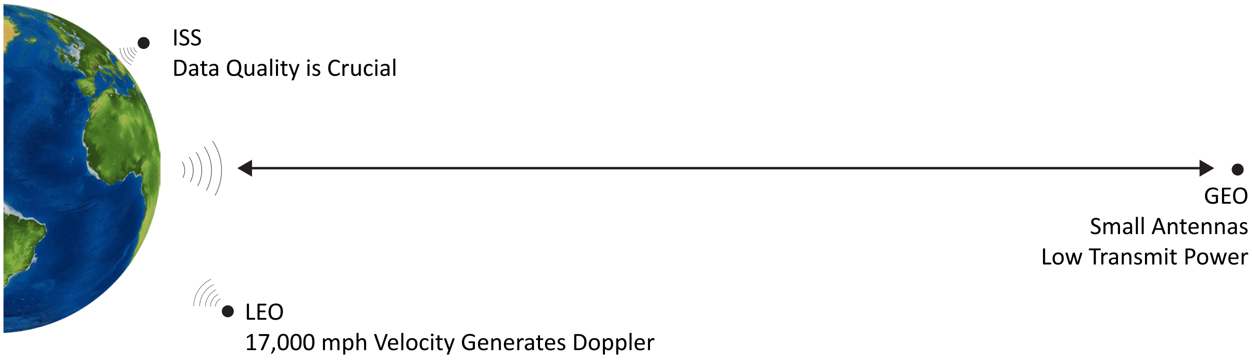
Part 1 - Some Fundamentals

Introduction

Satellite links are the means of communications between a spacecraft and their control systems here on earth. By definition, these are RF (radio frequency) links and understanding how they work is very much a mystery to many of us. A satellite waveform is defined by the modulation. In many cases, the modulation is designed to ensure the signal can be demodulated.

This tutorial certainly cannot make you an expert on satellite communications in this short tutorial. That takes a degree or two in electrical engineering and likely a matching number of years of practical experience.

But it can be helpful to understand the lingo and how these links work. In addition to defining the terms, this tutorial summarizes the aspects of satellite communications that constrain and influence the waveforms that are used.



Radio Frequency Links

This App Note focuses on non-transponded satellite links. These are the RF links that transmit telemetry or payload data from the satellite to the ground and the links that transmit command or uplink data from the ground to the satellite. There are modems (short for modulator/demodulator) on both sides of these links, one on the satellite and one at the ground antenna.

When transmitting, the modem first generates a waveform and then amplifies it before sending it to the antenna. The antenna radiates the wave and usually focuses the RF energy (power) in the direction of the receiving antenna/modem combination. Each RF link is a “channel” that connects the two modems.

The RF links for satellite communications have five key implementation drivers:

1) The link covers a long distance. The power radiated from an antenna decreases with the square of the distance. The signals coming from a geosynchronous satellite at 23,800 miles away are very faint (literally billionths of a watt), and the signal takes about 1/8 second to reach earth.

2) The link can have Doppler effects. Satellites in low earth orbit have high velocities as they fly over a ground antenna. This generates Doppler on the waveform, distorting the signal's frequency and phase.

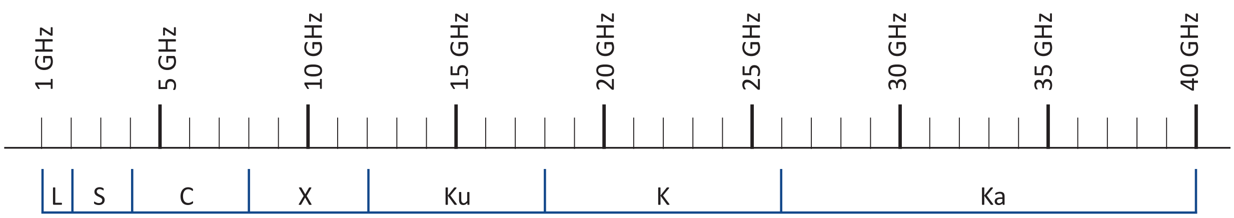
3) The link is asymmetric. The ground side antenna is capable of generating high power when transmitting while the satellite side has a relatively small antenna aperture for receiving that power. Conversely, the satellite side has limited transmit power, while the ground antenna can be quite large.

4) The link has continuous data. Unlike network-based communications where packets are sent only when there's data to send, each satellite link always contains some data to maintain synchronization. The data may be fill or idle data, but the link is never empty.

5) The link's QoS is important. There's no do over. Satellite communications waveforms are designed to have essentially no transmission errors, as they do not support retransmission for lost or corrupted data because of the long delay.

RF Bands

Radio Frequency Bands used for Satellite Communications Links



RF links use a carrier signal which is simply a sine wave at a fixed frequency. The RF spectrum is divided up into established frequency bands, and each band defines a range of frequencies.

For example, L-Band is the 1 to 2 GHz range of the radio spectrum, and S-Band is the 2 to 4 GHz range. Satellite systems operate in the frequency bands from L-Band to Ka Band, ranging from 1 GHz to 40 GHz. It's important to note that these same frequency bands are used for other links. Your home's wireless network operates in S-band.

Every satellite link is assigned a range within an RF Band, and it's this portion of the spectrum that the signal occupies when it is transmitted. The signals are filtered so they do not interfere with adjacent links. A satellite signal at L-band might be assigned to operate at 1.35 to 1.36 GHz.

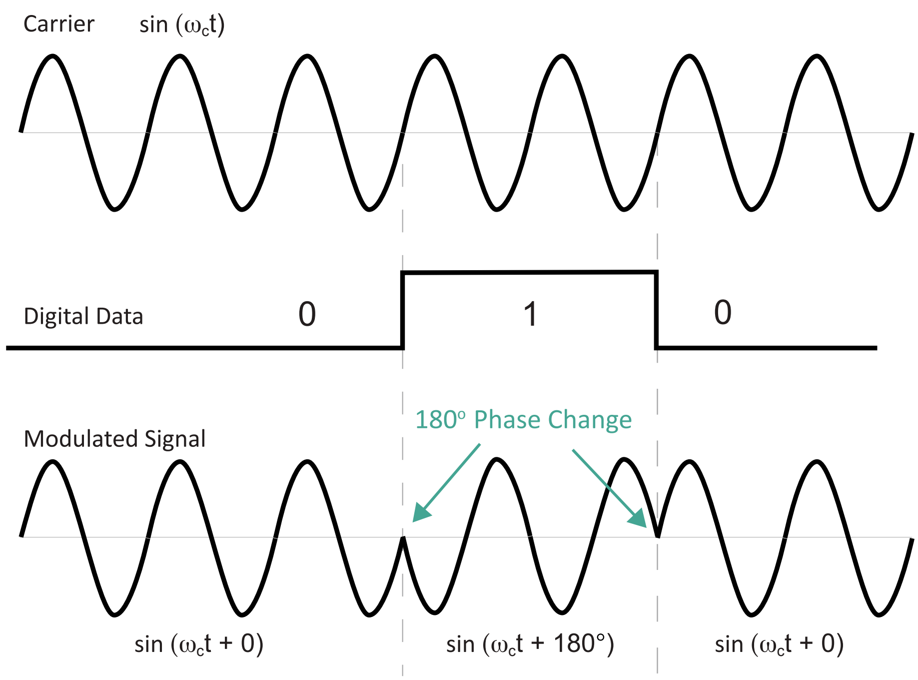
Part 2 - Modulation / Demodulation

Modulation

Modulation is the process of changing the pure carrier signal so as to convey the data that is being transmitted. The ground modem is modulating the uplink data onto the carrier signal. The modulation process increases the bandwidth of the signal. There are multiple ways to create this modulation:

- The modem can vary the amplitude of the sine wave, known as amplitude modulation.
- The modem can vary the frequency of the sine wave, known as frequency modulation.
- The modem can vary the phase of the sine wave, known as phase modulation.

Binary phase shift keying is one the simplest techniques to visualize and is shown below. Each time the bit being transmitted changes logic level (0 to 1 or 1 to 0), the phase of the carrier is shifted 180 degrees.



Satellite systems use much more sophisticated techniques to communicate large amounts of data in a small amount of spectrum over very long distances. Many satellite systems use phase modulation or even a combination of phase and amplitude modulation.

Demodulation

The demodulator has the harder job to do. It has to receive this modulated carrier and extract the modulating waveform to recover the information that was transmitted. There are several complicating factors that corrupt the received signal, which all good receivers are designed to handle.

The first is noise, which comes primarily from the input amplifier and the background noise the antenna is looking at. The antenna must collect and focus enough of the extremely weak signal to overcome the noise, and the input amplifier must be designed to add as little noise as possible. All electronics adds some noise to the signal, but since the signal is weakest at this point, it tends to set the signal to noise ratio.

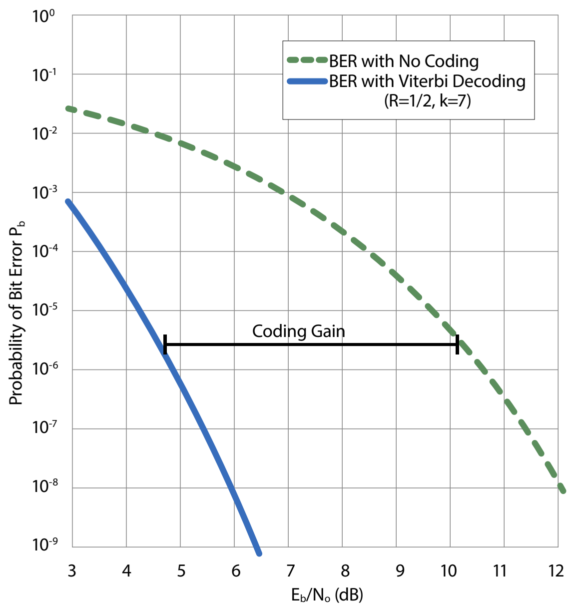
There's interference too, in that there is power from every other transmitter in sight of the antenna. The motion of the satellite relative to ground also changes the phase and frequency of the received signal (the Doppler effect). The receiver filters noise and interference that are outside the band of the desired signal. The demodulator tracks the movement of the signal (Doppler), and extracts the data from the remaining noise and interference.

Satellite communications engineers have cleverly designed ways to resolve all of these issues, but how that's done is more than well beyond this Tutorial.

Part 3 - Channel Coding

BER and Channel Coding

An important aspect of satellite links is the channel coding that is used to improve the bit error rate performance.



Bit error rate is a complicated topic in and of itself. A simplistic way to think of BER is that BER is the probability of a bit error at a given signal to noise ratio. As a signal degrades (less signal, more noise), the number of bit errors increases.

Channel coding is also known as forward error correction. The modulator performs the channel coding which adds redundant information to the transmitted data. This “encoding” is “decoded” back to the original data by the demodulator.

We all have performed channel encoding leaving a phone message for someone when we give them our number up front, record our message, and then repeat the number before hanging up. You’ve transmitted the same data twice in hopes of them getting it right as they write it down.

Channel coding reduces the required signal level needed to achieve a particular bit error rate. This is known as the coding gain. Coding gain allows transmitters to operate at lower power or to transmit at higher bit rates. The complexity in channel coding is on the decoding side. Most satellite downlinks use channel coding to conserve transmit power at the satellite. Satellite uplinks do not typically use channel coding because of the increased receiver complexity (and thus receiver power) that would be required on the satellite. Instead the ground transmits at higher power. The command decryptor on the satellite provides an effective guard against bit errors by rejecting commands that contain bit errors.

There are a number of coding techniques used, and they are usually named after their creators or given a name that describes the technique.

Block codes expand some number of input bits to a larger number of coded output bits. For example, CCSDS uses a Reed-Solomon (255, 223) block code which adds 32 check symbols to each block of 233 symbols, creating a code block that has 255 symbols. Interleaved block codes work well in correcting burst errors where several contiguous bits are corrupted.

Convolutional codes encode the bits in a sliding manner where the output bits are defined by some number of previous input bits. These forward error codes work well even with very noisy signals. Viterbi decoding is an optimal method of decoding a convolutionally encoded signal.

Modern systems use channel coding that is iteratively decoded. One that's now commonly used in satellite communications is the Low Density Parity Check (LDPC).

Concatenated coding involves using both block codes and convolutional codes to improve bit error rate performance. The modem first block encodes the data, puts this into frames, and then convolutionally encodes that data stream.

All this coding comes at a price in that the number of data bits (usually referred to as symbols) is increased and this decreases the effective data rate.

Part 4 - Bit Conditioning

Bit Conditioning

There's one more set of techniques, referred to as bit conditioning, that help out the demodulator/bit sync.

Pulse code modulation is a form of encoding the data bits. The common ones are NRZ-L, NRZ-M, and NRZ-S. What helps is remembering that NRZ stands for Non-Return to Zero, L stands for Level, M stands for Mark (Logic Level 1), and S stands for Space (Logic Level 0).

Code	Code Waveforms	Code Definitions
Value	1 0 1 1 0 0 0 1 1 0 1 0	
NRZ-L		1: is 'high' 0: is 'low'
NRZ-M		1: is a change 0: is no change
NRZ-S		1: is no change 0: is a change
Bio-L		1: 'high' to 'low' 0: 'low' to 'high'
Bio-M		1: no change at start of period 0: change at start of period
Bio-S		1: change at start of period 0: no change at start of period

NRZ-L is the one that makes sense to most of us as it looks like how digital data appears on an oscilloscope. With NRZ-M, every '1' in the bit stream changes the logic level. With NRZ-S, every '0' in the bit stream changes the logic level.

A bit synchronizer's job is made more difficult when there are long strings of bits without changes in the logic level. Bi-phase PCM codes guarantee at least one symbol transition for every bit. Another technique that removes long strings of '1's and '0's is to run the data through a randomizer. There are defined randomization polynomials that are used.

Finally, there's preamble insertion. A good example of this is the commanding uplink. Commands are sent intermittently, but the modulated data link has to remain continuous. The ground system transmits an idle pattern (such as alternating '1's and '0''s) between commands, and then prefaces each command sequence with a preamble.

This preamble is a known sequence of bits that the spacecraft's demodulator can detect and then know that what follows is command data, which it needs to pass along. Preambles are usually Barker Codes, a short sequence of bits that are easy to correlate on (i.e. find).

Part 5 - Summary of Terms

Summary

Link or Channel – the RF connection between a modulator and a demodulator

Bandwidth – the amount of RF spectrum the signal occupies (but be aware that's only one of many definitions)

Modulation – changing the carrier signal so that it contains the information being sent

Demodulation – receiving the modulated signal and recovering the information

Bit Error Rate – the probability of bit error at a specific signal-to-noise ratio

Coding – adding redundant data bits (or symbols) to increase the bit error rate

Conditioning – changing the logic levels before modulation to improve the bit synchronizer's performance

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