Small Satellite Radio Link Fundamentals

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Abstract

Small satellite radio systems often face link power budget, mass and volume constraints and restrictions. Additionally many small satellite systems are developed by student groups or start-ups with limited development resources. These challenges can be addressed utilizing commercial off the self (COTS) industrial solutions. Practical implementation of satellite links utilizing basic link theory and industrial standards and products is discussed.

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1 Introduction

The subject of the theory and design of satellite data links is covered rigorously in many texts, papers, and university courses. However, most of the available reference material often burdens the reader with excessive complexity and information that may not be necessary for a practicing engineer to plan and implement a working small satellite communication system. This text intends to sacrifice rigor for clarity.

A thorough study of the subject of radio communications is a big undertaking for the novice. What is provided here is a *minimally complex* and focused discussion on the *key concepts* needed for a student or practicing engineer to understand the full picture of a satellite link at the system level. This chapter outlines the basic theory followed by practical examples of radio hardware and systems. This primer will hopefully provide a solid foundation with which the reader can continue their research into more specific areas of interest.

1.1 Intended Audience

1.1.1 Students

Radio and communication system theory draws on many academic domains. Depending on academic focus, students will specialize in a specific domains like RF engineering, digital signal processing, digital communication, electromagnetics, network design, etc. This chapter aims to aid students in their understanding of the satellite communication system as a whole and provide the broad context and to work with a large-complex system. Demonstration of mastery of these general concepts will be very helpful for a student applying for an internship or entry level position.

1.1.2 System Engineers

Satellite system engineers may not have the specific radio communications domain knowledge to effectively understand communication system design trade-offs and effectively communicate with the domain experts they work with. Mastery of the concepts presented in this primer will be beneficial to those who need to achieve competency in the multiple domains of satellite system design.

1.1.3 Engineers Working on Specific Subsystems of Radio Communication Systems

Engineers working on communication systems often have a limited scope of their work. For example, engineers may develop expertise in antennas or power amplifiers or baseband processing, and this document provides the larger context to the system as a whole.

1.1.4 Start-up Founders

Satellite hardware start-ups whose founders who did not personally have practical communication system understanding will benefit from this chapter and have a working background to be able to perform basic system feasibility studies and be more effective in their hiring process.

2 RF Link Basics

A concise review of basic RF link theory is presented here. In a later section, practical hardware options will be introduced and discussed. The purpose of this text is to provide a high-level view of the satellite link design process. A solid grasp of the "big picture" is very helpful for initial feasibility analysis and early planning.

When approaching the problem of implementing a practical system for data transmission over an RF link, *three fundamental questions* need to be considered:

1. How much "signal power" enters the receiver?
2. How much "noise power" enters the receiver?
3. What level of throughput can be achieved given the ratio of 1 and 2 *(known as signal-to-noise ratio or SNR)*?

2.1 Signal Power

> *Antennas and their design are addressed in this section. This can be a complex subject but for the purposes of discussion all that needs to be understood is that an antenna is a device that transfers "guided" RF energy (energy traveling in a waveguide or coaxial cable) into "free space" radiation or vice versa.*

The determination of how much signal power enters a receiver over a free space link is a *simple geometry problem*.

2.1.1 Transmitting with an Isotropic Radiator

First consider a conceptual (but not actually realizable) antenna known as an "isotropic radiator." Such an antenna when fed some input transmit power P_T will produce a spherical wave front at distance R with P_T spread evenly across the surface of the sphere.

The surface area of a sphere is given by

$$A = 4\pi R^2 \left(\mathrm{m}^2\right)$$

The “power density” at some distance “R” is thus

$$\frac{P_T}{4\pi R^2} \left(\mathrm{W/m}^2\right)$$

Transmit Antenna

In reality it is impossible for a radiator to produce radiation that is equal power in all directions if such a property was desired. Also, it is often desired to focus the energy such that the power density in some direction is much higher than that of the *isotropic radiator.*

The ratio of the power density produced by an antenna relative to that of an “isotropic” radiator is the “antenna gain” (G_T).

> *An antenna with a gain >1 does not actually output more total energy than it receives at its input. It focuses the energy instead of radiating evenly in all directions. Antenna gain should not be confused with the term “gain” used in the context of amplifiers.*

The “power density” at some distance R given the actual antenna with a gain G_T is given by

$$G_T \frac{P_T}{4\pi R^2} \left(\mathrm{W/m}^2\right)$$

Receive Antenna

At the location of the receive antenna, it is now known what the power density of the incident field is from the preceding equation. The receive antenna can be described as having a “capture area” or “effective aperture,” in this case “receive effective aperture” for the analysis (A_R).

The receive power is thus given by

$$P_R = A_R G_T \frac{P_T}{4\pi R^2}$$

2.1.2 Antenna Gain and Effective Aperture

Gain and effective aperture are two equivalent ways to describe how well an antenna focuses energy. Conceptually for the purposes of link analysis, it is easier to think of a transmit antenna in terms of gain and of a receive antenna in terms of aperture.

However, these properties are identical whether the antenna is used in either a transmit or receive configuration, a property known as "reciprocity."

The relationship between gain and aperture is given by

$$A_E = \frac{\lambda^2}{4\pi} G$$

A derivation of this property can be found in Balanis (2005)

For certain types of antennas like reflector antennas or planar-phased arrays, the "aperture" is intuitive by inspection of the physical collector area. The "effective aperture" for a reflector is typically 60–70% of the actual area of the dish. For a planar-phased array, "effective aperture" can meet or exceed slightly the physical area. For other types of antennas, like a Yagi, the "aperture" is not obvious from the antenna construction.

The key takeaway from the aperture-gain relationship equation is that **for a given aperture, gain increases with increasing carrier frequency.**

2.2 Complete Link

The original receive power equation can be rewritten.

$$P_R = A_R G_T \frac{P_T}{4\pi R^2} \tag{1}$$

Using the aperture-gain relationship as two different equations utilizing either "aperture" or "gain"

$$P_R = G_R G_T \frac{\lambda^2 P_T}{(4\pi R)^2} \text{(this formulation known as Friis equation)} \tag{2}$$

$$P_R = A_R A_T \frac{P_T}{\lambda^2 R^2} \tag{3}$$

There is a **key insight** to be gained by examining the three different formulations of this equation, and these three different formulations of the same relationship describe three general classes of RF links:

1. Fixed aperture to fixed aperture
   Consider a point to point link between reflector antennas. The "aperture" of the antennas does not change with frequency. Equation (3) most directly represents this configuration. Note that "receive power" **increases** with increasing carrier frequency. This type of link is optimal for high throughput and benefits from high carrier frequencies. Links like these will often utilize carrier frequencies in the 10 s of Ghz to maximize throughput. A high throughput spacecraft radio system will generally fall under this category.

2. Fixed gain to fixed gain
   Consider a link between two low-gain antennas. Such a link is useful if communication needs to be maintained in any direction without pointing. Equation (2) most directly represents this configuration. Note that "receive power" **decreases** with increasing carrier frequency. An example of this sort of link would be radio or TV broadcast. Note that typical carrier frequencies for these purposes are no more than a couple of hundred Mhz.

   Ham radio operators operating in the "HF" band (3–30 Mhz) band routinely make contacts over thousands of kilometers with low-gain antennas and moderate transmit power levels. Long-range military communications also use similarly low-frequency links to reach extreme distances. The ionosphere aids this process by reflecting these signals allowing their path to avoid blockage by the curvature of the Earth.
3. Fixed aperture to fixed gain
   Consider a link between a ground-based dish and an omnidirectional antenna on a spacecraft. Such a link is beneficial because it does not rely on the spacecraft being able to point. Equation (1) most directly represents this configuration. Note that "receive power" **is independent** of carrier frequency. A low-speed TT&C (Telemetry, Tracking and Command) spacecraft radio will generally fall under this category since the spacecraft antennas are typically low-gain to provide attitude independent link closure.

The above simplified link equations do not include practical link impairments such as atmospheric absorption which is carrier frequency dependent.

Later discussion will utilize these formulas in logarithmic form as it is more convenient to deal with the extremely large range of power levels dealt with and is the standard approach in practice.

An excellent discussion of the logarithmic representation of these sorts of equations and representations of system parameters can be found in Chapter 13 of the "Handbook of Satellite Applications" in the section Understanding Decibels (Glover 2013). *It is recommended that the reader familiarize themselves with this section in order to follow later sections of this chapter which utilize logarithmic representations.*
Internet resources discussing the subject are also readily available (Decibel Tutorial 2019).

2.3 Overview of Basic RF Satellite Link Calculations

Simple calculations using these concepts allow for quick feasibility and performance estimations for satellite link performance.

2.4 Concepts Not Discussed but Recommended for Further Study

- Antenna and wave polarization
  - Linear polarization
  - Circular polarization
  - Polarization matching
  - Atmospheric absorption

2.5 Noise Power

This section discusses how to determine the "noise power" that enters a radio receiver. As discussed in the introduction, it is the ratio of the signal power to the noise power that will ultimately determine the overall throughput that the link is capable of. The discussion will be limited to "thermal noise" or more specifically "Johnson-Nyquist" noise.

Examples of more complex forms of "noise" that may be encountered

- *Multipath reception, for example, GPS receivers in a dense urban environment receiving multiple copies of the signal at different power levels and phase shifts*
- *Self-interference from emissions from the spacecraft itself. For example, EMI or out of band emissions from other radios*
  SNR is often extended to SINR (signal-to-noise and interference ratio) to account for these sorts of issues.

2.5.1 Noise Power from Matched Resistive Source

Consider a matched resistive source (e.g., 50 ohm termination) connected to the input of the receiver. The power generated by the resistive source is generated by the thermal agitation of charge carriers.

The power entering the receiver (load) is given by

$$P_n = k_b T B \text{ (W)}$$

P_n – Noise power (W)
k_b – Boltzmann constant ~ 1.38e−23 ($\mathrm{m^2 kg s^{-2} K^{-1}}$)
T – Temperature in Kelvin
B – Bandwidth over which power is measured (Hz)

Communication system analysis typically utilizes the bandwidth independent parameter **noise density**.

The total power is bandwidth times the noise density.

$$P_n = B N_0 \text{ (W)}$$

N_0 – Noise density (W/Hz)

The "power density" of the noise can be calculated by dividing the power by the bandwidth

$$P_D = k_b T \text{ (W/Hz)}$$

Note that the power density for the transferred power from a matched resistive source is solely dependent on the physical temperature of the resistive device.

At room temperature (290 K), P_D= 3.73e−21(W/Hz) = −174 dBm/Hz

2.5.2 Noise Power in Real Receiver System

The previous section discussed how the noise power density from a resistive source is solely dependent on its physical temperature.

For a real receiver, it is customary and convenient to determine an "effective noise temperature (Te)" for the receiver system. This allows the calculation of the noise density by multiplying by k_b

$$N_0 = k_b T_E$$

2.5.3 Ideal Antenna

Consider an ideal antenna. Such an antenna has no losses, has a tight beam with no sidelobes and delivers all energy that it picks up to its feed with zero loss.

With an imaginary antenna like this, the "effective temperature" will be determined by whatever radiated sources it is pointing at. If we assume that the targets behave like "black bodies," their physical temperature will be directly related to the output noise density by the $k_b T$ relationship. For the purposes of this discussion, it is assumed that the beam is narrow enough to only pickup radiation from the target (Table 1).

> *The sun is a convenient reference source for antenna characterization and performance validation* (Morgan 2018).

2.5.4 Real Antenna

A real antenna will suffer from sources of thermal noise other than the intended radiation that it is intended to receive. Consider a ground-based dish antenna used for communication with a spacecraft. Though it is pointed toward the "cold sky," it will pick up energy from sources like the following:

1. Thermal radiation from the atmosphere
2. Thermal radiation from the earth picked up by sidelobes

Table 1 Temperature of some common radiative sources

Target	Temp (K)	$k_b T$ (dBm)	Notes
Deep space	2.7	−192	Cosmic background radiation
Earth	270	−174	Typical average earth temperature
Sun	5800	−161	Typical average sun surface temperature

3. Radiation from lossy (resistive) paths for the RF current
   (a) Losses on dish surface or antenna elements
   (b) Losses in the feed network and preselect filters

Resources on the subject can be found in (Lambert and Rudduck 1992; Gary 2019; Kraus 1988).

For the purposes of this discussion, a Te value of 100 K can be used which is typical for a ground-based dish pointing at the cold sky.

A space-based antenna which has a beam pointing toward the earth will have a Te value of around 300 K, the temperature from the earth and additional resistive temperature from loss in the antenna itself.

2.5.5 Low-Noise Amplifier

Any receiver system requires active and passive devices to condition the signal for reception. These contribute added noise. Dealing with this impairment is achieved by placing a **low-noise amplifier (LNA)** as close as possible to or integrated with the antenna feed. If the gain of the LNA is sufficiently high, the received signal and antenna/LNA noise will be significantly higher than any downstream noise sources and so can be discarded by them since the LNA will be the dominant source of amplifier noise.

Resources on the subject "cascaded noise" be found in (Kraus 1988; Noise Figure 2019).

The LNA noise performance is specified by a term called "noise figure."

The "noise figure" is the ratio of noise power out of the LNA to the thermal noise from a matched resistive source on the input. Since the thermal noise of a "matched resistive source" is temperature-dependent as discussed before, the noise figure is specified at a "reference temperature," typically 290 K.

The hypothetical 100 K antenna source is not delivering kb∗290 noise density, so the NF is not directly useful for the satcom example.

The "noise figure" can be converted to a "noise temperature" with the following equation:

$$T_N = T_{REF} * \left(10^{\frac{NF(dB)}{10}} - 1\right)$$

For example, if the LNA has a "noise figure" of 1 dB, the Te is 75 K.

Recall the hypothetical ground and spacecraft antennas and the 1 dB NF LNA. The total Te is simply the sum of the antenna Te and the LNA Te.

Ground receiver: Te = 100 + 75 = 175 K
Space receiver: Te = 300 + 75 = 375

The **key point** here in this particular link example is that the noise figure parameter has a larger overall effect on the performance of the ground-based system since the earth pointing antenna is picking up significant radiated energy from the earth. A high-performance earth-based antenna such as one designed for radio astronomy will benefit from exotic (and extremely expensive) cryogenically cooled LNAs, but an earth-pointing space-based communications antenna receives little benefit from a cryocooled LNA.

> *Most integrated dish systems will include the LNA with the feed, and the overall system will be specified with an aggregate Te including the effect of the LNA. This figure of merit is typically called G/T which is the antenna gain divided by Te.*

2.6 Overview of Noise Considerations

When analyzing satellite RF links, the received "noise density" needs to be determined. This is a combination of noise picked up from unwanted radiated sources as well as internally generated noise in the LNA. It is most convenient for satellite links to calculate overall noise sources for the purposes of analysis as an "effective temperature." The overall "noise power" is calculated by multiplying the "noise density" by the bandwidth of interest.

2.7 Concepts Not Discussed but Recommended for Further Study

- Noise figure cascade analysis. This analysis will inform whether or not noise contributions of elements after the LNA can be ignored.
- Detailed antenna temperature analysis.

2.8 Signal-to-Noise Ratio and Link Budgets

2.8.1 Introduction

The previous section discussed how to calculate received signal power and noise/noise density based off some simple properties of an RF link. This section will discuss how to "close the link" and create a "link budget." The goal is to ensure that given the link conditions and the choice of modulation and coding, sufficient signal-to-noise ratio is maintained to meet some requirement for throughput and error rate.

2.8.2 Modulation and Error Correction

The subject of signal modulation and error correction can be a very deep and complex topic. Fortunately the SNR and throughput relationship for various forms of modulation and coding schemes can be found in reference materials and technical documentation.

In this text, the discussion will be limited to two types of modulation. FSK (frequency shift keying) and APSK (amplitude phase shift keying) as almost all satellite point to point links will use one or the other. High-speed links will typically utilize PSK/APSK with complex error correction schemes for maximum throughput. Low-speed/low-power links will often use FSK or M-FSK due to the simple hardware and low power requirements.

> *Complex communication systems such as the multiplexed multibeam links of say the iridium communication system are beyond the scope of the discussion here.*

2.8.3 Modulation

Phase Shift Keying and Amplitude Phase Shift Keying

The most common form of modulation for medium- to high-speed radio links is PSK or APSK. With this form of modulation, the phase and/or amplitude of a carrier wave is changed to encode information.

BPSK (Binary Phase Shift Keying)

The simplest form of PSK is “binary phase shift keying.” In this scheme the phase of the carrier is shifted between 0° and 180° to encode either a 1 or a 0.

A section of the carrier with a duration of the symbol period is known as a “symbol.” In this scheme there is one bit encoded per “symbol.” In such a case, the “bitrate” is equal to the “symbol rate.”

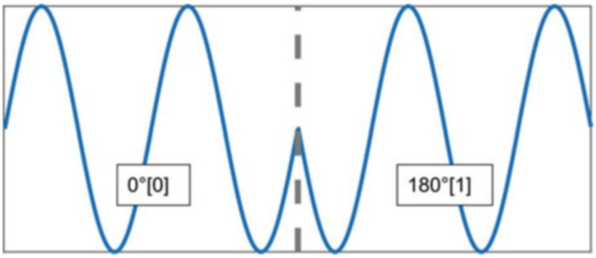
> *Error correction will be discussed later which involves “redundant” bits. In such a case, the bitrate to symbol rate will change depending on the redundancy fraction.*

Figure 1 shows the symbol waveforms of a BPSK modulated carrier transitioning from a “0” to a “1.” This example is unfiltered which would in practice yield unacceptably wide spectral content. Appropriate symbol filtering prevents this

QPSK (Quadrature Phase Shift Keying)

The number of bits per symbol can be increased by encoding multiple bits in a single symbol. With “quadrature phase shift keying,” there are 4 symbol states, 45, 135, 225, and 315°, so 2 bits per symbol can be encoded. The number of bits per symbol can be increased to 3 by using 8 phases, this is known as 8-PSK (Fig. 2).

Fig. 1 Example of BPSK modulation format. (Image: Matt Ligon 2020)



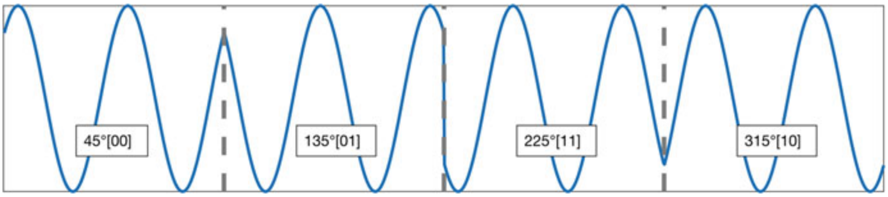


Fig. 2 Example of QPSK Modulated Signal. (Image: Matt Ligon 2020)

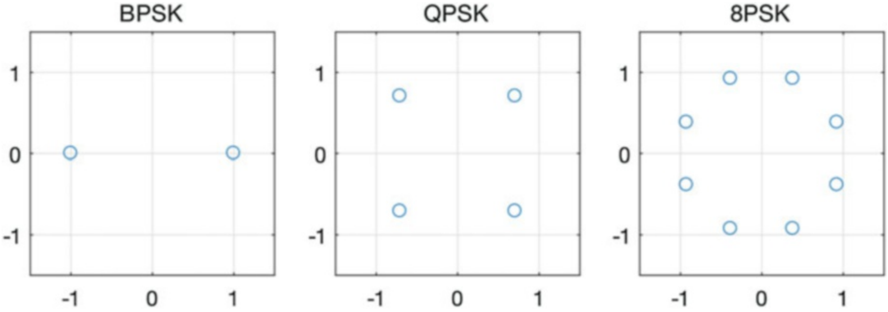


Fig. 3 Constellations for BPSK, QPSK, 8PSK,and 8PSK. (Image: Matt Ligon 2020)

PSK Constellation Diagrams

The common graphical representation for this type of modulation is to represent the symbols on a **constellation diagram**. Such a diagram is a polar plot that shows the amplitude and phase of each symbol.

Figure 3 shows BPSK, QPSK, and 8PSK represented on a "constellation diagram." Note that the 180d phase degree difference is clear from the BPSK plot and the 90d phase degree differences are clear from the QPSK plot and the 45d phase differences for 8PSK.

APSK Constellation Diagrams

Additional constant amplitude symbols could be added with reduced phase difference, 16-PSK, for example. This however is not an efficient use of the available phase-amplitude space. Instead to further increase the number of bits per symbol, amplitude is introduced as a variable resulting in what is called "amplitude phase shift keying." The 16 and 32 symbol constellations are shown below.

Higher-Order Constellation Diagrams

See Fig. 4.

Modulation Types and Required SNR

See Fig. 5.

With added noise, there is variability in the location of the received symbol. The size and spread of the received symbol "cloud" is dependent on the signal-to-noise

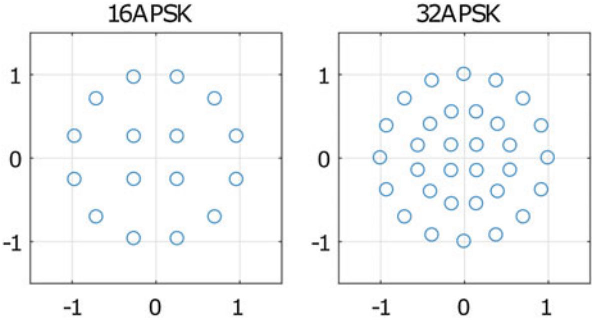


Fig. 4 16APSK and 32APSK constellation diagrams. (Image: Matt Ligon 2020)

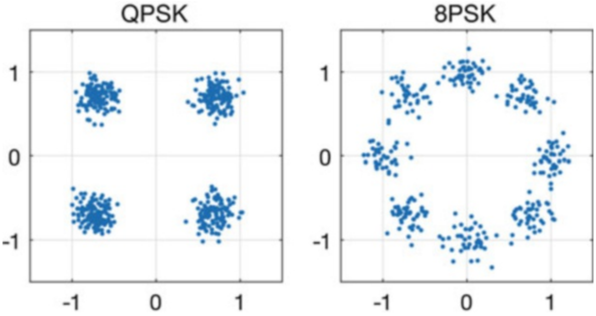


Fig. 5 QPSK and 8PSK constellations with 15 dB SNR. (Image: Matt Ligon 2020)

ratio. The “decision regions” or region that the received signal must fall to be interpreted correctly is smaller as the number of bits per symbol increases. This means that “higher order” (modulations with higher bits per symbol) require higher SNRs for correct interpretation of the received signal.

Alternate Constellation Configurations

These constellation schemes are not the only symbol arrangement used in commercial communication links. They are however particularly useful for satellite links with transmitters that are driven out of their nonlinear region because of their radially symmetric nature.

2.8.4 Error Correction

Due to the presence of noise, some fraction of the symbols will be interpreted incorrectly. Lower SNRs will result in a higher ratio of symbol errors. Practical communication systems deal with this problem by implementing “error correction.”

To put it simply, links that utilize “error correction” schemes add redundancy to the bitstream so that if a fraction of the bitstream is incorrect, the actual message can be reconstructed.

The subject of “error correction” is complex. Different schemes have different levels of performance which is related to the computing complexity of implementation. This text will not dive into the details of this subject, but the curious and mathematically inclined reader is encouraged to study the subject in more depth.

In this text, published specifications will be utilized to analyze practical RF links.

DVB-S2

The discussion of APSK modulation with error correction will be completed by referring to the DVB-S2 standard. The DVB-S2 standard defines packet framing, modulation types, and error correction schemes. The "DVB" refers to "Digital Video Broadcast" and was designed for the purpose of satellite digital television broadcast and backhaul. DVB-S2 is a very useful standard for general satellite data transmission as well.

Because of the considerable industrial investment in both the standard as well as the availability of inexpensive receiver hardware, it is a good option for inexpensive and low cost of development high-speed satellite links for CubeSats and SmallSats. DVB-S2 is by no means the only standard that can be used, but it is a high-performance well-documented standard that is useful as a reference. Traditional satellite systems commonly utilize standards defined by the CCSDS, for example.

Due to the sophisticated error correction implemented by DVB-S2, the processing requirements are high and require the use of FPGAs at high symbol rates. It is a useful standard for high throughput links but is not suitable for low-power low-speed links.

On the transmit side, DVB-S2 IP cores are commonly available for FPGAs. On the receive side, inexpensive commercial receiver hardware is readily available. For example, the TBS6903 PCI-E receiver card that can support 16APSK (5 bits per symbol) at 67.5MSPS (Mega symbols per second) can be purchased for 255USD.

The advantage of using a standard such as DVB-S2 is that there is thorough published information about the link performance and cheap to moderately priced commercially available receiver hardware. DVB-S2 supports QPSK through 32APSK and a variety of different coding rates (ratio of real bits total bits including redundancy). DVB-S2X further extends the available coding ratios as well as modulation types.

A key advantage of DVB-S2 is its implementation of error correction specifically **forward error correction** *based on concatenation of BCH (Bose-Chaudhuri-Hcquengham) with LDPC (Low Density Parity Check) inner coding* (DVB Fact Sheet 2018)

To reiterate, DVB-S2 is only a convenient standard that defines a specific implementation of modulation, framing, and error correction. These implementations are not exclusive to DVB-S2.

The DVB-S2 standard defines 23 MODCOD's. A MODCOD is a combination of modulation and ratio of data bits to total bits.

Table 2 DVB-S2 MODCOD definitions

Mode	MODCOD	Mode	MODCOD
QPSK 1/4	1	8PSK 5/6	15
QPSK 1/3	2	8PSK 8/9	16
QPSK 2/5	3	8PSK 9/10	17
QPSK 1/2	4	16APSK 2/3	18
QPSK 3/5	5	16APSK 3/4	19
QPSK 2/3	6	16APSK 4/5	20
QPSK 3/4	7	16APSK 5/6	21
QPSK 4/5	8	16APSK 8/9	22
QPSK 5/6	9	16APSK 9/10	23
QPSK 8/9	10	32APSK 3/4	24
QPSK 9/10	11	32APSK 4/5	25
8PSK 3/5	12	32APSK 5/6	26
8PSK 2/3	13	32APSK 8/9	27
8PSK 3/4	14	32APSK 9/10	28

The following table from the DVB-S2 standard (ETSI 2014) specifies the relationship (Table 2).

Example

MODCOD 12 utilizes 8PSK with a code rate of $3/5$. Each symbol encodes 3 "total bits" since 3 bits are encoded per symbol with 8PSK. The "$3/5$" refers to the ratio of "data bits" to "total bits" since extra bits are added for redundancy for the error correction.

If the symbol rate is 50MSPS, for example, that means there are 150 Mbps (3 bits per symbol for 8psk) including code bits and $3/5 * 150 = 90$ Mbps actual data rate at MODCOD:12

The important question however is how much signal-to-noise ratio is needed to support a certain MODCOD and subsequent data rate.

The DVB-S2 specification provides a table describing the ideal required SNR in the form of EsNo. EsNo is defined as the "energy per symbol" divided by the "noise density." In the table below, the specifications for a real demodulator have been added (Newtec AZ910) (Newtec 2019) to compare performance of a commercially available piece of hardware. In addition, the theoretical "Shannon capacity" has been added.

Shannon capacity and the Shannon-Hartley theorem will be discussed later, but for the purposes of the current discussion, understand that the "Shannon capacity" describes the theoretical maximum performance for a communications link.

ESNO or $E_S/N_0$is the ratio of **energy per symbol** divided by **noise density**.

Note that increases of "bits per symbol" known as spectral efficiency (η) requires higher EsNo, as discussed in the previous section.

Table 3 DVB-S2 modulation and required EsNo

MODCOD	Modulation	Code rate	DVB-S2 (bits/symbol)	DVB-S2 theoretical EsNo req (dB)	Newtec AZ910 demod EsNo req (dB)	Shannon limit EsNo req (dB)	Shannon limit capacity (bits/symbol)
1	QPSK	1/4	0.49	−2.4		−3.93	0.66
2	QPSK	1/3	0.66	−1.2	−0.70	−2.39	0.81
3	QPSK	2/5	0.79	−0.3	0.20	−1.38	0.95
4	QPSK	1/2	0.99	1.0	1.40	−0.07	1.18
5	QPSK	3/5	1.19	2.2	2.80	1.07	1.42
6	QPSK	2/3	1.32	3.1	3.60	1.76	1.60
7	QPSK	3/4	1.49	4.0	4.30	2.56	1.82
8	QPSK	4/5	1.59	4.7	5.10	3.02	1.98
9	QPSK	5/6	1.65	5.2	5.50	3.32	2.10
10	QPSK	8/9	1.77	6.2	6.60	3.81	2.37
11	QPSK	9/10	1.79	6.4	6.70	3.90	2.43
12	8PSK	3/5	1.78	5.5	6.30	3.86	2.19
13	8PSK	2/3	1.98	6.6	7.10	4.69	2.48
14	8PSK	3/4	2.23	7.9	8.40	5.66	2.84
15	8PSK	5/6	2.48	9.4	9.70	6.60	3.26
16	8PSK	8/9	2.65	10.7	11.10	7.21	3.67
17	8PSK	9/10	2.68	11.0	11.30	7.33	3.76
18	16APSK	2/3	2.64	9.0	9.60	7.18	3.15
19	16APSK	3/4	2.97	10.2	10.50	8.34	3.52
20	16APSK	4/5	3.17	11.0	11.50	9.02	3.77
21	16APSK	5/6	3.30	11.6	12.10	9.47	3.95
22	16APSK	8/9	3.52	12.9	13.30	10.21	4.35
23	16APSK	9/10	3.57	13.1	13.60	10.36	4.43
24	32APSK	3/4	3.70	12.7	13.60	10.80	4.30
25	32APSK	4/5	3.95	13.6	14.50	11.61	4.59
26	32APSK	5/6	4.12	14.3	14.90	12.14	4.80
27	32APSK	8/9	4.40	15.7	16.10	13.03	5.25
28	32APSK	9/10	4.45	16.1	16.50	13.20	5.37

With understanding of the concepts laid out, the definition **energy per symbol** is discussed below.

If the receive power is Prx and the symbol rate is Rs, it follows that the energy carried by each symbol is Prx/R. This is the **energy per symbol** or E_S

The discussion of "noise power" showed that it is a property of the antenna and receive system. How to simply determine signal power at the receiver was also discussed. By considering the additional variable of the symbol rate, "EsNo" can be calculated, and Table 3 can be consulted to determine the achievable MODCOD.

DVB-S2 and the Shannon Limit

In the previous section, the published behavior of a high-performance commercial standard called DVB-S2 was discussed. The level of performance of the standard can be determined by comparing it to what is known as the Shannon limit. Table 3 shows how many bits per symbol can be received given a certain EsNo. The Shannon limit will show what the maximum possible error free capacity of a "noisy channel" is.

The fundamental relationship between "C" channel capacity (bits per second), "B" bandwidth (Hz), "S" signal power (W), and "N" noise power (W) is given by the "Shannon-Hartley" theorem.

"Noise" in this context refers to "additive white Gaussian noise." Thermal noise has this property.

$$C = B\,log_2\left(1 + \frac{S}{N}\right)$$

The equation will now be reformulated.

Describe "S" as energy per symbol times symbol rate.

$$S = E_S R_s$$

Describe "N" as noise density times bandwidth.

$$N = N_0 B$$

Next it is asserted that $R_S = B$. In reality the ratio between the symbol rate and bandwidth for PSK/APSK is dependent on the implementation of the symbol filter. The discussion here will assume that they are equal.

Why is the minimum bandwidth dependent on symbol rate? This can be understood with a simple conceptual exercise. Imagine a stream of alternating ones and zeroes, 01010101, etc.

If this were to represent this with a sine wave where the peaks were ones and the troughs were zero, a sine wave with a frequency equal to the symbol rate would be needed. A lower-frequency wave would not be able to carry the information.

Rewrite the Shannon-Hartley theorem as follows:

$$\frac{C}{B} = log_2\left(1 + \frac{E_S R_S}{N_0 B}\right)$$

Assuming Rs = B yields

$$\frac{C}{R_S} = log_2\left(1 + \frac{E_S}{N_0}\right)$$

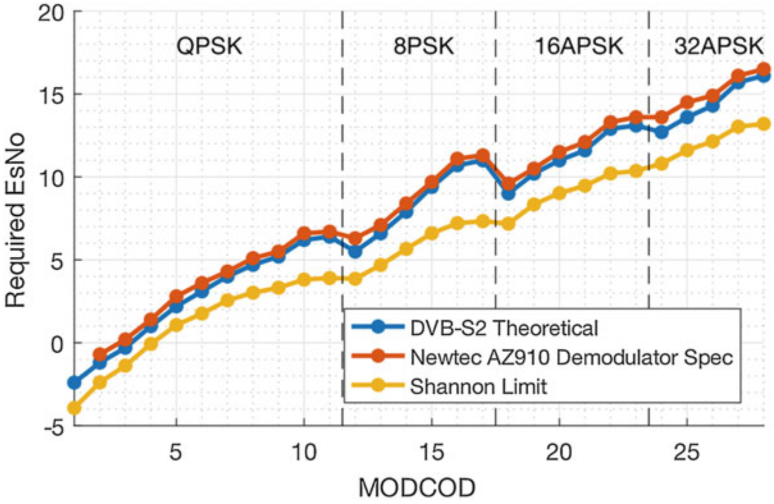


Fig. 6 EsNo required at different MODCODs. (Image: Matt Ligon 2020)

C(bits/s)/Rs(symbols/s) yields "spectral efficiency" η(bits/symbol):

$$\eta = log_2\left(1 + \frac{E_S}{N_0}\right)$$

Refer back to the DVB-S2 performance specification which shows the relationship between "spectral efficiency" and EsNo. The Shannon-Hartley theorem has been rewritten to show the theoretical maximum relationship between the two. The Shannon limit and the DVB-S2 performance are plotted in Fig. 6.

This plot shows the EsNo required for "quasi-error-free" operation of a theoretically ideal DVB-S2 channel, the specification for a commercial demodulator (Newtec AZ910), as well as the theoretical Shannon minimum EsNo required for a given MODCOD. It can be seen that the DVB-S2 implementation ranges from within 1 to 4 dB of the theoretical minimum.

Note the regions where the DVB-S2 plot has a larger deviation from Shannon. These are the regions where there is a smaller ratio of code bits to data bits. The error correction is less effective as the ratio of code bits to data bits tends toward zero. If there were no code bits, ***no error correction at all*** *could be performed. Since DVB-S2 is a standard intended for broadcast use, the performance is specified such that a consumer will experience a glitch rarely. This is referred to as "quasi-error-free."*

Example DVB-S2 Link Budget

As an example the Planet Labs "Dove HSD" high-speed downlink system is studied. A thorough discussion of the system was published at the 31st Annual AIAA/USU

Table 4 Dove HSD key link parameters

Parameter	Value	Unit	Notes
Transmit power	2	W	
Tx antenna gain	10	dBiC	Circular polarized helical antenna
Symbol rate	70	MSPS	
Max distance	2050	km	Distance at 5d Elevation
G/T	29	dB/K	G/T for ground dish. G is gain, and T is "effective antenna temperature" Planet uses a mix of 4.5 and 5 m diameter dishes.

Conference on Small Satellites. It is recommended that the reader study the paper thoroughly for background on implementation details of both spacecraft and ground systems (Devaraj et al. 2017) (Table 4).

Recall the link equation from the previous section

$$P_R = G_R G_T \frac{\lambda^2 P_T}{(4\pi R)^2}$$

This equation shows how to determine the received power. EsNo needs to be determined to calculate the link throughput.

Recall the relationship between "effective temperature" and "noise density"

$$N_0 = k_b T_E$$

as well as the relationship between signal power, energy per symbol, and symbol rate

$S = E_S R_s$ or $P = E_S R_s$ to match the power symbol in the link equation

Expand the link equation

$$\frac{E_S R_s}{N_0} = \frac{G_R G_T \frac{\lambda^2 P_T}{(4\pi R)^2}}{k_b T_E}$$

and reformulated

$$\frac{E_S}{N_0} = \left(\frac{G_R}{T_E}\right)(G_T)(P_T)\left(\frac{\lambda^2}{(4\pi R)^2}\right)\left(\frac{1}{k_b}\right)\left(\frac{1}{R_s}\right)$$

The specific terms are discussed and given abbreviations and logarithmic units.

$$\left(\frac{G_R}{T_E}\right)[\mathrm{G/T}](\mathrm{dBi/K})$$

Gain of the receive antenna divided by the effective temperature. As discussed prior this G/T term is the standard figure of merit for a ground dish receiver antenna.

$$(G_t)[\mathrm{Gt}](\mathrm{dBi})$$

This term describes gain of the transmit antenna, which is a ratio of power density relative to that of an "isotropic" radiator. The "i" in the unit dBi refers to this.

$$(P_t)[\mathrm{Pt}](\mathrm{dBW})$$

This term describes gain of the transmit antenna. The unit dBW refers to the fact that it is a ratio relative to 1 W

$$\left(\frac{\lambda^2}{(4\pi R)^2}\right)[\mathrm{PL}](\mathrm{dB})$$

This term describes what is called "path loss." This is the reduction of energy density over distance due to the fact that the energy is spreading over a larger "spherical" wave front. The unit is dimensionless and is thus simply dB.

$$\left(\frac{1}{k_b}\right)[1/\mathrm{Kb}](\mathrm{K}\cdot\mathrm{Hz})/\mathrm{dBW}$$

As discussed in the "Noise Power" section, The k_bT term defines the noise power.

$$\left(\frac{1}{R_S}\right)[1/\mathrm{Rs}]$$

This is the symbol rate.

The link equation is now rewritten in logarithmic form. Note that the terms that have been inverted are now subtractions instead of additions.

$$\begin{aligned}\frac{E_S}{N_0}(dBHz) = G/T(dBi/K) + G_T(dBi) + P_t(dBW)\\ +PL(dB) + [1/Kb]((K\cdot Hz)/dBw) + [1/Rs](1/dBHz)\end{aligned}$$

A tabular link budget based on this equation is shown below. The numbers highlighted in red are summed together to yield the resulting EsNo (Table 5).

Table 5 Example DVB-S2 link budget

Parameter	Value	Unit
Distance	2.05E+06	m
Tx power	2.00	W
Carrier frequency	8.20E+09	Hz
speed of light	3.00E+08	m/s
wavelength	0.04	m
Boltzmann constant [Kb]	−228.59	dBW/(K·Hz)
Symbol rate	7.00E+07	Hz
Tx power dB [Pt]	3.01	dBW
Tx ant gain [Gt]	10.00	dBi
Path loss [PL]	−176.9531265	dB
1/Boltzmann constant [1/Kb]	228.59	(K·Hz)/dBW
1/symbol rate [1/Rs]	−78.45	1/dBHz
G/T [G/T]	29.00	dBi/K
EsNo	**15.20**	dBHz

Note that this link budget does not include any margin, atmospheric loss, antenna polarization mismatch, or other impairments. The resulting EsNo is a theoretical maximum given the basic link parameters

Referring to the DVB-S2 performance chart, it can be seen that an EsNo of 15.20 dB would allow the link to run at MODCOD 26. This is 32APSK with a ⅚ code rate with 4.12 bits per symbol. The example symbol rate is 70MSPS thus yielding a total throughput of 288.4 Mbps.

In reality that speed would not be achievable with the link. In practice the link needs to be run with sufficient margin. Other losses due to pointing inaccuracy, atmospheric attenuation, and other non-idealities need also to be considered (Table 6).

If a total of 5 dB is added to account for margin and impairments, the practical EsNo would be 10.20 dB. This allows the link to be run at MODCOD 19 (16APSK ¾) with 2.97 bits per symbol. At 70MSPS this is 207.9 Mbps.

The level of operating margin can be tuned to achieve maximum throughput

ACM (Adaptive Coding and Modulation)

DVB-S2 supports a wide range of “bits per symbol” depending on the available EsNo. The EsNo at the receiver is most significantly affected by the distance to the satellite. Planet’s Dove and SuperDove systems dynamically command the spacecraft transmitter to adjust the MODCOD to maximize throughput given the existing link conditions. It does not matter if the spacecraft is far away, has some hardware issue with its antennas or transmit chain, or if there is a pointing problem. By

Table 6 Example link budget with margin and additional losses added

EsNo	**15.20**	dBHz
Margin	−3.00	dB
Implementation loss	−2.00	dB
Design EsNo	**10.20**	dBHz

utilizing ACM a link can be maintained under adverse conditions albeit at a reduced data rate.

For **CubeSats and SmallSats**, ACM is very important function to have. Such spacecraft systems have limited power, are often experimental, lack reliable ADCS, and may not perform to the design specification due to rapid development and limited ground performance validation.

Comparison of Planet's SuperDove to DigitalGlobe WorldView-4 Satellite Downlink Performance

The example presented in the previous section was based on the HSD1 (high-speed downlink ver. 1) system implemented in the "Dove" spacecraft system.

Planet's latest CubeSat system "SuperDove" implements an upgraded radio system "HSD2" that utilizes 6× 76.8MSPS channels and can achieve over 1 Gbps.

Planet presented a paper on the implementation of this system at the 31st Annual AIAA/USU Conference on Small Satellites (Devaraj et al. 2019).

The DigitalGlobe WorldView constellation as well as their planned legion constellation operate at data rates of up to 1200 Mbps (DigitalGlobe 2012). Planet's SuperDoves can exceed this rate in peak operating conditions, but their overall average under good link conditions is about 900 Mbps.

The reader may be very surprised that a low-cost CubeSat a tiny fraction of the size and power budget of a WorldView class satellite is capable of similar data throughput rates. The answer to this question illustrates how SmallSats can "punch above their weight" compared to traditional satellite systems (Table 7).

The link budget shown above is from the WorldView-4 FCC filing. The data rate is 400 Mbps per polarization. With both polarizations the total throughput is 800 Mbps.

Examination of this link budget reveals several important insights into the design of the WV4 downlink system.

1. The radio system is designed to meet a 400 Mbps per polarization requirement in a worst-case condition. The system cannot speed up and take advantage of shorter slant ranges or better link conditions. **The system runs at a constant rate regardless of conditions. The system cannot fully take advantage of whatever link conditions are available:**
    (a) Rain loss accounts for 1.7 dB of the budget. The system cannot take advantage of dry conditions by speeding up.
    (b) A full **8.5 dB** of link margin is maintained under these worst-case conditions.

Table 7 WorldView-4 link budget from FCC Filing (DigitalGlobe 2012)

Frequency	8185	Mhz
Orbit height	770	km
Elevation	5	degrees
Data rate	400	Mbps
Bandwidth	200	Mhz
EIRP	57.1	dBm
Slant range	2718.88	km
Ground G/T	31.4	dB/K
BER	3.00E−05	
Required Eb/No (uncoded)	9.4	dB
Hardware implementation BER loss	−2.5	dB
Actual required Eb/No	**11.9**	
Spacecraft antenna diameter	19.7	in
Approx. HPBW	6.3	degrees
Gain of spacecraft antenna	29.1	dBic
Loss between HPA and antenna	−9.8	dB
Pointing loss	−1	dB
Transmitter Po	7.5	W
EIRP	57.1	dBm
Path loss	−179.4	dBm
Total loss (rain)	−1.7	dB
Required Eb/No	9.4	dB
Crosspol interference loss	−0.3	dB
Received C/N	23.4	dB
Implementation loss	−2.5	dB
Available Eb/No	20.4	dB
Downlink margin	**8.5**	**dB**

(c) The transmitter delivers 7.5 W of power, yet there is **9.8 dB** of loss between the transmitter and antenna.
(d) The antenna is **20 in** in diameter. If the power amplifier was placed right at the feed avoiding the 9.8 dB of loss, the antenna could have been approximately 6 in in diameter and produce the same transmitted power density. Additionally, a smaller antenna would require less accurate pointing.

The author has no additional information about the WV4 system other than what is publicly available from their FCC filings. The author's statements are based on some assumptions based on publicly available information.

The point is that designers of SmallSats and CubeSats **need not assume** that their subsystems will necessarily be hopelessly outclassed by traditional systems. Traditional systems typically include large safety margins for performance parameters due to their high-confidence, requirements-driven design approaches.

Small satellite radio systems with limited volume and power resources **should be designed to be able to operate at the maximum possible performance level given available link conditions.**

> *Of course the large difference in telescope aperture between a WorldView satellite and a Planet Dove result in great difference in optical resolution. The example here shows how non-primary subsystem performance need not be assumed to scale with size and cost of the satellite system. As a counterpoint a satellite which has a communications payload such as an Internet satellite will have radio hardware that operates as close as possible to the available theoretical link limit.*

2.9 Overview of Link Analysis

A link analysis for PSK/APSK, specifically as implemented with DVB-S2 was discussed. This information can be used as reference for implementation of a similar system. This discussion covered high-performance links which necessarily involve high power and compute requirements. The next section will cover simpler, lower-power systems for links that do not need high throughput.

2.10 Low-Power/Low-Speed Links and COTS Chip-Based Implementations

Integrated transceiver chips are an attractive option for low- to medium-speed satellite links with very tight power, volume, and cost budgets such as CubeSats; though they are intended for terrestrial use, their range can be extended with external amplifiers. Additionally external frequency conversion can be done to support channel carrier frequencies unsupported by the chip. An example of a CC1110-based satellite radio is the “OpenLST” an open source project released by Planet in 2018 (Klofas 2018).

> *There are several complexities associated with frequency conversion in this context. Feasibility/difficulty is dependent on specific implementation. Additional detail on the subject is out of scope for this discussion.*

The transmit power can be increased with the addition of an external power amplifier which can be selected to meet link requirements.

These integrated chips typically have internal LNAs with relatively high noise figure (and equivalently high effective temperature). A low-noise amplifier with a lower $T_E$can be added to the receive chain and will dominate the overall noise performance as long as its gain is sufficiently high.

A higher reliability system based on FSK or other modulation types could be implemented by utilizing an SDR (software-defined radio). Examination of the published performance of commercial COTS chips however is useful for performance estimation.

2.10.1 FSK-Based Implementations

Typical transceiver chips utilize “2-ary non-coherent frequency shift keying” (2-FSK) to modulate data. With 2-FSK, bits are encoded by shifting the carrier frequency up or down. The size of this shift is called the *deviation*. 2-FSK utilizes two tones to encode data so there is one “bit per symbol.” An excellent reference source for details on FSK can be found on the Atlanta RF website (Texas Instruments).

The primary configuration options for FSK are baud rate (which just means symbol rate), deviation, and receive filter bandwidth.

Higher rate links will need larger deviations and larger bandwidths. Larger bandwidths lead to higher receive noise power, and thus higher signal power is needed as well. With reduced received signal power, the bandwidth must be sufficiently small so that SNR can be sufficiently high. Coherent FSK has higher performance and not dependent on the receiver bandwidth, but the significantly higher processing power required may make it unsuitable for a simple low-power link.

> *Using spread spectrum techniques, reduced bandwidth is not needed with reduced receive power. This is pointed out here so that the reader does not assume that the lower rates necessarily require lower receiver bandwidths at a fundamental level.*

Depending on the device, there is a minimum receiver bandwidth; this will limit the ability for the chip to operate efficiently at very low speeds.

The Texas Instruments CC1110 has a minimum filter bandwidth of 58 khz, whereas the minimum on the CC1125 is 3.8 kHz. The minimum baud rate for the CC1110 is 1.2 khz. The CC1125 does not have a minimum baud rate but does have reference specifications for as low as 300 Hz operation (Texas Instruments).

Doppler Shift

The discussion of narrow channels necessitates a discussion of **Doppler shift** caused by the relative velocity between transmitter and receiver. For example, at 500 Mhz and 500 km orbital altitude, the range of Doppler shift is about +/−10 kHz.

If the carrier frequency offset caused by Doppler prevents reception, **Doppler compensation** must be performed. Based on the orbit geometry, instantaneous expected Doppler can be calculated, and the ground side radio can be tuned to compensate.

Receivers must tolerate some level of carrier frequency offset as frequency references are not perfect. If the offset is small relative to the bandwidth of the signal, it can likely be ignored, though the receiver bandwidth may need to be widened. If the offset is significant, say for the minimum 3.8 khz

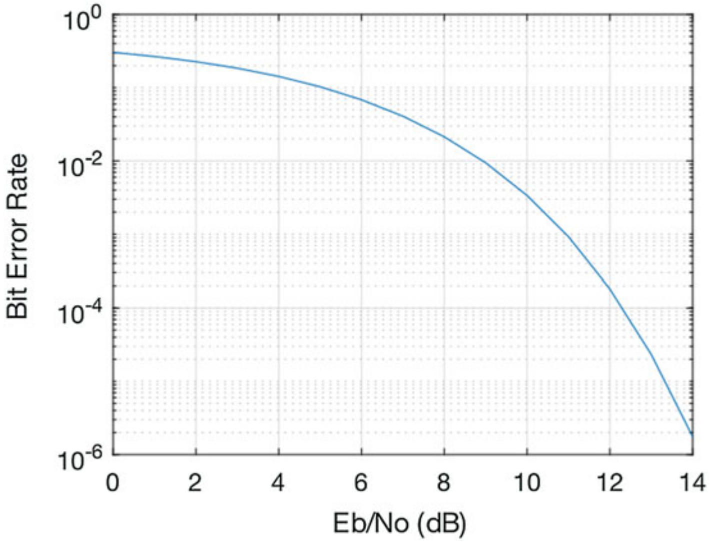


Fig. 7 Theoretical performance of non-coherent 2-FSK. (Image: Matt Ligon 2020)

filter bandwidth of the CC1125, accurate Doppler compensation is an absolute necessity.

The scaling is linear with frequency, so at 2 Ghz the shift would be about +/−40 kHz. Links operating at higher carrier frequencies are more affected by Doppler.

2.10.2 Link Throughput Estimation

In order to estimate the throughput of a chip-based link, the datasheet published performance can be referenced. The datasheets for CC series transceivers list “sensitivity” for different data rate configurations. The theoretical performance of 2-FSK shown in Fig. 7 can also be referenced.

In datasheets for most CC devices, “sensitivity” is the input power level required to achieve lower than a 1% bit error rate. The difference between a 1% BER and, for example, a 10^-5 BER can be determined by referring to the theoretical 2-FSK “waterfall curve” shown in Fig. 7.

A few example link budgets are shown here which show the level of received power for some reference links.

From the datasheets for the CC1125 and CC1310, the “sensitivity” specifications are plotted. Additionally the power required for an ideal 2-FSK receiver at 1% BER is plotted as well as the Shannon limit. These theoretical curves are plotted assuming that the receiver temperature is 900 K. This is representative of the high noise temperature of these chips due to their relatively high noise figure. The performance can be increased with the addition of a higher-performance LNA.

Referring to the example links, the “low-power downlink” (Table 8) could comfortably operate at 1 kbps; the high-power uplink (Table 9) could run

Table 8 Low-power downlink example. 70 cm UHF low-power downlink at 2050 km range

Parameter	Value	Unit
Distance	2.05E+06	m
Tx power	1.00	W
Carrier frequency	4.70E+08	Hz
wavelength	0.64	m
Tx power dB [Pt]	0.00	dBW
Tx ant gain [Gt]	0.00	dBi
Path loss [PL]	−152.12	dB
Rx ant gain [Gt]	10.00	dBi
Rx power [Pr]	−142.12	dBW
Rx power [Pr]	**−112.12**	dBm

Table 9 High-power uplink example. 10 W from 2 m dish 2 Ghz uplink at 2050 km range

Parameter	Value	Unit
Distance	2.05E+06	m
Tx power	1.00	W
Carrier frequency	2.00E+09	Hz
speed of light	3.00E+08	m/s
wavelength	0.15	m
Tx power dB [Pt]	10.00	dBW
Tx ant gain [Gt]	30.50	dBi
Path loss [PL]	−164.70	dB
Rx ant gain [Gt]	0.00	dBi
Rx power [Pr]	−124.20	dBW
Rx power [Pr]	**−94.20**	dBm

comfortable at 200 kbps. The moon link (Table 10) may barely operate at 300 bps when using these sorts of chips, and the very narrow bandwidth would require accurate Doppler compensation.

2.10.3 Spread Spectrum

As discussed prior, the FSK-based CC chips minimum filter bandwidths limited their performance at very low rates and also increased Doppler sensitivity. The utilization of spread spectrum techniques as implemented in an SDR, for example, allows for low bitrate operation at high symbol rates.

Direct Sequence Spread Spectrum

Most commonly, spread spectrum is achieved by encoding a bit with a “spreading code.” The coded data will be increased in length by the size of the code

Table 10 Moon to earth example. Moderate gain (10 dBi) low-power (1 W) tx to 5 m earth dish at 8 Ghz

Parameter	Value	Unit
Distance	3.84E+08	m
Tx power	1.00	W
Carrier frequency	8.00E+09	Hz
speed of light	3.00E+08	m/s
wavelength	0.04	m
Tx power dB [Pt]	0.00	dBW
Tx ant gain [Gt]	10.00	dBi
Path loss [PL]	−222.20	dB
Rx ant gain [Gt]	50.00	dBi
Rx power [Pr]	−162.20	dBW
Rx power [Pr]	**−132.20**	dBm

and thus requires a proportionally higher symbol rate and bandwidth to transmit.

Recall that increasing the bandwidth will reduce SNR. In fact spread spectrum signal power may be up to tens of dB below the noise power. The signal can be retrieved from the noise however because the spreading codes are known. By correlating the received signal with the codes, the data can be retrieved.

The codes used are orthogonal to each other, that is, when correlated with each other, the result is zero.

Shannon Limit Revisited

Shannon theorem shows that maximum channel capacity is achieved with increasing bandwidth, but this reaches an asymptotic limit.

This limit is given by

$$C \approx 1.44 \frac{S}{N_0}$$

Recall that

$$N_0 = k_b T_E$$

The signal power S can now be solved for which is the required signal power level given a receiver temperature Te. In Fig. 8 this has been plotted for Te = 900 K.

The slope of the Shannon limit closely matches that of the trend of the transceiver chips and roughly ranges from 15~20 dB away from the chip sensitivity specification. Recall that a DVB-S2 implementation utilizes highly computationally expensive forward error correction to operate close to the Shannon limit.

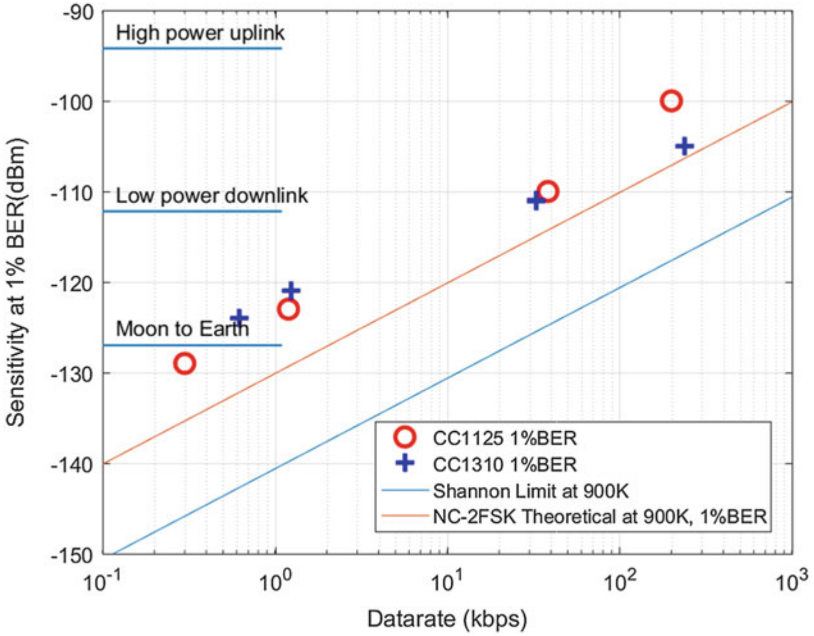


Fig. 8 CC1125 and CC1310 published sensitivities at 1% BER. (Image: Matt Ligon 2020)

2.11 Interference and EMI

The above discussion has assumed that thermal noise was the only noise source. In practice, interference from earth sources can be significant. At 450 Mhz, which is Planet’s allocated UHF receive band for Dove and SuperDove, noise power is regularly 20 dB and above the thermal noise floor over large regions of land. Though this band is set aside for earth observation communications, it appears that the widespread usage of nearby bands and their leakage emissions adds up to a significant degree when seen on a wide scale by a spacecraft. At the 2.056 Ghz band that is allocated for earth observation, such interference is minimal, and the system can operate in a thermal noise limited regime.

Another very likely source of interference is self-generated noise from the spacecraft itself. Noise from high-speed clocks, data lines, switching power supplies, as well as leakage energy from transmitters can jam receivers. The effort involved in preventing and or mitigating these sorts of problems is not insignificant and can present an expensive challenge.

3 Conclusion

Satellite radio links utilizing both sophisticated and simple modulation schemes can be planned utilizing basic link theory and published information from industrial standards and products. Standards such as DVB-S2 and CCSDS provide detailed performance information for high-speed, high-performance satellite links. FSK and spread spectrum performance can be estimated from published specifications for commercially available integrated solutions.

4 Cross-References

- ▶ Flight Software and Software-Driven Approaches to Small Satellite Networks
- ▶ High Altitude Platform Systems (HAPS) and Unmanned Aerial Vehicles (UAV) as an Alternative to Small Satellites
- ▶ Hosted Payload Packages as a Form of Small Satellite System
- ▶ Network Control Systems for Large-Scale Constellations
- ▶ Overview of Small Satellite Technology and Systems Design
- ▶ Power Systems for Small Satellites
- ▶ RF and Optical Communications for Small Satellites
- ▶ Small Satellite Antennas
- ▶ Small Satellite Constellations and End-of-Life Deorbit Considerations
- ▶ Small Satellites and Structural Design
- ▶ Spectrum Frequency Allocation Issues and Concerns for Small Satellites
- ▶ Stability, Pointing, and Orientation

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