Project CubeSat - Telemetry

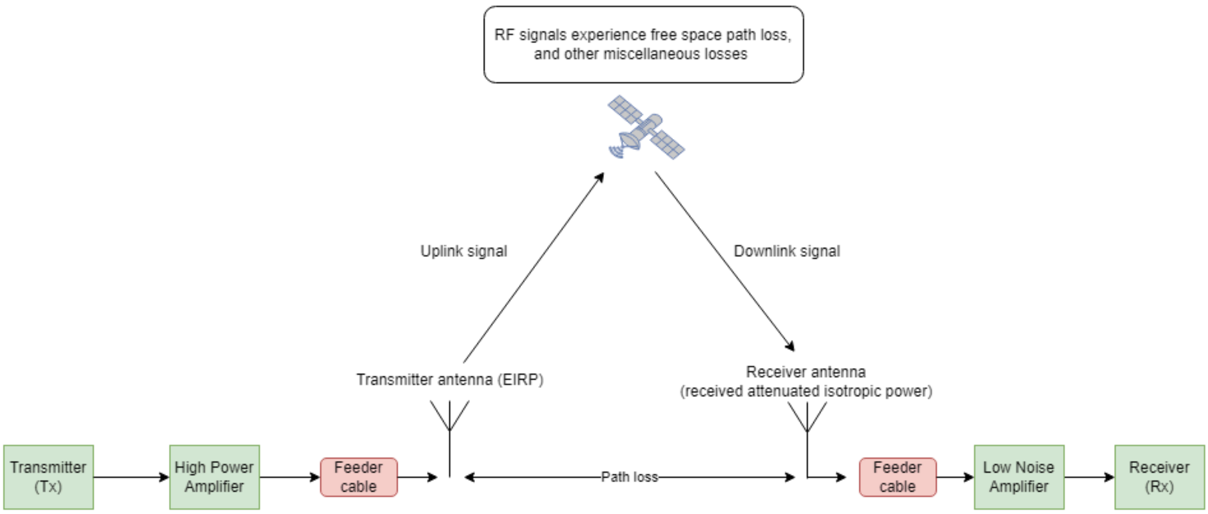
LINK BUDGET

Treatment of the RF link budget for a CubeSat downlink to a ground station

Link budget analysis is a prerequisite to design a satellite communication system, as it assists in quantifying the link performance. It involves accounting for all the power gains and losses, adding the gains and subtracting the losses that a radio frequency (RF) signal experiences within a satellite communication system.

Generally speaking, establishing a reliable communication link between a transmitter and a receiver is the ultimate goal of radio-link design. In particular, a CubeSat establishes two types of duplex radio links, uplink and downlink, with ground stations and with other CubeSats. Despite the key role of the communication subsystem, the power that a CubeSat can dedicate is limited by its weight and size constraints. Here we are discussing the link budget expression for the downlink, i.e., CubeSat-to-ground communications. The link design must ensure the ability to transmit and receive data directly from space to Earth or through one or more communication relays.

Received Power (dBm) = transmitted power (dBm) + gains (dB) – losses (dB)



Link budget calculations use power budget analysis to establish an approximate level of performance without resorting to link-level simulation. Link budget specifies the system parameters necessary to ensure that the information is received intelligibly with an adequate signal-to-noise (SNR) ratio.

A link budget is a set of parameters that define a communication link in terms of the power available for a reliable connection between the transmitter and receiver. The satelliteto-ground link (downlink)'s energy-per-bit to noise spectral density, which measures the reliability of the link, is calculated based on the link budget. The energy-per-bit to noise spectral density at the ground station can be expressed as

$$\frac{E_b}{N_o} = \frac{P_\mathrm{t}\, G_\mathrm{t}\, G_\mathrm{r}}{L\, kT\, R_\mathrm{b}},$$

where Pt is the transmitted power, Gt and Gr are the transmitter and receiver antenna gains, T is the system temperature noise, Rb is the target data rate, k is the Boltzmann constant, and L is the overall loss. The overall loss accounts for the losses occurred while the signal propagates from the satellite to ground station, which can be attributed to four main components as follows:

- Free-space path loss, Lp, because of the basic power loss that increases inversely with the square of the distance propagated.
- Atmospheric loss, La, due to absorption and scattering of the field by atmospheric particulates, for instance, signal attenuation caused by rainfall.
- Polarization loss, Lpol, due to an improper alignment of the receiving antenna subsystem with the received wave polarization, leading to polarization mismatch.
- Antenna misalignment loss, Laml, due to the difficulty of steering to the ground station antenna in exactly the correct direction of the CubeSat.

More precisely, the overall loss L can be represented as

$$L = L_\mathrm{p}\, L_\mathrm{a}\, L_\mathrm{pol}\, L_\mathrm{aml}.$$

The free-space path loss Lp is given by

$$L_p = \left(\frac{4\pi d}{\lambda}\right)^2,$$

where d is the distance between the ground station and the satellite and λ is the wavelength of the signal. Note that d depends on the parameters of the LEO orbit such as the minimum elevation angle φ, angle between the position of CubeSat in orbit and the ground station θ, and CubeSat's altitude h from the center of Earth. Based on these parameters, d is calculated as

$$d = \sqrt{(R_E + h)^2 - R_E^2 \cos^2 \phi} - R_E \sin \phi,$$

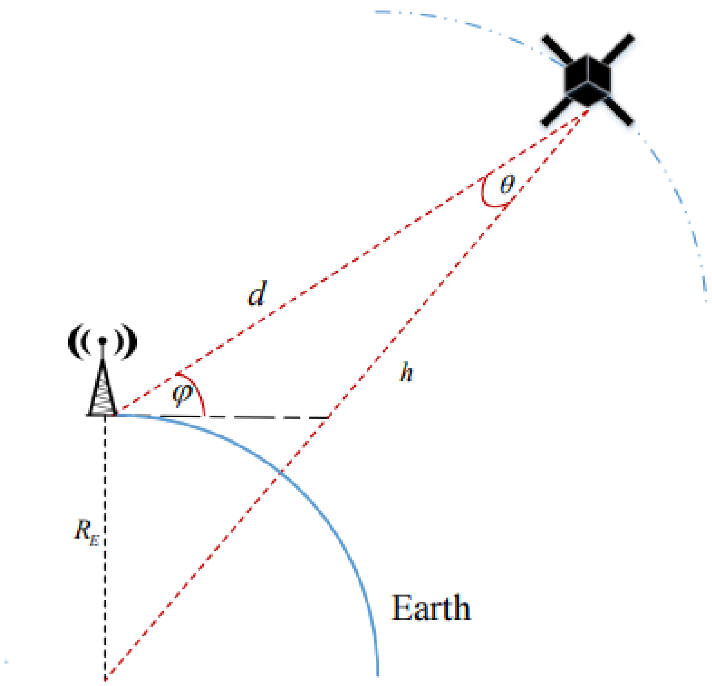


Fig. 9: Schematic description of a LEO CubeSat trajectory

Fig. 9 depicts the relationship between these parameters and the distance. For illustration purposes, we consider LEO orbits with three different altitudes and calculate the distance between the satellite and

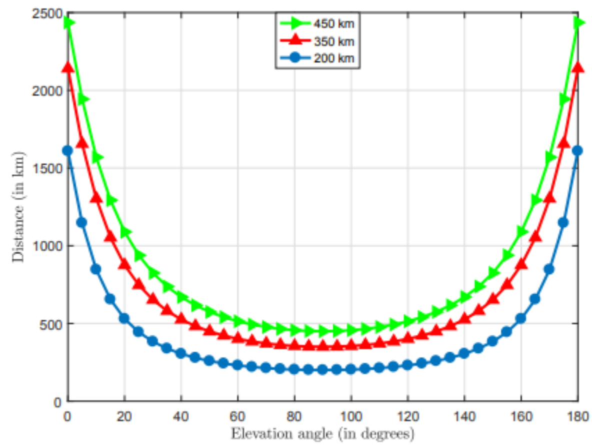


Fig. 10: Impact of the elevation angle on the distance between the satellite and the ground station.

the ground station as shown in Fig. 10. It is clear from Fig. 10 that the distance between the ground station and the satellite is minimal when the elevation angle is 90 degrees. To best characterize the effect of the elevation angle on the path loss, we consider VHF-band and L-band frequencies and calculate the path loss with respect to the elevation angle as shown in Fig. 11. It is clear that the path loss is low at the

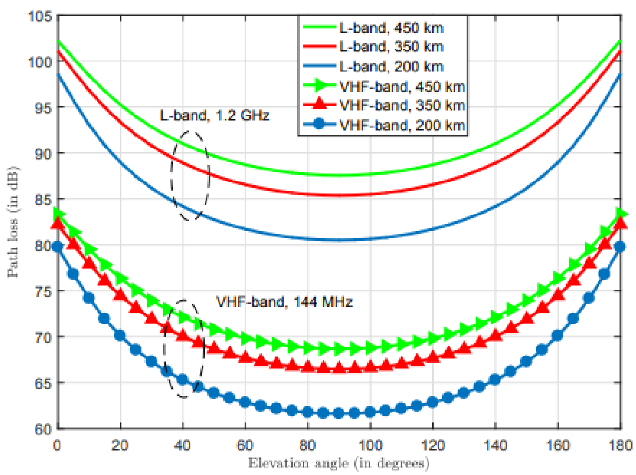


Fig. 11: Impact of the elevation angle on the path loss at different frequency bands.

90-degree elevation angle due to the shorter distance. Also, at higher frequencies, the path loss increases with the altitude of the satellite.

EIRP

EIRP is the amount of power that would have to be radiated by an isotropic antenna to produce the equivalent power from the actual antenna in the direction with highest antenna gain.

EIRP is the total radiated power (*Pt*) from a transmitter antenna times the antenna gain (*Gt*).

$$EIRP = Pt \times Gt$$

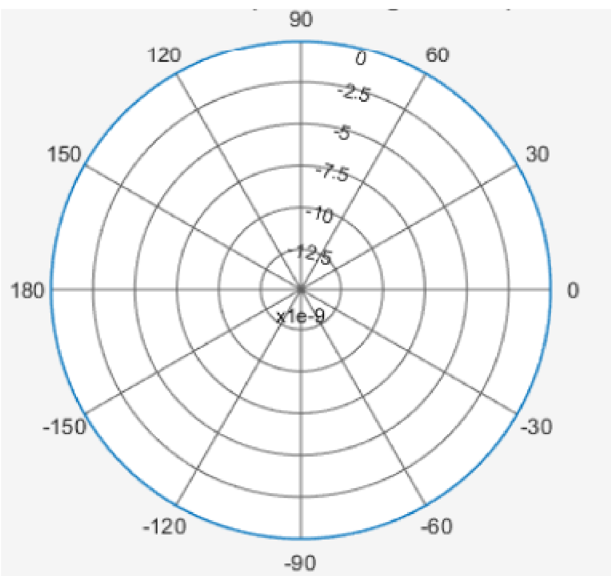
If expressed in decibels:

$$EIRP\,(\text{dBm}) = Pt\,(\text{dBm}) + Gt\,(\text{dBi})$$

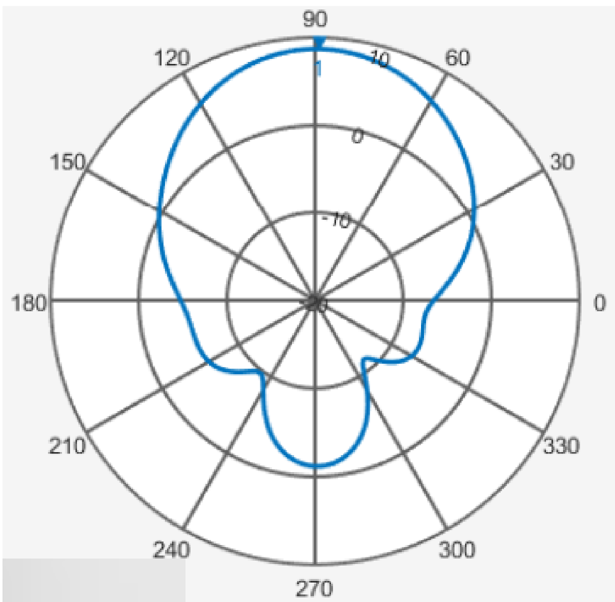
The EIRP enables comparisons between different emitters regardless of type, size, or form.

Considering different losses such as feeder loss *Lf* and pointing loss *Lp* into account:

$$EIRP\,(\text{dBm}) = Pt\,(\text{dBm}) + Gt\,(\text{dBi}) - Lf - Lp\,(\text{dB})$$



Plot 1



Plot 2

Plot 1 - This plot shows an isotropic antenna 2-D radiation pattern for all azimuth angles at 0 degrees elevation.
Plot 2 - This plot shows a directional helix antenna 2-D radiation pattern with a main lobe, a back lobe, and side lobes.

Feeder Loss

This loss occurs in several components between the antenna and the receiver or the transmitter device, such as couplers, filters, and waveguides. Feeder loss is due to the resistance and imperfections in the transmission line material, which causes part of the signal energy to be dissipated as heat.

On the transmitting end, feeder losses are typically a part of the output of the high power amplifier (HPA) and the radiating antenna. Similarly, on the receiving end, feeder losses are typically a part of the output of the antenna to the input of the low noise amplifier.

Free Space Path Loss

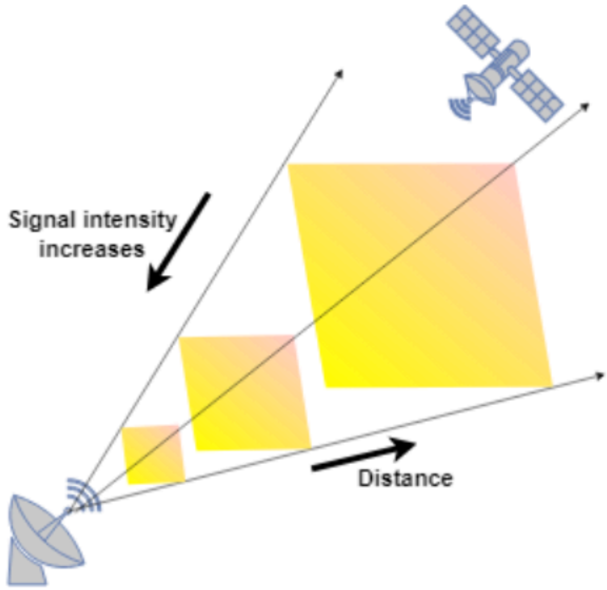
FSPL refers to the spread of the signal through space, which results in loss of the strength of the signal. Calculate FSPL using Friis transmission equation, according to which the loss is proportional to the square of the distance and the square of the frequency.
For an isotropic antenna that radiates equal power (P_t) in all directions, the power density is evenly distributed over the surface of a sphere with the isotropic antenna at its center. The intensity (I) of the signal is:

$$I = P_t / 4\pi d^2,$$

where d is the distance between the transmitter and the receiver.

The power at the receiving antenna is $Pr = I \times A\text{eff}$, where:

- Aeff is the effective area of the receiving antenna.
- Aeff = λ2/4π , where λ is the wavelength of the signal.



Substituting *I* and *A*eff, *Pr* is:

$$P_r = \left(\frac{P_t}{4\pi d^2}\right)\left(\frac{\lambda^2}{4\pi}\right),$$

Thus, FSPL

$$(L_p) = \frac{P_t}{P_r} = \left(\frac{4\pi d}{\lambda}\right)^2$$

Polarization Loss

Polarization mismatch between the transmitter and the receiver antennas leads to electromagnetic (EM) power loss. EM waves are characterized by electric and magnetic fields. A basic property of plane EM waves in free-space is that the directions of the electric and magnetic field vectors are orthogonal to their direction of propagation. EM wave polarization refers to the orientation of the electric field vector.

An antenna used to receive polarized electromagnetic waves achieves its maximum output power when the antenna polarization matches the polarization of the incident electromagnetic field. Otherwise, there is polarization loss, which can lead to a degree of signal coupling, in turn causing signal degradation. Polarization can be linear, circular, or elliptical, depending on the shape traced by the electric field vector. Polarization mismatch is characterized by a polarization loss factor, which describes the fraction of incident power that has the correct polarization for reception.

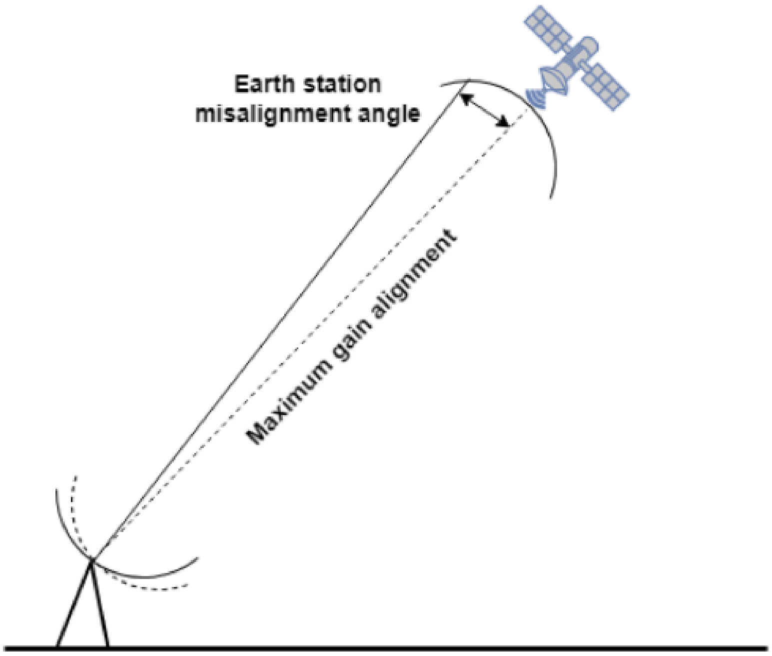
When signals traverse the ionosphere, an orthogonal component can emerge, leading to depolarization. You can quantify the impact of this phenomenon through these two metrics.

- Cross-polarization discrimination (*XPD*) — When a wave transmits with a given polarization, *XPD* is the ratio at the reception point of the power received with the expected polarization to the power received with the orthogonal polarization.
  The cross-polarization discrimination depends both on the characteristics of the antenna and on the propagation medium.
- Cross-polarization isolation (*XPI*) — When two radio waves transmit with the same power and orthogonal polarization, *XPI* is the ratio of the co-polarized power in a given receiver to the cross-polarized power in that receiver.

Raindrops contribute to depolarization as well. Ideally, a raindrop assumes a spherical shape to minimize the energy required for its cohesion. In reality, however, raindrops take on a flattened shape, resembling a spheroid with one axis longer than the others. The orientation of raindrops is randomized, influenced by factors such as wind, causing them to tilt. This tilt induces a rotation in the polarization of radio waves, which can be as much as 10 degrees. Such rotation poses a significant issue for systems using linear polarization, but it is less problematic for circular polarization, where the rotation merely adds to the existing spin of the wave.

Additionally, above the rain layer, there is often a layer of ice that can also lead to depolarization. Ice crystals typically form needle-like or plate-like shapes. Depolarization is negligible when these crystals are randomly oriented, but can occur when there is alignment.

Antenna Pointing Loss

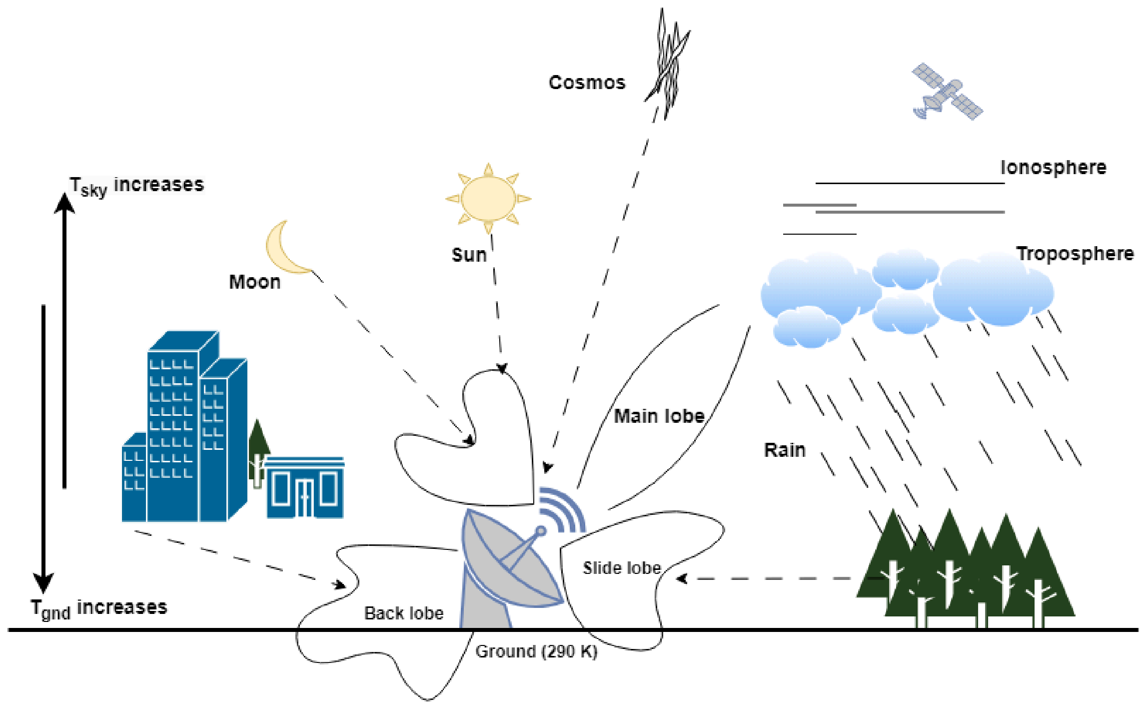


Correct alignment between an Earth station and satellite antennas provides maximum gain. Misalignment can occur either at the satellite or at the Earth station. Satellite-based misalignment must be considered during the design of the satellite, but the Earth station-based misalignment is the antenna pointing loss, and it is typically less than 1 dB. Calculating antenna misalignment losses (AML) requires statistical data, so these values are an approximation based on real data observed in several ground stations.

Along with pointing loss, misalignment loss can also be due to misalignment in the direction of polarization. These losses are quite small. Thus, antenna misalignment loss is inclusive of pointing loss as well as polarization loss.

Antenna Noise Temperature

Antenna noise temperature represents the noise level an antenna produces in a given environment. This measurement is not the physical temperature of the antenna. The total noise temperature of the antenna depends mainly on sky noise (T_{sky}) and ground noise (T_{gnd}).



Tsky consists of two main components: atmospheric and background radiation. Because the upper atmosphere is an absorbing medium, the sky noise increases with elevation. *Tgnd* contributes dominantly to the antenna noise picked up through side lobes. Ground noise temperature increases with the decrease in elevation angle, as the side lobes intercepting the ground increase. A deep dish picks up less ground noise at lower elevations than a shallow one.

Direction of transmission also affects the antenna noise temperature. In the uplink transmission from a ground station antenna to space, the antenna temperature is quite low. For a satellite antenna transmitting downlink to the ground station antenna on Earth, the antenna temperature is around 290 K, which is the noise temperature of the Earth.

System noise temperature is the sum total of the thermal noise generated by all the components of the receiver chain, that is, the summation of antenna noise temperature and the noise contribution of the rest of the receiver system.

Modulation and Coding

A fundamental feature of CubeSat communication systems is the design of the modulation and coding schemes. Since the weight and cost of CubeSats are limited, there are major constraints on the transmitted power. Hence, achieving a reliable communication with limited energy over LMS channels is a challenging issue. Depending on the CubeSat mission, the design of the modulation and coding schemes should take into account the proper trade-off between several parameters. These parameters can be summarized as follows:

- The operational frequency band, e.g., the UHF, S, X, and Ka bands, and the allocated bandwidth.
- The target data rate.
- The duration of ground passes (i.e., the period during which the CubeSat is able to communicate with the ground station).

For example, the available bandwidth at a higher frequency band such as the X-Band can reach 375 MHz, while the target bit rate is on the order of 150 Mbps for typical earth-exploration CubeSat missions. Hence, binary modulation methods, along with low-rate channel codes with high error-correction capabilities, are preferable over higher-order modulation schemes with high-rate forward error correction (FEC) codes. This is attributed to the reduction in the required power in the former case with the existence of more redundant data for efficient error correction, leading to higher power efficiency.

Frequency Band	Mission type	Modulation techniques
S-Band	Space Research Earth Exploration	GMSK, filtered OQPSK GMSK, filtered OQPSK
X-Band	Space Research Earth Exploration	GMSK, filtered OQPSK 4D 8-PSK TCM, GMSK, filtered OQPSK, 8-PSK, $M-$PSK with $M \in \{16, 32, 64\}$
Ka-Band	Space Research Earth Exploration	GMSK with precoding GMSK, filtered OQPSK, 8-PSK, $M-$PSK with $M \in \{16, 32, 64\}$

Generally, choosing a suitable CubeSat modulation technique requires a trade-off between several metrics, i.e., the bandwidth and power efficiency, the BER performance, and the complexity of the spacecraft transceiver. In the following, an overview of the most common CubeSat modulation and coding schemes is presented.

Conclusions

We envision CubeSats enabling a wide range of applications, including Earth and space exploration, rural connectivity for the pervasive Internet of things (IoT) networks, and ubiquitous coverage. Current CubeSat research is mostly focused on remote-sensing applications. Unfortunately, few efforts have been made to offer communication solutions using CubeSats, which could involve CubeSat swarms for ubiquitous coverage, optical communication for high data rates, integration with future cellular systems for back-hauling, etc. Therefore, in this paper, we have reviewed the literature on various facets of CubeSat communications, including channel modeling, modulation and coding, coverage, networking, and upper-layer issues. We also outlined several significant future research challenges, that highlight how CubeSat technology is a key enabler for the emerging Internet of space things. Both the existing literature collection and the research problems we propose form a promising framework for addressing the global problem of the digital divide. In short, this paper is a good starting point for the academic and industrial researchers focusing on providing communication solutions using CubeSats.

THANK YOU

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References:

- "CubeSat Communications: Recent Advances and Future Challenges" - https://s3vi.ndc.nasa.gov/ssri-kb/static/resources/1908.09501.pdf
- Satellite Link Budget - https://www.mathworks.com/help/satcom/gs/satellite-link-budget.html