Application Note AN1200.81:

Doppler Immunity of the LR-FHSS Modem

Table of Contents

List of Figures

List of Tables

1 Introduction

LR-FHSS is a physical communication layer with technology with characteristics that make it ideally suited to high-density IoT networks, such as satellite communications [1]. Because satellite communication links benefit from lower link budget requirements when in fast-moving, Low Earth Orbit (LEO), LR-FHSS was also designed with high Doppler immunity in mind.

In this Application Note we quantify the Doppler immunity of LR-FHSS so that satellite and ground station users can design reliable communication which can operate in the presence of Doppler effects.

2 What is LR-FHSS?

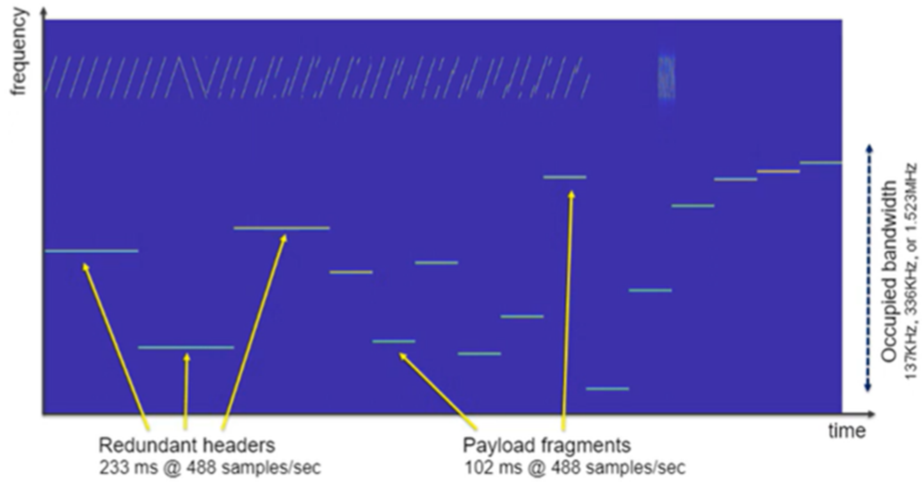

Figure 1. An LR-FHSS Packet Compared with SF12 and SF7 LoRa Transmitting the Same Data

Long range, frequency hopping spread spectrum (LR-FHSS) is an ultra-narrowband GMSK communication layer that uses fixed symbol rate of 488.28 bps.

An example LR-FHSS packet is shown in Figure 1. It shows the main constituent parts of the packet: three hopped headers (only one of which needs to be received for successful detection of the ensuing data), followed by the payload data, which is divided into several frequency-hopped fragments.

The modulation employs a variety of coding rates, number of channels and channel spacings to give different properties to the modulated signal. These properties include:

Occupied bandwidth: the bandwidth encompassing all the frequency hopped channels, and

Effective data rate: the data rate obtained once the overhead introduced by the Vertibi coding is considered.

There are three LR-FHSS modem settings available today, two for Europe and one for the US. Each intended for use in the license free ISM band for that region:

EU 868 MHz Band: 136.72 kHz and 335.94 kHz

US 915 MHz Band: 1523.4 kHz

3 Doppler Effect

The Doppler effect arises due to the compression of the radio wave front introduced by the relative motion of a radio transmitter to a radio receiver. The phenomenon is illustrated below:

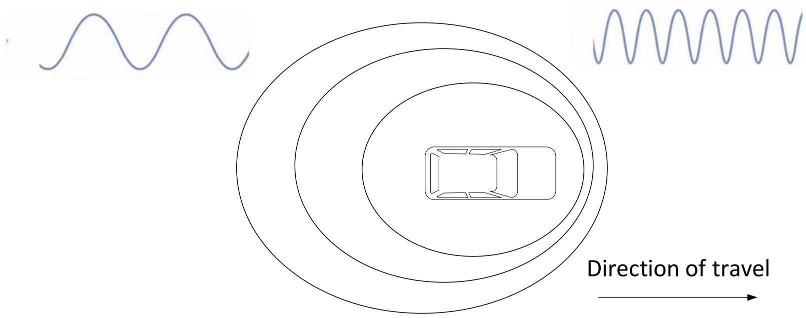

Figure 2. The Doppler Effect

In this case, the relative motion of the vehicle introduces a Doppler shift of increased frequency whilst travelling towards the receiver, and a drop in frequency as it passes. The attendant frequency shift is given by:

$$f_D = \frac{v}{\lambda} \qquad \textbf{Equation 1}$$

Where v is the relative speed between transmitter and receiver and λ is the radio wavelength. With the rate of frequency change given by:

$$\frac{df_D}{dt} \qquad \textbf{Equation 2}$$

4 Doppler Limits on LR-FHSS

There are two principal Doppler limits that must be considered in the design of a satellite LR-FHSS link:

1) The absolute frequency error tolerance to a static frequency offset of the link: which imposes a limit on the Doppler shift.
2) The receiver's capacity to accommodate frequency drift within a single packet: limiting the maximum Doppler rate.

4.1 Doppler Shift Limit

The maximum permissible frequency offset between an LR-FHSS transmitter and receiver is shown in the second column of Table 1. This limit encompasses all sources of frequency error between transmitter and receiver: including the drift of the reference crystal oscillator.

Table 1. Maximum Relative Frequency Error for LR-FHSS

Occupied Bandwidth	Max Frequency Offset	Effective Data Rate		Channel Spacing	N Channels
136.72 kHz (EU)	**31.64 kHz**	CR 1/3	162 bps	3.91 kHz	35
		CR2/3	325 bps		
335.94 kHz (EU)	**32.03 kHz**	CR 1/3	162 bps	3.91 kHz	86
		CR2/3	325 bps		
1523.4 kHz (US)	**38.3 kHz**	CR 1/3	162 bps	25.4 kHz	60
		CR2/3	325 bps		

4.2 Doppler Rate Limit

Because the underlying modulation and reception process is identical, irrespective of the occupied bandwidth, the same receiver frequency tracking rate is observed for all modem settings:

$$\left.\frac{df_D}{dt}\right._{MAX} = 800 \text{ Hz/s} \qquad \textbf{Equation 3}$$

To illustrate these limits we will work through an example of an orbital satellite link using LR-FHSS modulation.

5 Satellite Orbital Scenario

In the following example, we consider an LR-FHSS uplink from ground-station to satellite in the 915 MHz band. The satellite is assumed to orbit at a distance of 500 km. At this orbital distance, the satellite will be travelling close to 8 km/s.

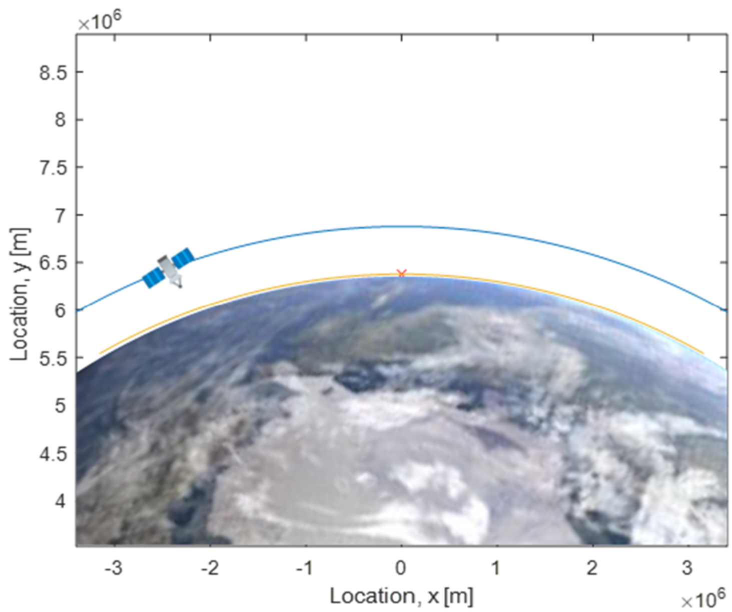

Figure 3. The Orbital Path Used in the Example Scenario With Ground Station at the Red Cross

In this scenario the resulting Doppler shift is shown on the left y-axis of the figure below. (Because the Doppler shift is proportional to frequency, we use the highest frequency of the US ISM band we are targeting of 928 MHz). The maximum shift is +22.7 kHz as the satellite approaches the ground station which then drops to -22.7 kHz as the satellite passes.

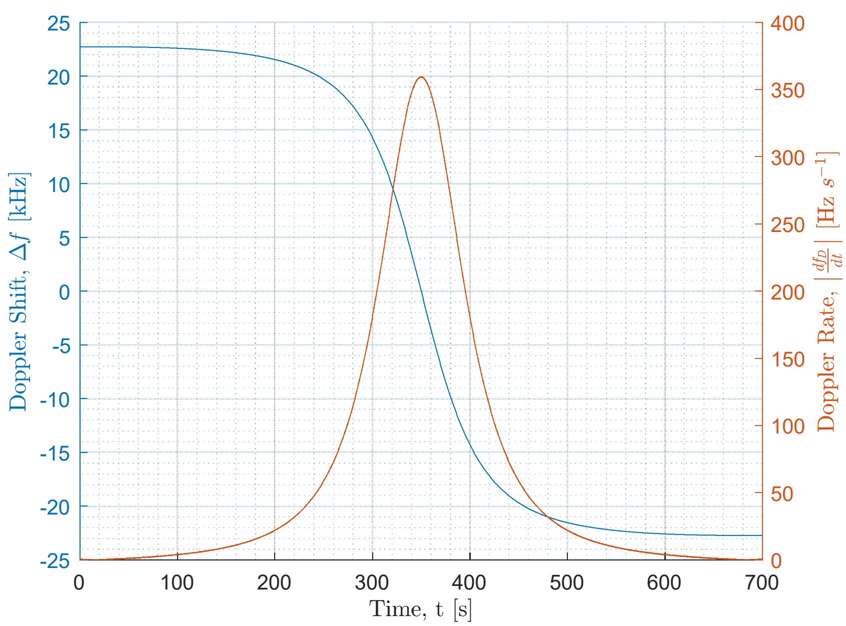

Figure 4. The Doppler Shift and Doppler Rate Incurred in the Example Scenario

The Doppler rate in Hz/s is shown on the right y-axis of Figure 4. This shows a maximum rate of change of 349.9 Hz/s at the satellites zenith (when it is directly overhead).

5.1 Doppler Shift Immunity and Frequency Error

Referring to Table 1, we see that for 1523.4 kHz operation in the US, the maximum tolerable frequency error is 38.3 kHz (41.2 ppm at 930 MHz). To determine if this limit is exceeded, we must sum all of the sources of frequency error in our communication system, including the Doppler shift of Figure 4, and see if it exceeds this limit.

Table 2. Frequency Error Budget for Application Example

Error Source	Error ppm	Error Hz
Satellite Frequency Error	5.0 ppm	4 650 Hz
Ground Station Frequency Error	5.0 ppm	4 650 Hz
Doppler Shift	24.4 ppm	22 700 Hz
Total Frequency Error	**34.4 ppm**	**32 000 Hz**
Max Frequency Error	**41.2 ppm**	**38 300 Hz**

Assuming that both sides of the communication link employ a TCXO with 5 ppm of error (all causes of drift considered), then the resulting frequency error budget is shown in Table 2. Here we see that the total frequency error does not exceed the prescribed limit – resulting in a functional communication link.

5.2 Doppler Rate Immunity

The Doppler rate immunity is ensured, as the peak rate of 349.9 Hz (seen in Figure 4) does not exceed the receiver limit of 800 Hz/s.

6 Conclusion

In this Application Note we have defined the limits of the Doppler immunity of the LR-FHSS receiver, so that ground station designers can ensure the design of reliable communication uplink systems. We have also performed a link-design example showing the compatibility of LR-FHSS with both the Doppler shift and Doppler rate seen in a 915 MHz uplink communication to a LEO satellite.

7 References

[1] AN1200.64 "LR-FHSS System Performance" Semtech Corporation, October 2022

[2] AN1200.80 “LoRa Modem Doppler Immunity”, Semtech Corporation, October 2023

8 Revision History

Version	ECO	Date	Changes and/or Modifications
1.0	069315	October 2023	Initial Version

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