Atmospheric Communications with FSO and RF Transmission

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Introduction

There are two main methods to transmit information wirelessly. One method is Free-Space Optical (FSO), which uses light as the medium to transmit signals. The other method is Radio Frequency (RF) transmission, which uses radio waves to transmit data. RF systems are commonplace in consumer electronics such as phones, radios, Wi-Fi, Bluetooth, and more. FSO systems are not as common in consumer electronics but can still be found in any infrared based remote. This tech note will explore some of the differences and tradeoffs between the two technologies and determine the best fit for data downlink from a flight computer.

FSO vs RF

Overview

Since the two technologies, FSO and RF, are both capable of wireless communication, why choose to implement one over the other? One advantage of RF communication is that the signal is transmitted with electromagnetic waves. This allows the signal to penetrate buildings and other objects. With a FSO system, the signal is transmitter optically, so the transmitter and receiver must be within line of sight of each other. Consequently, the RF system is much more robust when it comes to placement of the transmitter and receiver, and the channel can have more sources for noise and attenuation.

Looking at the data in Table 1, we can see more of the tradeoffs between FSO and RF systems. FSO systems only suffer from turbulence and blocking in the line of sight between the transmitter and receiver, which can include physical objects or weather phenomena like fog and rain. RF systems suffer from destructive interference caused by the channel acting as a filter (multipath fading) and other disturbances like rain. FSO channels also have more bandwidth than RF channels, so they can accommodate more users and more data throughput at the same time.

	FSO	RF
Typical Data Rate	100 Mbps to ~ Gbps	< 100 Mbps
Channel Security	High	Low
Component Dimension	Small	Large
Source of Loss	Atmospheric turbulence and onbscuration	Multipath fading, rain, other users

Table 1: Comparison of FSO and RF systems.

Another tradeoff is the security of the system. An FSO signal can only be intercepted or disrupted if the line of sight is tampered with. An RF signal can be intercepted if a receiver is set to the correct frequency and can be disrupted if a powerful signal is broadcast at the same frequency. Since the FSO system is harder to disrupt and intercept than the RF system, it is more secure.

Finally, FSO system components are more compact than RF system components. For a FSO system, the transmitter is composed of a laser diode and the receiver is a photodiode. These semiconductor devices are very small, often a few millimeters in diameter. RF transmitters and receivers both contain antenna with the size of the antenna inversely proportional to the frequency.

RF systems are more robust than FSO systems, but that robustness comes with decreased performance. A robust system would implement both FSO and RF technologies, switching between the two to use the optimal technology at the right time. The main factor in deciding to use FSO or RF is signal to noise ratio (SNR).

SNR Comparison for FSO and RF

The signal to noise ratio (SNR) is a measure of signal power over average noise power:

$$\frac{E_b}{N_0} \tag{1}$$

In an FSO system under ideal conditions this is sufficient for the SNR. In an RF system there is always multipath fading loss, even under ideal conditions. As a result, for the same signal power and average noise power, the SNR for an RF system will always be less than an FSO system. This is reflected in the bit error rates (BER), or the rate at which transmitted data is received incorrectly (Figure 1).

At high SNR ratios, the BER for FSO systems is much better than that of RF systems. This reinforces the notion that FSO systems have better optimal performance than RF systems although the window of operation is much tighter.

While Figure 1 accounts for ideal conditions, this is not realistic. Rain and fog are the main contributors to noise in data uplink and downlink. While rain would not be an issue with a flight computer since the rocket would be launched under good weather conditions, the interference caused by clouds would be like that caused by fog. In FSO systems the fog reduces visibility, but in RF systems the fog's scattering effect is negligible for frequencies less than 10 GHz.

While FSO systems have better peak performance than radio frequency systems, optics require favorable operating conditions. Consequently, optical communication systems cannot be used for as many applications as RF systems. FSO systems face a few main challenges for data links: cloud coverage obscuring line of sight, limited range based on precision of laser and power limits, and the need to maintain line of sight with a rocket traveling very fast. Due to the difficulty in finding ideal conditions for an FSO system, an RF system is the industry standard for data links.

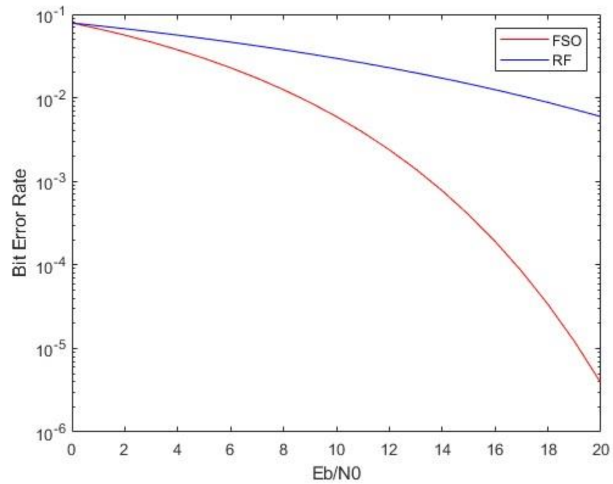

Figure 1. Comparison of BER and Eb/N0 (SNR) for FSO and RF systems.

RF Transmission Systems

An RF transmission system is composed of several main functional blocks. The raw data is collected, compressed, and encoded to prepare for transmission. The preprocessed data modulates a carrier signal at a set frequency, and the modulated carrier is transmitted. The transmitted signal is distorted by the channel (the Earth's atmosphere in the case of terrestrial and satellite communications) and is detected at the receiver. The receiver processes the received signal to recover the original data.

Frequency and Modulation

The two most important parts of an RF communication system are the transmission frequency and modulation. Most satellite communications use the UHF, L, S, C, X, Ku, K, and Ka bands (Table 2). These range from 300 MHz to 40 GHz, which is a very wide range. High frequency signals in these bands require more specialized hardware compared to lower frequencies. The transmitter and receiver for these signals will demand more time and effort to design and implement. For amateur rocketry, these systems are too costly to implement unless an inexpensive solution can be found commercially.

Letter Designation	Frequency Range	C	4-8 GHz
HF	3-30 MHz	X	8-12 GHz
VHF	30-300 MHz	K_u	12-18 GHz

UHF	0.3–1 GHz	K	18-27 GHz
L	1-2 GHz	K_a	27-40 GHz
S	2-4 GHz	mm	40-300 GHz

Table 2. IEEE Radio Frequency band designations

There are many different methods of modulating signals, but phase-shift keying (PSK) and quadrature amplitude modulation (QAM) are two of the most common for transmitting digital data. QAM uses a constellation of M symbols (Figure 2), where each symbol represents $\log_2 M$ bits. QAM is a power efficient method of transmitting many bits at the same time. The type of modulation chosen has a direct impact on the BER of the RF system. A higher number of symbols results in more errors but is more efficient. Since power consumption is a concern for a flight computer, QAM with symbols is preferred to QAM with 4 symbols even though the error rate is higher.

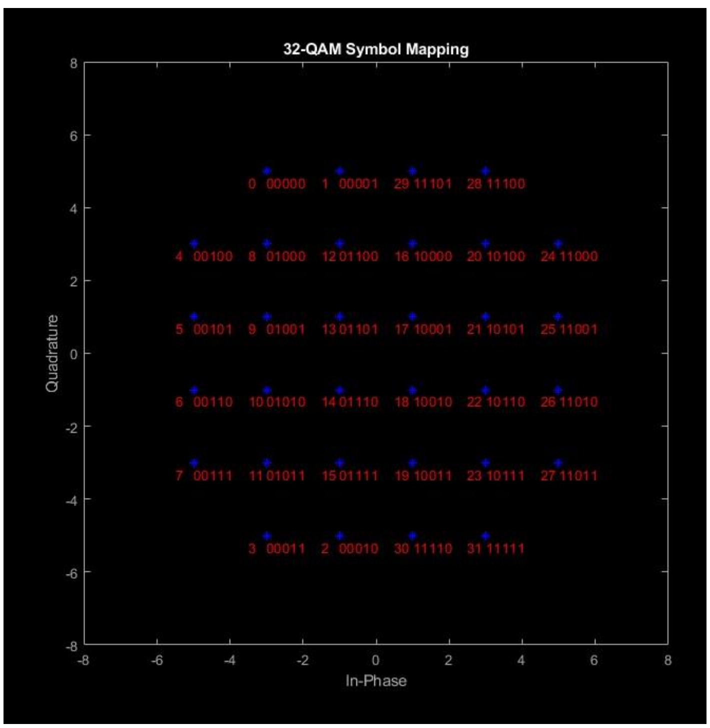

Figure 2. Example 32-QAM constellation using binary bit encoding.

Conclusion

While our flight computer will not be used with a satellite, many of the issues discussed will still apply. For a data downlink from the rocket, an RF system is much more appropriate than an FSO system. While FSO has higher performance, the requirements for optimal operation are far too strict for our team to implement a working system. That said, an RF system is also unlikely to work perfectly. The entire flight computer and downlink must be powered from a battery, so transmission power will be limited, and we may not be able to generate a high SNR. Since we do not have the resources to develop a system that has a carrier frequency of GHz, our system will be limited to the VHF or UHF frequency bands. The effects of weather such as rain, fog, and clouds will be negligible in the communication channel due to the lower frequency. This will help the SNR, but it may not be enough. At a high altitude, it is possible we may not even receive the signal from the rocket.

References

1. "IEEE Standard Letter Designations for Radar-Frequency Bands," in IEEE Std 521-1976 , vol., no., pp.1-8, 30 Nov. 1976, doi: 10.1109/IEEESTD.1976.7428784.

2. L. Bai et al., "An Atmospheric Data-Driven Q-Band Satellite Channel Model With Feature Selection," in IEEE Transactions on Antennas and Propagation, vol. 70, no. 6, pp. 4002-4013, June 2022, doi: 10.1109/TAP.2021.3137285.

3. "Second Generation Framing Structure, Channel Coding and Modulation Systems for Broadcasting, Interactive Services, News Gathering and Other Broadband Satellite Applications; Part 1 (DVB-S2)." *DVB*, 10 Feb. 2020, https://dvb.org/?standard=second-generation-framing-structure-channel-coding-and-modulation-systems-for-broadcasting-interactive-services-news-gathering-and-other-broadband-satellite-applications-part-1-dvb-s2.

4. Y. Zhang, Y. He and G. Dong, "Downlink Design and Operating Mode Optimization of Remote Sensing Satellite Data Transmission System," 2021 IEEE/ACIS 20th International Fall Conference on Computer and Information Science (ICIS Fall), 2021, pp. 281-284, doi: 10.1109/ICISFall51598.2021.9627354.

5. Yang Zhang, Youngil Park, ByungYeon Kim and KiDoo Kim, "Performance analysis of hybrid FSO/RF system," 2011 Third International Conference on Ubiquitous and Future Networks (ICUFN), 2011, pp. 279-283, doi: 10.1109/ICUFN.2011.5949176