	**Nominal**	**Favorable**
Power mode	LORA_HIGH	
Data rate [bps]	610	
Pointing losses GS [dB]	2	
Pointing losses PQ [dB]	0	
GT [dB]	1.4	1.4
GR [dB]	10.8	11.4
PT [dBm]	27	28.5
EIRP [dBm]	28.4	29.9
PR [dB]	-114.7	-112.6
SNR [dB]	-7.7	-5.6
Link margin [dB]	**7.3**	**9.4**

Table 5: Scenario 1 link budget for 20° elevation

Scenario 2: downlink 45° pointing

In this scenario, the ADCS performance has decreased leading to a 45° pointing accuracy and total PQ pointing losses of 4 dB. Transmission power is in LORA_HIGH mode at +30 dBm.

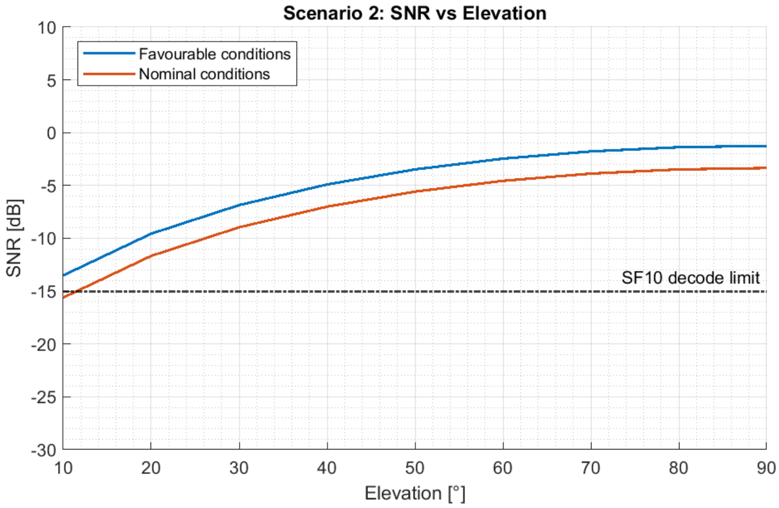

Figure 5: Scenario 2 SNR to elevation

Conditions	**Nominal**	**Favorable**
Power mode	LORA_HIGH	
Data rate [bps]	610	
Pointing losses GS [dB]	2	
Pointing losses PQ [dB]	4	
GT [dB]	1.4	1.4
GR [dB]	10.8	11.4
PT [dBm]	27	28.5
EIRP [dBm]	28.4	29.9
PR [dB]	-118.7	-116.6
SNR [dB]	-11.7	-9.6
Link margin [dB]	**3.3**	**5.4**

Table 6: Scenario 2 link budget for 20° elevation

Scenario 3: downlink 45° pointing reduced power

In this scenario, the available power is below the threshold level and communication mode has switched to LORA_LOW with power of +22 dBm. The spacecraft might be tumbling, and communications must be restricted to short beacon packets as the connection might be disrupted and available power is low.

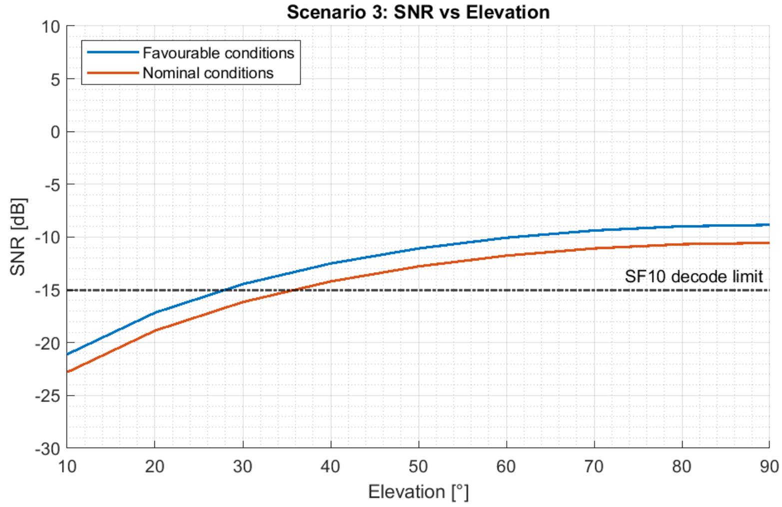

Figure 6: Scenario 3 SNR to elevation

Conditions	**Nominal**	**Favorable**
Power mode	LORA_LOW	
Data rate [bps]	610	
Pointing losses GS [dB]	2	
Pointing losses PQ [dB]	4	
GT [dB]	1.4	1.4
GR [dB]	10.8	11.4
PT [dBm]	19.8	20.9
EIRP [dBm]	21.2	22.3
PR @ 20° [dB]	-125.9	-124.2
SNR @ 20° [dB]	-18.9	-17.2
Link margin @ 20° [dB]	**-3.9**	**-2.2**
PR @ 40° [dB]	-121.2	-119.5
SNR @ 40° [dB]	-14.2	-12.5
Link margin @ 40° [dB]	**0.8**	**2.5**

Table 7: Scenario 3 link budget for 20° and 40° elevation

Please note that in this scenario, under adverse conditions the SNR is not sufficient to decode packets below 40° elevation. However, as discussed previously, the considered noise figure of -107 dB is conservative and this scenario requires further testing as soon as the final GS hardware is available. Furthermore, the scenario where transmission power of the PQ is limited implies no data packets are being sent. Only beacon packets are sent in this mode and they can be received by any TinyGS station, so the limitation on the elevation angle does not have a strict influence on the data rate. This scenario will therefore not be considerd in final link results.

Scenario 4: uplink 45° pointing

In this scenario, the GS is transmitting at full power which is +32 dBm. The satellite attitude is sub-optimal with a pointing accuracy of 45°, with additional pointing losses of 4 dB. This is the only uplink scenario studied, as the transmission power is never limited at the GS and thus this scenario can be considered as the worst-case. No further analysis is required as the link margin increases with better pointing accuracy.

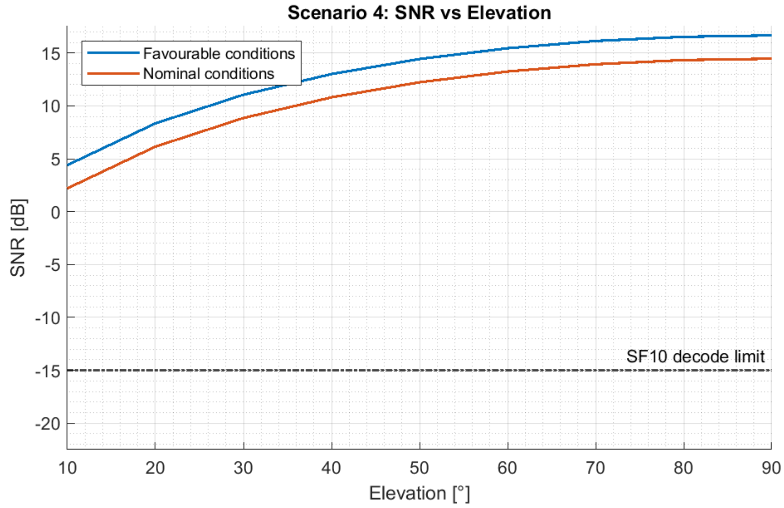

Figure 7: Scenario 4 SNR to elevation

Conditions	Nominal	Favorable
Power mode	N/A	
Data rate [bps]	610	
Pointing losses GS [dB]	2	
Pointing losses PQ [dB]	4	
GT [dB]	1.4	1.4
GR [dB]	10.8	11.4
PT [dBm]	28.8	30.4
EIRP [dBm]	39.6	41.8
PR [dB]	-116.9	-114.7
SNR [dB]	6.1	8.3
Link margin [dB]	**21.1**	**23.3**

Table 8: Scenario 4 link budget for 20° elevation

In the uplink scenario the link margin is positive under every working condition. This is due to the higher transmission power of the GS and the low noise environment in space compared to the GS location. Therefore, the limiting scenario for the space link is always the downlink transmissions.

Data Budget

To verify the compliance to the requirements regarding the data budget, the mean data transmitted per orbit and per day has been calculated. The initial requirement calls for an average daily data rate of 300 kb. The analysis has been performed on three different orbits and considering the GS located in Padova (latitude 45.4110°, longitude 11.8917°). The orbits and contact times have been propagated for 30 days in March 2026 using GMAT software to account for the evolution of the orbital parameters. Mean daily and per orbit values have been therefore normalized over the number of orbits elapsed in 30 days. This timeframe is sufficient to create a valid normalized access time to the GS: as it can be seen in the results below, the access pattern to the GS is periodic and therefore it will repeat periodically over a fixed period of time.

	Orbit 1	**Orbit 3**	**Orbit 3**
Height [km]	420	480	550
Inclination [°]	51.6	97	98

Table 9: Orbital parameters for analysis

Access analysis

The access time for each considered orbit has been evaluated, focusing on both per orbit and per day contact times. Mean results are found in table 11.

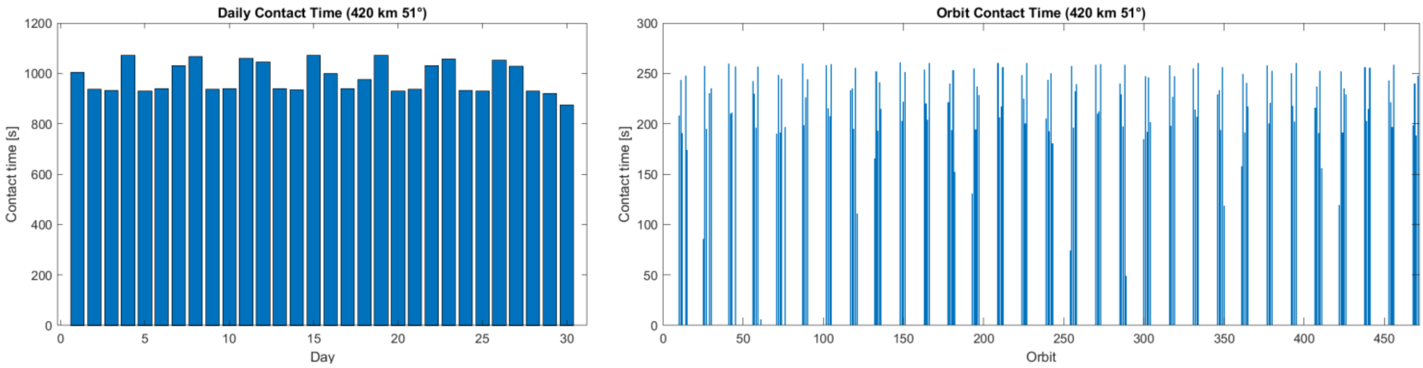

Figure 9: Access analysis results for orbit 1

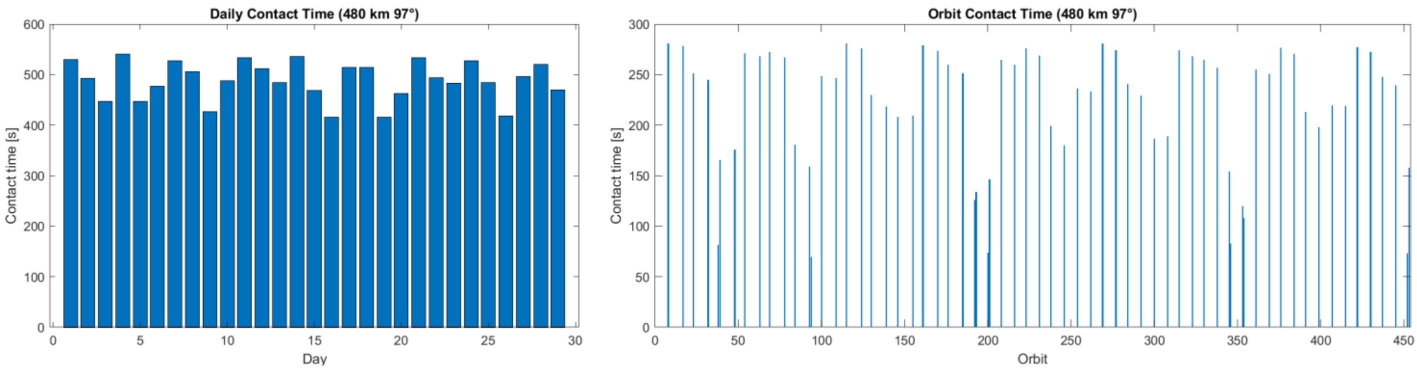

Figure 8: Access analysis results for orbit 2

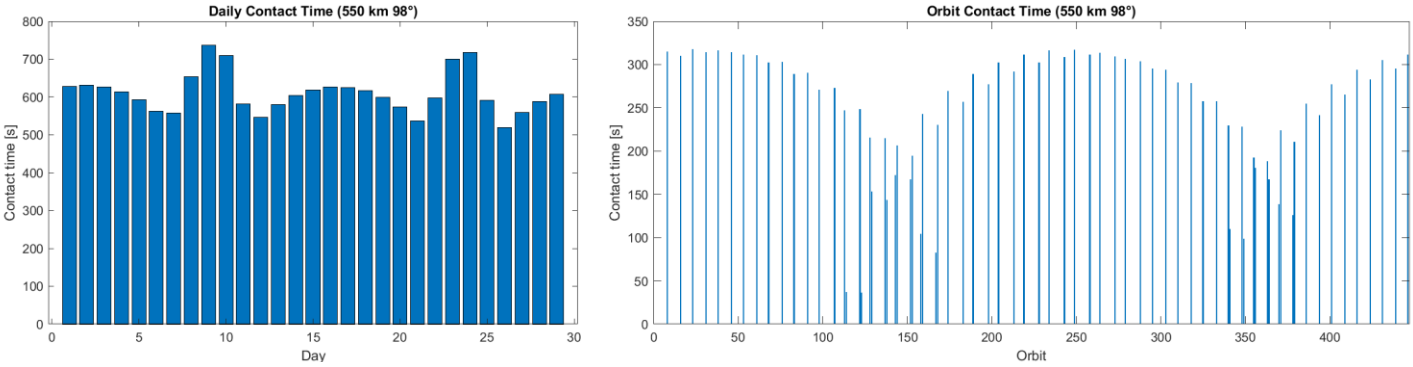

Figure 10: Access analysis results for orbit 3

From this analysis, it can be seen how SSO orbits allow a more consistent access frequency, while lower inclination orbit have better mean data rate but distributed not homogenously among orbits. Moreover, subsequent SSO orbits in general do not have direct access to the GS: this is an important operational constraint, as the next pass will always be delayed by about 12 hours. Instead, low inclination orbits allow contact in subsequent orbits and thus the operations can be scheduled in a more contained time period.

The lack of contact between passes over J2050 GS can be mitigated by using multiple GSs for downlink, such as the ones available in the TinyGS network. However, such approach can not be studied analytically as the performance of each GS is not known as they are built by radio amateurs and do not follow a standard specification. Empirically, the TinyGS network can receive even low power (< 500 mW) LoRa signals from currently operational satellites; therefore, it is very likely that our satellite will also be received as its transmission power is higher (1 W). In this analysis it is best to consider the worst-case scenario so such additional GSs are not considered.

Results

For LoRa links, the data rate can be computed by using the following formula.

$$C = SF\frac{CR}{2^{SF}}BW$$

Calculating channel capacity for SF ranging from 12 to 8 using parameters discussed in previous sections, we obtain the results in table 11. SF10 is the optimal value obtained from the link budget, therefore it has been used to obtain the results in table 12.

SF	8	9	10	11	12
Data rate [bps]	1950	1100	610	336	183

Table 10: Data rate at SF value

Multiplying the data rate for the access time we obtain the results in table 11.

	Orbit 1	Orbit 2	Orbit 3
Mean orbit contact time [s]	64.78	31.89	40.38
Mean daily contact time [s]	981.53	488.43	610.10
Max interval between contacts [h]	18.26	12.88	13.06
Mean orbit data transfer [kb]	39.51	19.45	24.63
Mean daily data transfer [kb]	598.73	297.94	372.16

Table 11: Data and access time results

Using a SF value of 10, the average daily data rate is compatible with the required amount of 300 kb/day for every scenario considered. Decreasing the SF value can lead to even better performance of the link. As the value can be set by software, the performance of the link can be tuned based on actual hardware performance. Further work will be done exploring the possibility of increasing the CR ratio by using a different error correcting approach, and better characterization of the noise environment at the GS will increase the link margin, which in turn means enabling lower SF values ang higher data rate.

Conclusions

Given the requirement of 300 kb per day provided by the software team, the Telecom subsystem has been optimized for maximum data transfer with a focus on mission flexibility whenever possible. From the optimized LoRa values calculated in this report, the following results can be obtained for the link margin for a 550 km orbit, which represents the worst scenario for the link budget. The link and data budget final summary is reported in table 12, considering all orbits.

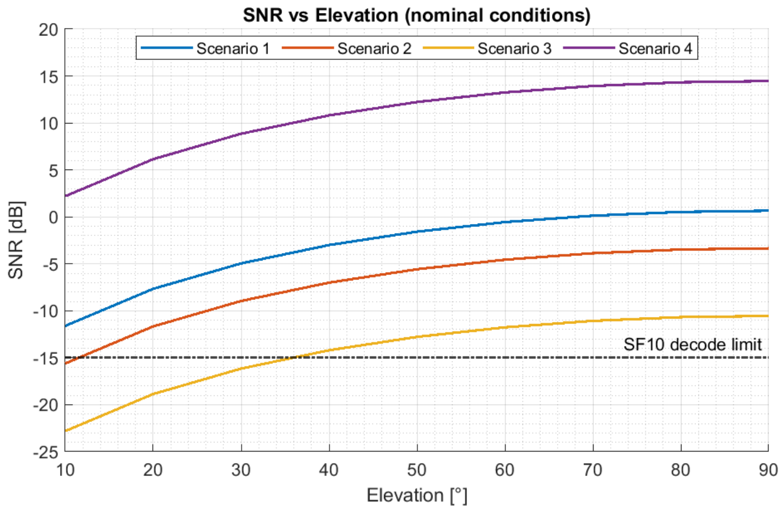

Figure 12: Link margin in nominal conditions

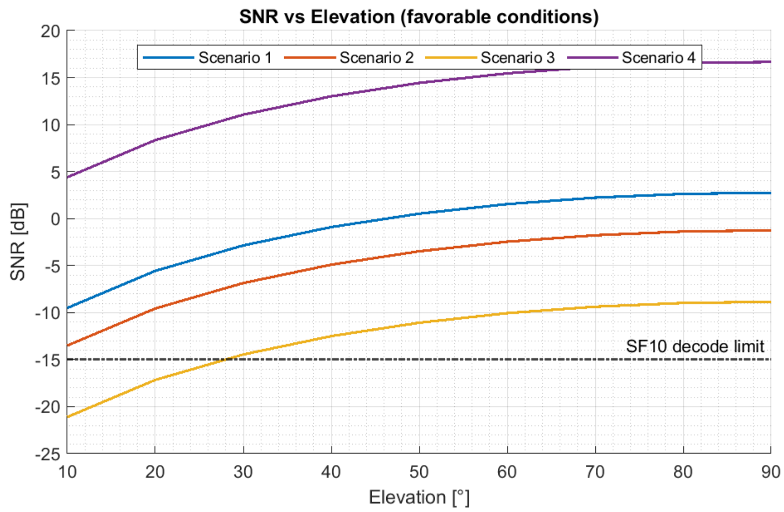

Figure 11: Link margin in favorable conditions

It can be noted that for the chosen SF value of 10 the link marking is positive for elevations down to 20°. This greatly improves the access time to the GS compared to higher minimum elevation values and provides great flexibility to the mission profile. The total mean data transfer along with the link margin for each orbit, are reported in the next table. Please note that these values are referred to the downlink case, ignoring the beacon performance and therefore ignoring the results from scenario 4. The obtained values are compatible with the data volume of 300 kb/day planned for the primary mission objectives for every possible orbit.

	Orbit 1	Orbit 2	Orbit 3
BW [kHZ]	125		
CR	4/8		
SF	10		
Data rate [bps]	610		
Link margin nominal [dB]	5.3	4.3	3.3
Link margin favorable [dB]	7.4	6.4	5.4
Mean daily data transfer [kb]	598.73	297.94	372.16

Table 12: Link and data budget results