Application Note:
LR-FHSS System Performance

Disclaimer

Long Range-Frequency Hopping Spread Spectrum (LR-FHSS) is a high link-budget, high-performance technology combining the benefits of a modulation employing low energy per bit and advanced frequency hopping schemes to achieve improved coexistence, spectral efficiency and sensitivity. Semtech Corp. holds patents directed to aspects of the LR-FHSS technology.

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1 Introduction

1.1 Purpose of this Document

This application note summarizes the Long-Range Frequency-Hopping Spread Spectrum (LR-FHSS) features and requirements in a wireless system, including regulatory compliance, physical layer transmission performance, network performance and implementation considerations.

1.2 Scope of this Document

SX1261[1], SX1262[2] , LR1110[3], and newer chipsets support LR-FHSS packet transmission:

- SX1261 and SX1262 only perform GMSK modulation with intra-packet-hopping, frame preparation is done by the host MCU.
- LR1110 includes a full-featured LR-FHSS modem.

LR-FHSS demodulation can be achieved by all V2 gateways with the applicable firmware update.
LR-FHSS can only be used for uplink communication (end device to gateway).
LR-FHSS modulation can be used in the uplink with different network Layer 2 (L2) protocols, sending packets from end devices to the gateway.
Downlink packets should use other modulations, such as LoRa or frequency-shift keying (FSK).
LoRaWAN® Regional Parameters Specification version RP2-1.0.2 (and onwards) includes LR-FHSS data rates in the EU868 and US915 bands.
Although LoRaWAN is used as an L2 protocol example in some discussions, this application note is generally applicable to any communication that uses LR-FHSS physical layer modulation, regardless of the networking protocol.

This manual should be used in conjunction with:

- SX1261/1262 Datasheet
- LR1110 Datasheet
- LR1110 User Manual

[1] Details in: https://www.semtech.com/products/wireless-rf/lora-core/sx1261
[2] Details in: https://www.semtech.com/products/wireless-rf/lora-core/sx1262
[3] Details in: https://www.semtech.com/products/wireless-rf/lora-edge/lr1110

2 LR-FHSS

2.1 Overview

LR-FHSS is a long-range physical layer modulation that uses a frequency-hopping spread spectrum (FHSS) scheme, developed and patented by Semtech. It enables intra-packet frequency-hopping to achieve better capacity, sensitivity, and interference rejection than traditional modulation schemes that use a single channel.

It encodes a low data rate bit stream onto a comparatively wide bandwidth by switching frequency rapidly during the transmission of a single radio packet. The bandwidth used by the frequency-hopping algorithm can be set between 39.06 kHz and 1.5742 MHz. The 6 dB modulation bandwidth is 500 Hz. The LR-FHSS instantaneous modulation baud rate is 488.28125 baud, using 2-GMSK modulation and BT=1.

With hopping enabled, each LR-FHSS packet is spread over multiple frequency grids.

The packet header contains information used by the gateway to compute the frequencies that the packet will use. Multiple headers are transmitted to ensure reception robustness.

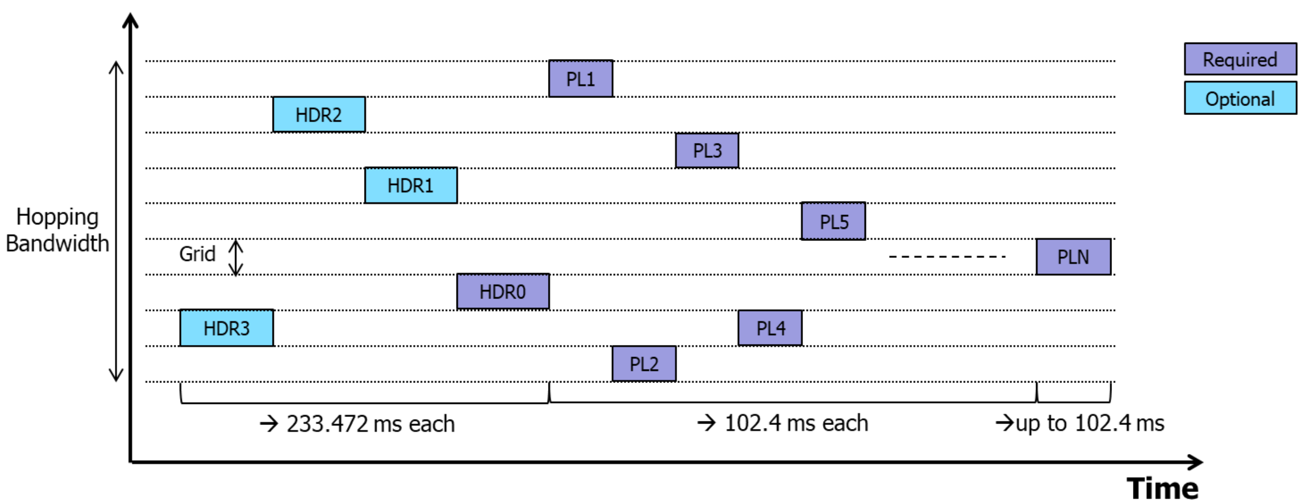

Figure 1: Frequency Profile of Single LR-FHSS Packet

A wide range of channel bandwidths, number of hopping grids, and grid spacing can be selected from **Table 1** below for maximal flexibility with respect to adapting to different regional regulations, available channels, required robustness, and applications.

Table 1: List of LR-FHSS Channel Bandwidth, Channels and Number of Grids

	Channel Bandwidth (kHz)	Total Number of 488 Hz Channels	Number of Hopping Grids	
			3.9 kHz spacing	25.39 kHz spacing
0	39.06	80	10	NA
1	85.94	176	22	NA
2	136.7	280	35	NA
3	183.59	376	47	NA
4	335.94	688	86	NA
5	386.72	792	99	NA
6	710.90	1480	185	NA
	722.66		NA	28
7	761.70	1584	198	NA
	773.44		NA	30
8	1523.4	3120	390	60
9	1574.2	3224	403	62

Depending on different regions and modulation configurations, the LR-FHSS can achieve a similar or lower data rate compared to those achieved by LoRa modulation.
The time-on-air (ToA) of typical configurations is listed in Table 2 below.

Table 2: Time on Air for LR-FHSS and LoRa® Packets

Modulation	Parameters	ToA, 20 bytes PL	ToA, 64 bytes PL
LR-FHSS	CR 1/3, HDR=3	1868	4121
	CR 2/3, HDR=2	1051	2178
LoRa	SF10BW125[4]	371	698[5]
	SF12BW125, low-data-rate-optimizer (LDRO)	1318	2793

A comparison of data rate and ToA is presented in the table below.

Table 3: Typical Data Rate and Time-on-Air

Modulation	Data Rate w/o FEC Overhead (bps)	CR	Informative Data Rate (bps) [6]	ToA with 20 bytes PL and CRC (ms)
LR-FHSS	488.28	1/3	162.76	1868
		2/3	325.52	1051
LoRa SF10BW125	1220.70	4/5	976.56	371
LoRa SF12BW125	366.21	4/5	292.97	1318

[4] "SF" in the context of LoRa radio modulation refers to the Spreading Factor, which controls the speed of the data transmission.
[5] Cannot operate in FCC region and bands where dwell-time limits of 400 ms apply.
[6] Without considering the preamble, physical layer header and CRC.

2.2 Benefits

LR-FHSS can provide the following benefits:

- In regions with restrictions on dwell time, LR-FHSS can work around the limitations by intra-packet hopping, thus using slower data rates and carrying a longer payload.
- In spectrum-limited bands/regions, using LR-FHSS can further improve capacity and range compared with LoRa. The modulation provides significant additional capacity for lower data rate devices where the spectrum is limited.
- The LR-FHSS modulation provides additional robustness in the presence of interference.

3 Regulatory Compliance and Benefits

This section describes the regulatory compliance of LR-FHSS, and its potential advantages in some situations, when compared to other PHY modulations used in Low Power Wide Area Networks (LPWAN).

3.1 U.S. ISM Bands

In FCC-regulated regions like North America, there is a 400 ms dwell time limitation for transmitters less than 500 kHz wide.
For LR-FHSS with the intra-packet hopping scheme, the dwell time limit restricts each hopping section, rather than the whole packet. Hence, the total packet time-on-air (ToA) can exceed 400 ms. As a result, LR-FHSS enables the device to transmit longer payload packets at lower data rates.

Without dwell time limitations, LR-FHSS can achieve the following benefits.

- Additional sensitivity and link margin compared to the lowest LoRa (SF10BW125) configuration.
- No single packet payload length limitations[7], which can simplify the system and reduce frame fragmentation overheads. For example, due to the 400 ms dwell-time limit, the LoRa SF10BW125kHz payload is limited to around 24 bytes. LR-FHSS does not have a payload limitation because the total packet duration is not restricted.

In addition, a typical LoRaWAN® gateway, with 8 or 16 reception channels, is categorized as a hybrid system with an 8 dBm/3 kHz power density limitation if using LoRa® modulation. That converts to about 22 dBm output power for BW125 LoRa.
A single LR-FHSS channel is spread over multiple grids. In the FCC regions, more than 50 grids are enabled for FCC compliance, therefore, 30 dBm end devices can be supported by all LR-FHSS gateways.

3.2 Part 90 Licensed Bands

Users who own some uplink/downlink spectrum in licensed bands can build an LR-FHSS based network.
Compared to LoRa modulation solutions, networks with LR-FHSS provide significantly larger capacity while maintaining long range capabilities.

[7] There is no limitation from FCC dwell-time perspective, but the limitation from the chipset still applies.

3.3 Europe 868 MHz Band

Without saturating the limited spectrum, causing significant collisions, and potential packet loss, LR-FHSS enables higher packet capacity with the available spectrum and still maintains a similar link margin to BW125SF12.

Compared with LoRa using BW125, LR-FHSS has the following benefits:

- With the same number of devices served, LR-FHSS allows a higher packet rate to be generated by each device[8].
- With the same packet-generating rate, a single gateway can support a larger number of end devices.
- The system runs in a tighter spectrum due to the LR-FHSS channel bandwidth configuration flexibility. Potentially, it can enable the system to use a cleaner channel in an environment where frequency-selective interferers are present. For example, LR-FHSS can be fit into a 200 kHz gap between RFID interrogator channels.
- With the same gateway capacity, LR-FHSS enables use of a lower data rate and improved link margin.

3.4 Limited ISM Spectrum

In some regions, such as India, the ISM band spectrum is scarce. LR-FHSS provides significant additional capacity for low data rate end devices where a large number of LoRa channels cannot be allocated.

[8] Duty cycle allows

4 Physical Layer Transmission

This section describes the LR-FHSS physical layer performance: Point-to-point wireless link performance from the end device to the gateway, link budget, interference rejection, field measurement results, and potential LoRa® improvements by repetition.

Note
The LoRa performance information presented in this chapter is based on the technology in SX1262 and SX1301, adhering to the LoRaWAN® Regional Parameters. With newer chipsets (like LR1110, SX1302) and more robust coding rates, the transmission range and drift tolerance can be improved.

4.1 Link Budget

In the FCC region on the 915 MHz band, the LR-FHSS enables the transmitter with higher output power because it is categorized as a CRF part 15.247 FHSS system. As a result, the device can be certified to output 30 dBm, 8 dB more than is allowed for LoRa with an 8/16 channel gateway.
On the receiver side, the gateway achieves 2 dB better sensitivity compared to LoRa SF10BW125.

Table 4: Link Budget Comparison in FCC Region

	LoRa/FSK (8/16 channel gateway)	LR-FHSS	Difference
Maximal transmit (Tx) Power	22 dBm	30 dBm	8 dB
Best Sensitivity	-135 dBm	-137 dBm	2 dB
Link Budget	157 dB	167 dB	10 dB

This 10 dB link budget improvement can be converted to about 3X free-space transmission distance improvement, and 1.5X in a terrestrial propagation scenario.
In ETSI-regulated regions, the LR-FHSS has a similar link budget as the lowest LoRa data rate (SF12BW125kHz) in LoRaWAN.

4.2 Robustness and Interference Rejection

Semtech conducted a series of blocking tests for both LR-FHSS and LoRa, to compare their robustness against interference.
The V2 gateway was used as the receiver device under test (DUT), and an SX1262 EVK was used as the transmitter.

4.2.1 Co-Channel Blocking

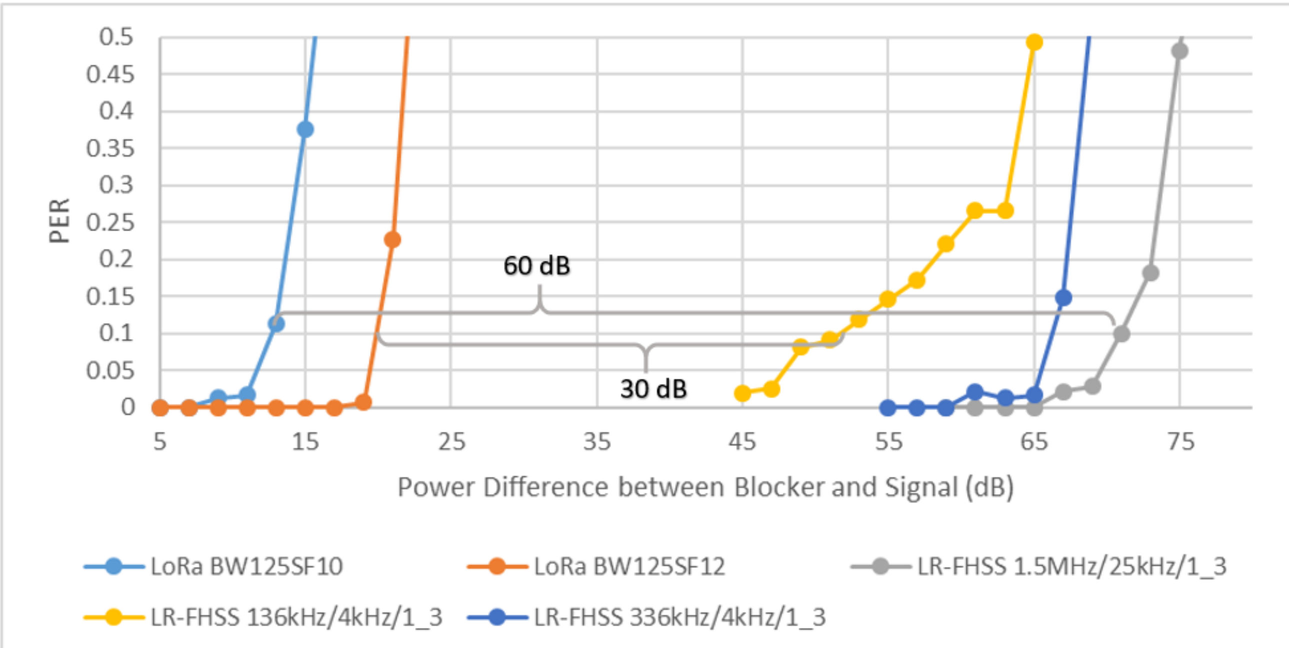

Figure 2: Co-Channel Blocking Performance with CW Blocker

The legend shows the spreading factor and channel bandwidth for LoRa, and the hopping bandwidth, hopping grid and coding rate for LR-FHSS.

From the result presented, the LR-FHSS provides better rejection if a CW blocker is in its channel. A wider LR-FHSS channel bandwidth could further improve the rejection, due to the lower chance of colliding with the CW blocker.
The performance gain is:

- About 60 dB in FCC regions when comparing 1.5 MHz LR-FHSS over SF10BW125.
- Greater than 30 dB in ETSI regions.

4.2.2 Adjacent Channel Rejection

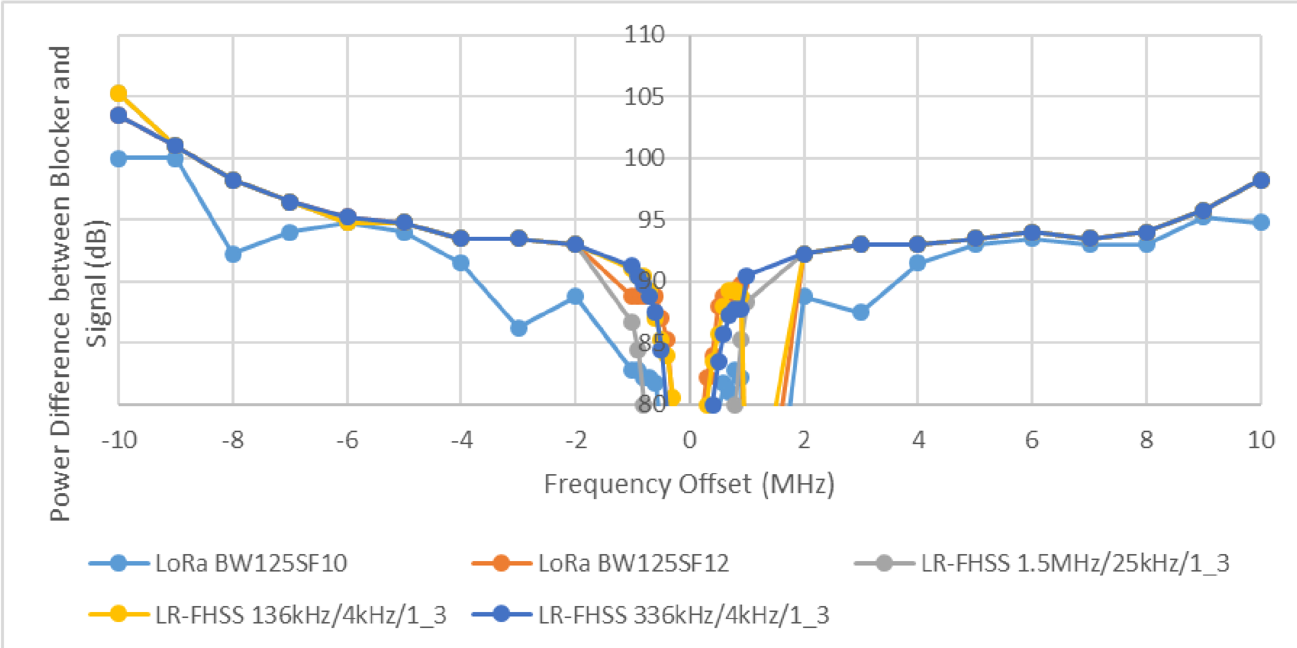

Figure 3: Adjacent Channel Rejection Performance with CW blocker, -10 to 10 MHz Offset

When the blocker and signal are more than 1 MHz apart, most modulations perform similarly except LoRa SF10BW125kHz which has a slightly degraded ACR.

More than 90 dB blocking is measured for all other modulation configurations, for frequency offset of >2 MHz.

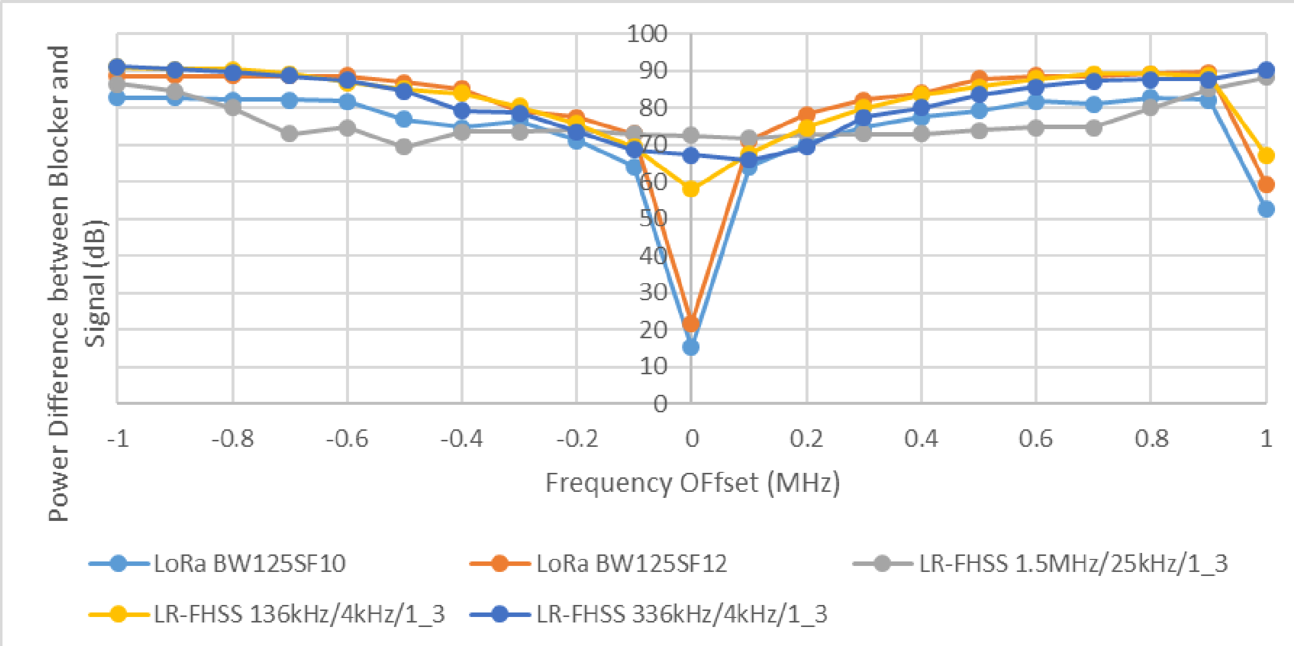

Figure 4: Adjacent Channel Blocking Performance with CW blocker, -1 to 1 MHz offset

The blocking performance of a smaller frequency offset is shown above.
When the blocker frequency is within the channel frequency, there is degradation in the blocking since the blocker energy cannot be rejected by the receiver filter directly. For example, when the blocker frequency offset is within +/- 700 kHz, there is a slight reduction in the rejection, but more than 70 dB rejection is still achieved.
This is generally applicable to both LR-FHSS and LoRa. However, for LoRa, with an in-band blocker (such as +/- 60 kHz for BW125 LoRa), the rejection is achieved by the LoRa processing gain and is limited to about 20 dB.

4.2.3 Channel Blocking Conclusion

On top of the proven robust co-channel blocking performance by LoRa modulation, the LR-FHSS provides additional rejection capability with its intra-packet hopping and channel coding.
If the blocker is not in the wireless channel (but in an adjacent channel), both modulations (LoRa and LR-FHSS) perform similarly with a larger frequency offset.
The rejection with CW is:

- Greater than 55 dB for all frequencies between +/- 1 MHz,
- Greater than 90 dB for any frequency offsets larger than 1 MHz.

4.2.4 Burst Blocker Rejection

Though burst interference can corrupt a portion of the LR-FHSS packet, it can use the coding overhead to recover the corrupted data. In addition, if the hopping option is enabled, each LR-FHSS packet is hopped among multiple frequency grids over a wide bandwidth, making it difficult for the blocker to jam a large portion of the packet.

We evaluated the duty cycle tolerance to a burst blocker. The blocker was set to the same frequency as the signal, and the blocker power was significantly stronger than the signal (83 dB above the signal level). The blocker was generated with a period of two seconds, and varying ToA. The result is presented in the duty cycle.

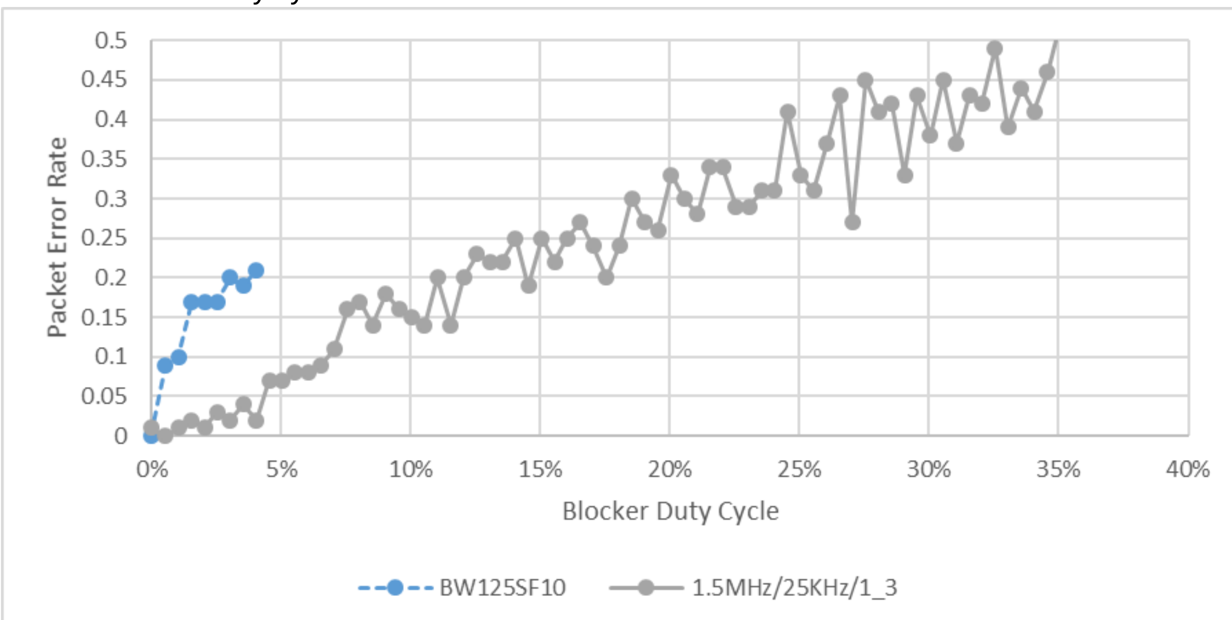

Figure 5: Co-Channel Blocking Performance with Different Duty Cycles in the FCC Region

In configurations for the FCC region, the LR-FHSS provides significantly better tolerance in the blocker duty cycle. For example, at 4% duty cycle (dwell 80ms every two seconds), the SF10BW125kHz packet error rate (PER) is about 20%, while LR-FHSS PER can be maintained at less than 3%.

4.3 Repetition

Though superior blocking performance is measured with LR-FHSS. LoRa packets can be transmitted multiple times thanks to its shorter ToA, thus achieving improved over-the-air transmission robustness in some conditions while at the same time maintaining a similar battery consumption budget. This scheme can utilize the time and frequency diversity in the channel.

For example, with the burst blocker above, LoRa SF10BW125kHz shows 20% PER at 4% duty cycle. When repeatedly transmitting the same packet twice, the PER becomes $(20\%)^2$ = 4%, which is comparable with LR-FHSS. However, in some conditions, when LR-FHSS has a significant performance gain over LoRa, the repetition cannot help LoRa to achieve similar performance.

Moreover, the repetition can increase the device power consumption, reduce the network capacity and increase the average uplink latency, discussed later.

4.4 Field Measurement

Semtech conducted a real-world field trial to evaluate the real-world communication range and quality, with the gateway (receiver) mounted on the roof of the Semtech Neuchâtel office.
The transmitter power was fixed at 14 dBm.

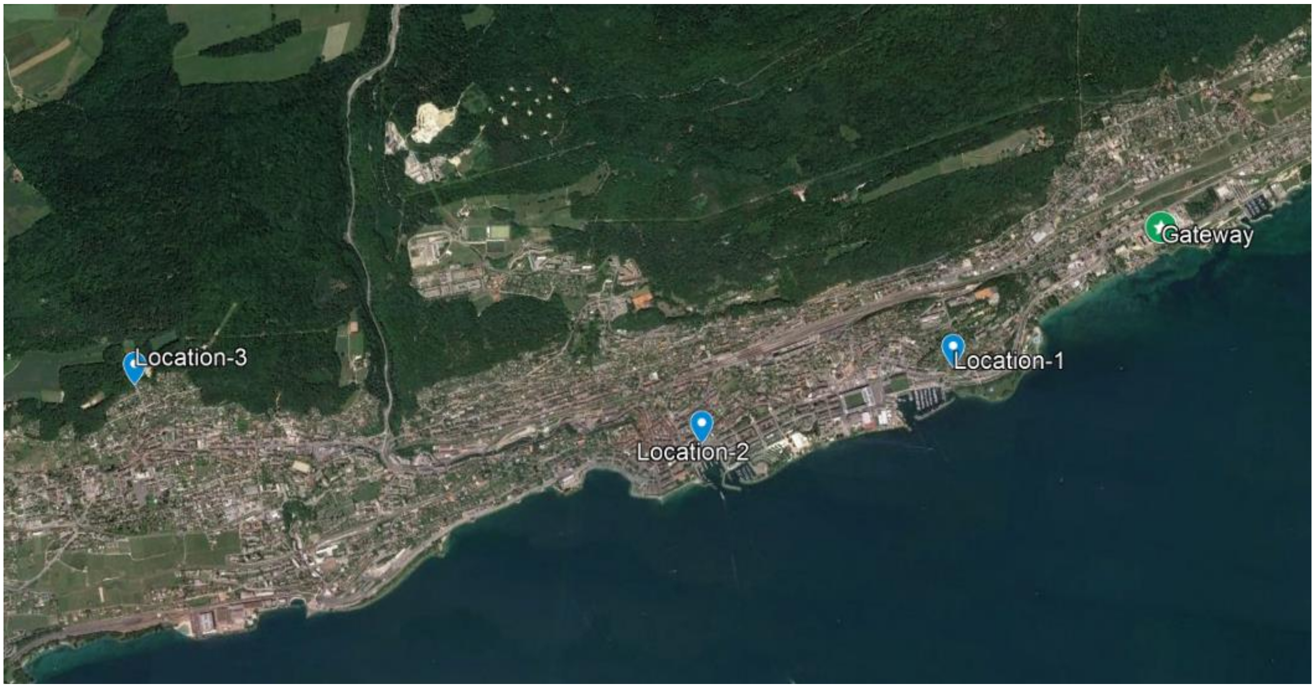

Figure 6: Field Test Map

The field measurements were taken at 868 MHz using several FCC and ETSI modulation parameters. The packet error rate is a combined metric of wireless transmission range and interference rejection in the suburban environment.
Since LoRa SF10 has a shorter ToA, we calculated the error rate with three repetitions (the same packet was transmitted three times).
We assumed that each packet reception was independent. In the real world, the performance gained by repetition can be lower due to the limited time diversity.

From the results (see Table 5):

- In Federal Communications Commission (FCC) regions, with a similar total ToA, 3X SF10BW125kHz can have a similar error rate to LR-FHSS with a 2/3 coding rate (CR2/3), but LR-FHSS with a 1/3 coding rate (CR1/3) has superior performance.
- In ETSI regions, LR-FHSS typically has an even better performance than LoRa SF12.

For FCC regions, the transmission quality can be further improved by using 22 dBm output power directly from the SX1262 or LR1110 power amplifier (PA), or up to 30 dBm allowed by the regulation. A <20% error rate can be maintained at 3.9 miles (6.3 km) with LR-FHSS and a 1/3 coding rate, in the tested suburban environment.

Table 5: Packet Error Rate of Field Measurements

	Distance	**Miles**	**0.93**	**1.86**	**3.91**
		km	**1.5**	**3**	**6.3**
	Modulation Parameter		**PER**		
FCC Parameter (25 kHz grid)	LoRa® SF10		11%	65%	54%
	LoRa SF10, 3X		0%	28%	16%
	LR-FHSS, 1.5MHz, CR_1/3, HDR3		1%	5%	4%
	LR-FHSS, 1.5MHz, CR_2/3, HDR2		3%	15%	21%
ETSI Parameter (3.9 kHz grid)	LoRa SF12, LDRO		4%	23%	32%
	LR-FHSS, 1.5MHz, CR_1/3, HDR3		1%	4%	6%
	LR-FHSS, 1.5MHz, CR_2/3, HDR2		2%	13%	22%
	LR-FHSS, 336kHz, CR_1/3, HDR3		1%	7%	7%
	LR-FHSS, 336kHz, CR_2/3, HDR2		3%	21%	22%
	LR-FHSS, 136kHz, CR_1/3, HDR3		0%	11%	19%
	LR-FHSS, 136kHz, CR_2/3, HDR2		3%	20%	28%

5 Network Performance

In this chapter, we discuss a single-hop star network that consists of one or more gateways and multiple end-node devices. The network capacity and latency are discussed.

5.1 Capacity

Semtech has conducted a simulation on the network capacity using LoRa® or LR-FHSS modulation with a single gateway. The mathematical model used in the simulation is based on real deployment field tests.

Based on previous measurements, the single-channel LoRa network with ALOHA channel access can achieve a capacity of 150k packets per day with Adaptive Data Rate (ADR) enabled and mostly SF7 traffic. If the network only utilizes SF12, about 5k packets per day capacity (no ADR) can be achieved. The estimation is based on 10% PER.

For a PER target of 10%, the LR-FHSS simulation result is presented below.

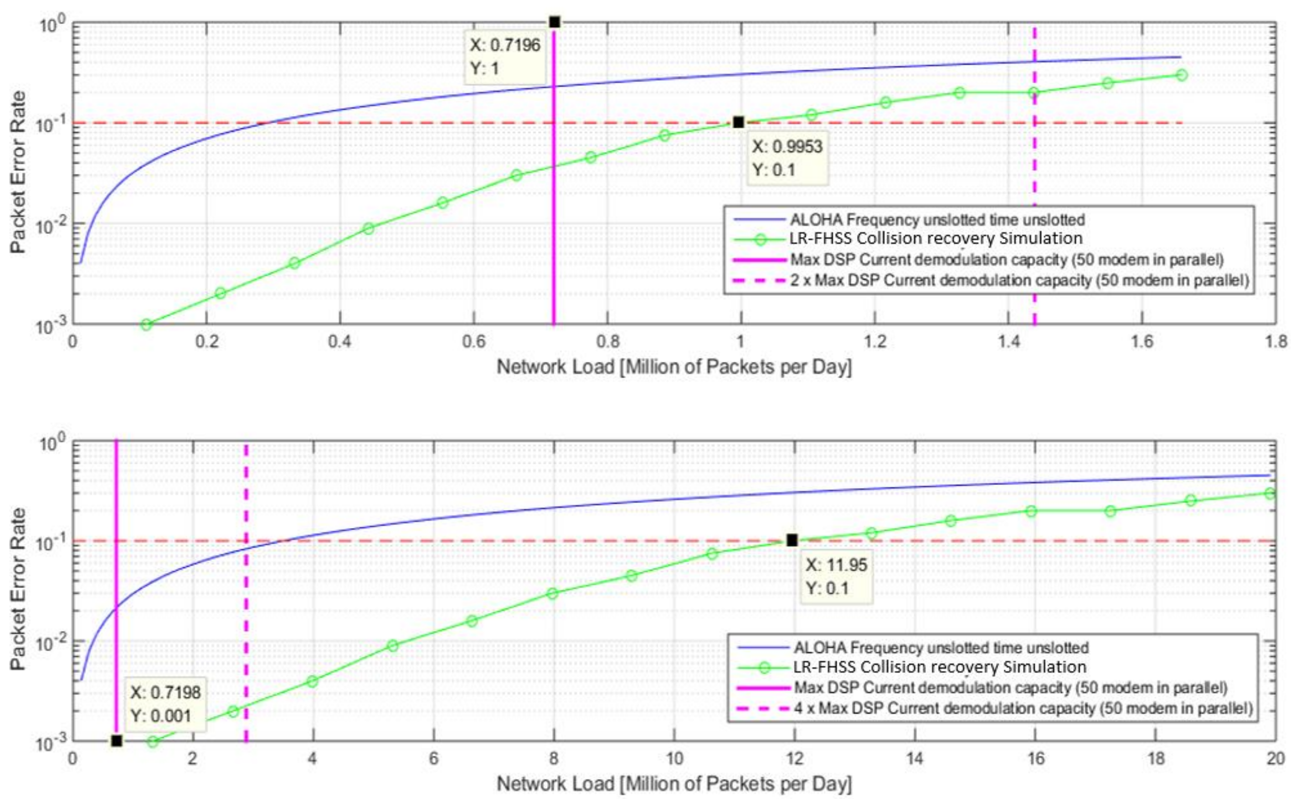

Figure 7: LR-FHSS Single Gateway Capacities (Top: 125 kHz Channel, Bottom: 1.5 MHz Channel)

In ETSI regions, a narrow 125 kHz channel frequency is simulated; 1 million packets can be delivered with a 10% error rate. If the FCC region channel plan is used with a 1.5 MHz channel bandwidth and >3000 available frequencies to hop, a single gateway can achieve 11 million packets at a 10% PER, if we only consider the limiting factor of collision.

In the reference gateway design, the system capacity is limited by the digital signal processing (DSP) capacity. The real-world limit is 700k packets per day with current software.

Table 6: Summary of the Single Gateway Network Capacity

	Capacity in Uplinks per Day per Gateway	
	In a 125 kHz Channel	**In a 1.5 MHz Channel**
LoRa mostly SF7	150k	1.2M (8 channels)
LoRa SF12	5k	40k (8 channels)
LR-FHSS	1,000k theory limit	11,000k theory limit
	700k based on the current implementation	

For devices far away from the gateway using low data rates (LoRa SF12 or LR-FHSS), the LR-FHSS achieves 140X (700k/5k) better capacity.
The uplink capacity per gateway is simulated with multiple gateways covering the area.
With LR-FHSS, the per-gateway capacity decreases with increased gateway density, while the per-gateway capacity improves with higher gateway density when using LoRa modulation.

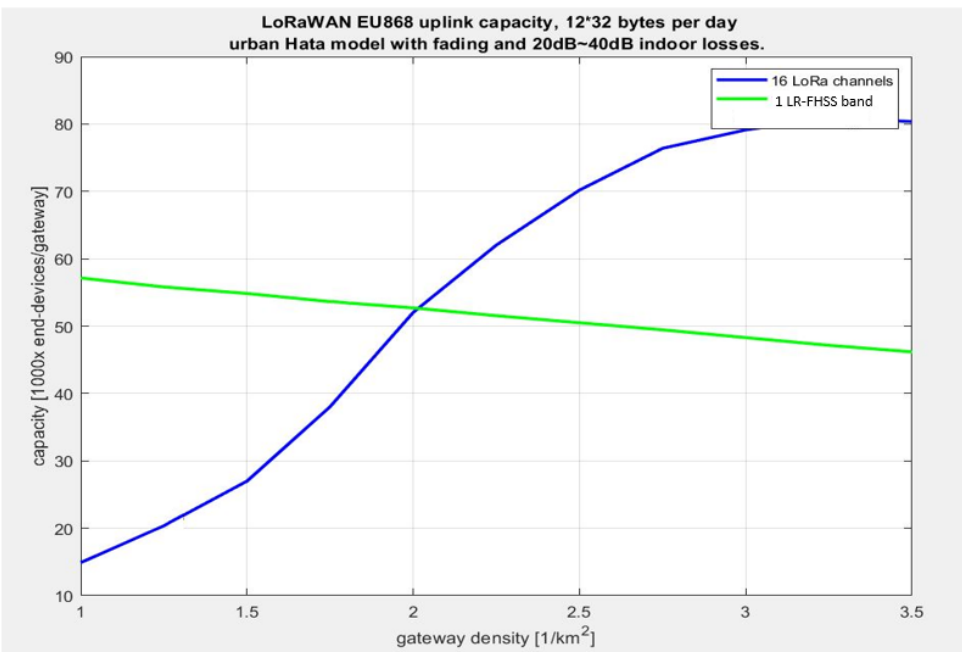

Figure 8: Per-Gateway Capacities with LR-FHSS and LoRa with Multiple Gateways in the Same Area

This suggests that LR-FHSS has improved network capacity in isolated gateway deployment scenarios, such as satellite communications, or rural deployments with low gateway density. In dense urban area deployment, LoRa can perform equivalently or better.

5.2 Latency

The downlink latency is very dependent on the L2 protocol, which is not in the scope of this application note.

We will discuss here the latency between end-device start transmission and the gateway receiving the full packet, without considering any backhaul latency between the gateway and the cloud. If no repetition is enabled, the uplink latency is the packet ToA. With packet repetition enabled, the uplink latency can be longer if the first attempt fails.

For example, with LoRaWAN, the uplink latency is increased to $Delay_{UL,n-1}$ if the first (n-1) packets failed to be received.

$$Delay_{UL,n-1} = [(n-1)T_{interval} + T_{toa}]$$

Where $T_{interval}$ is the interval between uplink attempts, which is typically more than three seconds in LoRaWAN.

Assuming the maximal attempt is N, The maximal latency is $Delay_{UL,Max}$, or the frame is lost.

$$Delay_{UL,Max} = T_{toa} + (N-1)T_{interval}$$

If we consider the following parameters and calculate the probability each uplink attempt is received, the uplink latency can be calculated with the results shown below.

Table 7: Estimated Uplink Latency

	Modulation		**LoRa BW125SF10**	**LR-FHSS CR1/3**
Assumption	ToA		371ms	1868ms
	Single Packet PER		20%	4%
	Maximal Attempts		2	1
	Estimated PER with Repetition		20% × 20% = 4%	4%
	Interval		5	
Calculation Result	Estimated Uplink Latency (s)	Average	1.204 s	1.868 s
		Worst Case	5.371 s	1.868 s

Typically, LR-FHSS has longer average uplink latency due to its longer ToA, but the worst-case latency is smaller than LoRa, because of the better performance with a single send.

5.3 Geolocation Capability

With time difference of arrival (TDOA), the network can calculate the geolocation of the end device without additional hardware or power consumption in the device, if the network uses V2 gateways and has enough coverage overlap that more than three gateways can receive the same LoRa packet.

LR-FHSS does NOT support TDOA geolocation.

Note

Other geo-location technologies, such as the GNSS/Wi-Fi AP scanning performed by the LoRa Edge platform, are still compatible with LR-FHSS.

6 Implementation Considerations

6.1 Gateway

LR-FHSS demodulation can be achieved on the LoRa® Gateway V2 reference design with external DSP capabilities. LoRa® 16-channel and 64-channel reference designs are available.
The current reference design uses Semtech SX1388 FPGA and OMAPL138 DSP. LoRa 16-channel reception is supported by the two SX1301 baseband processors. Up to 64 channels are supported by the add-on board with additional baseband processors.
Gateways built with the LoRa SX1301 chipset, which supports geolocation[9] are compatible with the LR-FHSS reception after a firmware update.

6.2 End-Node

6.2.1 Power Consumption and Battery Life

The power consumption required to deliver a certain amount of data depends on the packet ToA, which is shown in **Table 2**.
For devices with a high link budget and robustness requirement: LR-FHSS CR2/3 has a shorter ToA than SF12BW125kHz LoRa, but slightly longer than SF10BW125kHz LoRa. The CR1/3 has the longest ToA among the parameters listed, and offers the best robustness among blockers.
However, most devices spend most of their lifetime in deep sleep mode, which is independent of the uplink ToA.
Assuming a typical sensor device using SX1262[10] without external PA, 6 reports per day with 20 bytes physical payload, the annual power consumption is shown in **Table 8**.

Table 8: Annual Power Consumption with Modulations and Repetitions

Modulation	Annual Power Consumption (mAh)			
	Repetitions	1	2	3
LR-FHSS	CR 1/3	323		
	CR 2/3	258		
Modulation	SF10BW125kHz	205	234	264
	SF12BW125kHz	280	384	488

LoRa frames can be transmitted multiple times to improve performance with time diversity. As a result, though most LR-FHSS configurations have longer ToA, the total annual power consumptions are all between 200-300 mAh for LR-FHSS, SF10 LoRa, and SF12 LoRa without repetition.

[9] Like the Wirnet iBTS gateway by Kerlink, or MultiTech Conduit® v2.1 Geolocation Base Station.
[10] Assuming 130 mA Tx current, 10 mA Rx current, 20 µA sleep current.

6.2.2 Frequency Offset Tolerance

In the LR-FHSS receiver, the bandwidth of the digital receiver filter must be adapted for the channel configurations in LR-FHSS.
The frequency tolerance[11] can be derived from the receive (Rx) bandwidth and actual channel bandwidth.
The frequency accuracy requirement for typical LR-FHSS is listed below.

Table 9: Frequency Offset Tolerance

	Actual Channel Bandwidth (kHz)	**Rx Bandwidth (kHz)**	**Frequency Tolerance (kHz)**	**Max Device XTAL error allowed[12]**	
				@ 915 MHz	**@ 868 MHz**
LR-FHSS	39.06	100	30.47	30.3	32.1
	85.94	100	7.03	4.7	5.1
	136.7	200	31.65	31.6	33.5
	183.59	200	8.205	6.0	6.5
	335.94	400	32.03	32.0	33.9
	386.72	400	6.64	4.3	4.6
	710.90	800	44.55	45.7	48.3
	722.66	800	38.67	39.3	41.6
	761.70	800	19.15	17.9	19.1
	773.44	800	13.28	11.5	12.3
	1523.4	1600	38.3	38.9	41.1
	1574.2	1600	12.9	11.1	11.9

We marked the configuration with a frequency error tolerance larger than 30 ppm in green, which suggests that most crystals can fulfil the requirement in the end device. For other configurations, a more accurate Temperature Compensated Crystal Oscillator (TCXO) is suggested.
LoRaWAN regional specification utilizes three different LR-FHSS channel bandwidths (with gray background in the above table) that are compatible with crystals, hence most existing LoRaWAN devices can be upgraded to support LR-FHSS without hardware modifications.

[11] With no observable sensitivity degradation.
[12] Assuming 3 ppm maximal offset in the gateway.

6.2.3 Frequency Drift Tolerance

Unlike the frequency offset, the frequency drift tolerance sets the limit of the frequency offset between the beginning and the end of the packet. It requires a certain thermal relief design on the hardware, so the RF power amplifier (PA[13]) will not heat the crystal (if a crystal is used), resulting in a drift of the reference frequency while transmitting packets.

For LR-FHSS, the frequency drift limitation is 100 Hz/s without observable performance degradations, and up to 300 Hz/s with up to 1.5 dB sensitivity degradation.
For LoRa devices, the frequency drift between the beginning and the end of the packet is specified as $\frac{BW}{3\times 2^{SF}}$ or $\frac{16\times BW}{3\times 2^{SF}}$ respectively, with or without Low Data Rate Optimization (LDRO) in SX1261/2. This converts to about a 58 Hz/s requirement on the existing SX1261/2-based devices.

In the LR1110, using the latest LoRa receiver, the frequency drift tolerance is relaxed to 120 Hz/s.
As a result, the LR-FHSS demodulator can provide similar or better frequency drift tolerance compared with large-SF LoRa, despite the typically longer ToA. It suggests that there is no additional thermal relief scheme necessary in the device hardware to support LR-FHSS, so existing LoRaWAN end devices can be fitted for LR-FHSS without hardware changes.

[13] Inside or outside of the transceiver.

7 Summary

In this application note, we compared LR-FHSS performance with LoRa® in a wireless communication system. With a series of mathematical calculations, simulations, lab measurements, and field trials, the following conclusions can be made:

- LR-FHSS packets typically have a longer ToA than a LoRa packet, depending on the specific configuration.
- LR-FHSS provides an even better link budget and transmission range than LoRa SF10BW125kHz for operation in ISM 915 bands in FCC regions. This converts to increased coverage by a single gateway.
- LR-FHSS has a similar link budget when compared with SF12BW125kHz for users in licensed bands in FCC-regions, and ETSI-regulated regions.
- LR-FHSS robustness against in-channel blocker or interferer is further improved, when compared with LoRa. It provides a similar rejection with an adjacent channel blocker, and can tolerate higher duty cycle blockers.
- LR-FHSS shows better PER performance than LoRa SF10/12 in a brief field measurement.
- LR-FHSS has better network capacity with the same channel bandwidth in systems using an isolated gateway. As the gateway density increases, the LoRa network can provide equivalent or better network capacity.
- LR-FHSS typically has a longer time-on-air, but the power consumption is similar to LoRa devices if LoRa repetition is utilized. Still, smaller-SF LoRa transmissions can save a fair amount of battery consumption if the end device is close to the gateway.
- LR-FHSS and LoRa-enabled receivers have similar requirements for frequency offset and frequency drift within the packet. Devices designed for LoRa modulation (with SX1261/2 and LR1110) can typically be used for LR-FHSS without hardware modifications.

In summary:

- LR-FHSS is suitable for wireless applications with low gateway density and limited spectrum, but requiring extreme range, high robustness and large capacity without geolocation capability needs, for example: networks in rural areas, and satellite applications.
- LoRa modulation is a better fit for applications with medium/dense gateway deployments, for example, low-power wide-area network (LPWAN) in suburban/urban environments.

8 Glossary

Term	Description
ACR	Adjacent Channel Rejection
ADR	Adaptive Data Rate
AP	Wi-Fi Access Point
BW	Bandwidth
CR	Coding Rate
CRC	Cyclical Redundancy Check
CW	Continuous Wave
ETSI	European Telecommunications Standards Institute (Europe)
FCC	Federal Communications Commission (US)
FER	Frame Erasure Rate
FSK	Frequency Shift Keying
GMSK	Gaussian Minimum-Shift Keying
LoRa	Semtech chip for long range wireless radio frequency communication LoRa® is a registered trademark of Semtech Corporation
LoRaWAN	Long Range, low power, Wide Area (LPWA) Networking Standard managed by LoRa Alliance®
LR-FHSS	Long-Range Frequency-Hopping Spread Spectrum
OTA	Over-The-Air
PA	Power Amplifier
PER	Packet Error Rate
PHY	Physical Layer
SF	Spreading Factor
TDOA	Time-Difference Of Arrival
ToA	Time on Air

9 Revision History

Version	ECO	Date	Modifications
1.0	-	Jul 2021	Initial Version
1.1	-	Dec 2021	Marcom edits
1.2	060546	Feb 2022	Public Release

Important Notice

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