Coexistence of LoRaWAN and UHF RFID

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Introduction

LoRaWAN® is a low power wide area network (LPWAN) protocol that offers a compelling mix of long-range, large link margin and low power consumption[1]. In recent years, we have seen an explosive expansion in the deployment of LoRaWAN networks which addresses the needs of today's Internet of Things (IoT) applications.

An illustration of the LoRaWAN protocol stack is shown in Figure 1. The physical layer can be implemented in the sub-GHz ISM bands, for example, 902-928MHz in North America.

The ISM bands are unlicensed and anyone can operate within them as long as they comply with regulatory requirements regarding transmitting power, power density, and frequency- hopping. In some regions, dwell times and duty cycles are also regulated. The purpose of these requirements is to minimize the interference of various wireless systems operating on the same frequency bands[2]. But despite these regulations, interference between different systems can still occur, especially when a listen-before-talk (LBT) mechanism is not required.

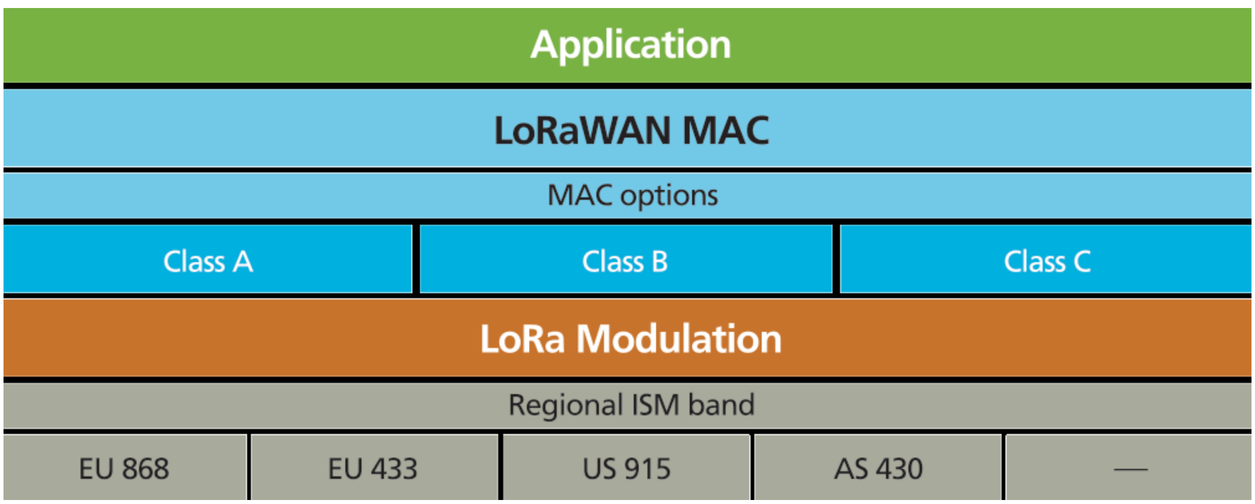

Figure 1: LoRaWAN Protocol Stack

One of the potential interferences which has attracted attention is the signal from the RFID systems, specifically the UHF RFID systems which operate on the same 902 MHz - 928MHz frequency band in North America, following EPC Gen2[3]. These dense RFID systems are frequently deployed in large retail stores,

[1] AN1200.22 "LoRa Modulation Basics", available at https://www.semtech.com/products/wireless-rf/lora-transceivers/sx1272
[2] AN1200.26 "LoRa™ and FCC Part 15.247: Measurement Guidance", available at: https://www.semtech.com/products/wireless-rf/lora-transceivers/sx1272
[3] "EPC Radio-Frequency Identity Protocols Generation-2 UHF RFID", https://www.gs1.org/sites/default/files/.../epc/uhfc1g2_2_0_0_standard_20131101.pdf

airports, museums, and other large facilities which require inventory functionality. However, there is great potential for the concurrent deployment of LoRaWAN-based IoT solutions in these same locations.

Semtech and other LoRaWAN ecosystem companies executed a joint investigation on the LoRaWAN performance when co-locating and co-existing with a densely deployed UHF RFID system. The study portion of the investigation evaluated the impact of the RFID system on a LoRaWAN network, and attempted to identify an optimized solution to mitigate the interference. The solution from the study portion of this investigation was validated by several field trial tests. The validated solution also provides a reference for when a LoRaWAN network co-exists with other high-power systems that generate frequency-selective interference.

This study involved multiple stages of the investigation, theoretical calculation, controlled lab measurements, channel plan optimization, and field measurements conducted in large-footprint retail stores.

This paper focuses on the configuration, methodology, results, and conclusions from the channel optimization and field measurement aspects of this study.

Background

LoRa®-based Devices and the LoRaWAN Protocol

A LoRaWAN network is typically deployed in a star-of-stars topology, in which gateways relay messages between end-devices and a central network server[4]. The gateways are connected to the network server via standard IP connections. They act as transparent bridges, simply converting RF packets to IP packets and vice versa. The wireless communication takes advantage of the long-range characteristics of the LoRa physical layer, which allows a single-hop link between the end-devices and one or more gateways. LoRa-based end-devices are capable of bi-directional communication. There is also support for multicast addressing groups so that it is possible to make efficient use of the spectrum during specific tasks.

[4] "LoRaWAN Specification v1.1", available at: https://lora-alliance.org/resource-hub

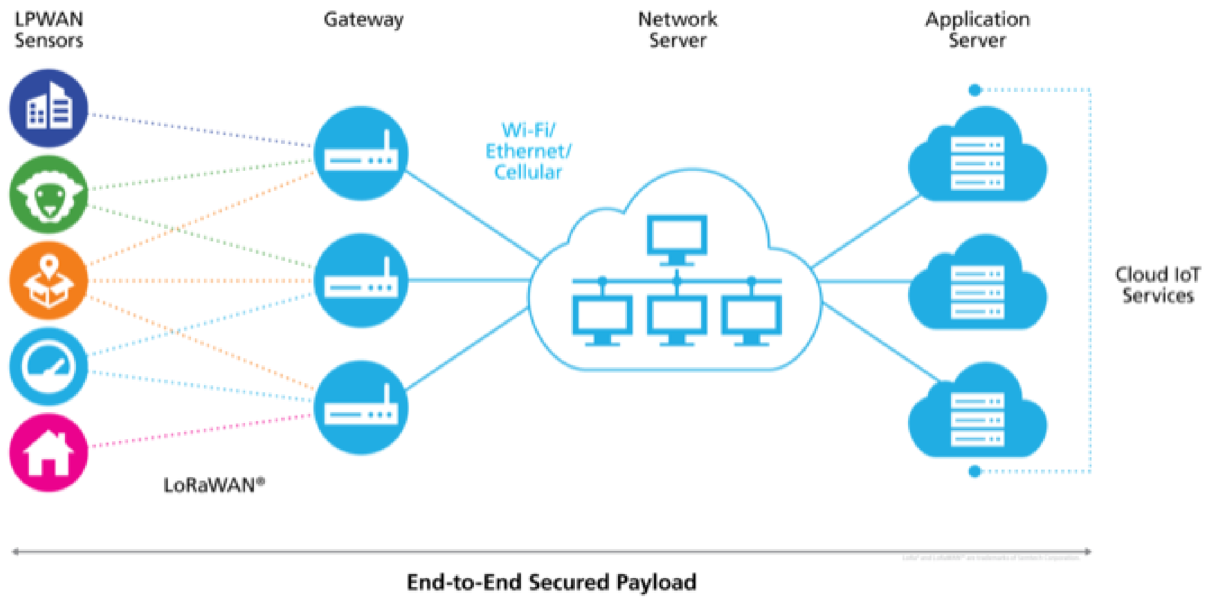

Figure 2: LoRaWAN Network Architecture

As described in the introduction, the LoRaWAN physical layer relies on the LoRa/FSK link between the end-devices and gateways, which uses the sub-GHz ISM bands[5]. Though robust to the co-channel and adjacent channel interferences, some penalties can still be measured when strong interferers coexist, sharing the same spectrum and space.

The LoRaWAN regional parameters for North America has a fixed uplink and downlink channel plan. There are a total of 64 125kHz uplink channels, spreading across the 902.3MHz to 914.9MHz bands, with 200kHz channel spacing. For the downlink, eight 500kHz channels are specified, occupying the 923.3MHz to 927.5MHz range, with a channel spacing of 600kHz.

EPC Gen2 RFID System

The UHF RFID system in this study is deployed indoors for inventory-related applications. For this study, we primarily considered the passive RFID system. The Interrogator ("Reader") communicated with one or more Tags by modulating a carrier using Phase Reversal Amplitude Shift Keying (PR-ASK), which itself used Pulse-Interval Encoding (PIE) with a reference time interval of 25µs. This implementation is as defined by the EPC Gen2 Air Interface Specification for a high-density multiple Interrogator environment.

The Interrogator both enables and communicates with the Tag using PR-ASK modulation. The Interrogator switches to continuous wave (CW) mode after its downlink information has been delivered. The carrier

[5] "LoRaWAN® Regional Parameters RP002-1.0.0", available at: https://lora-alliance.org/resource-hub

tone is then used by the Tag during the Tag-to-Interrogator communications period (i.e., the "Backscatter" communications).

To achieve the desired range, the effective radiated power (ERP) of the Interrogator signal can be quite high. The RFID system in this study delivered four watts (36 dBm) of output power with the help of a 6 dBi antenna. Additionally, it used a channel spacing of 500kHz, pseudo-randomly hopping over a minimum of 50 channels, and had a channel dwell-time approaching 400 ms, the maximum dwell-time allowed in the region.

The primary Tag sidebands were centered at 250kHz from the Interrogator CW frequency, as illustrated in Figure 3. The ERP of these sidebands is a function of incident energy. Typically these are much lower than the Interrogator signal power.

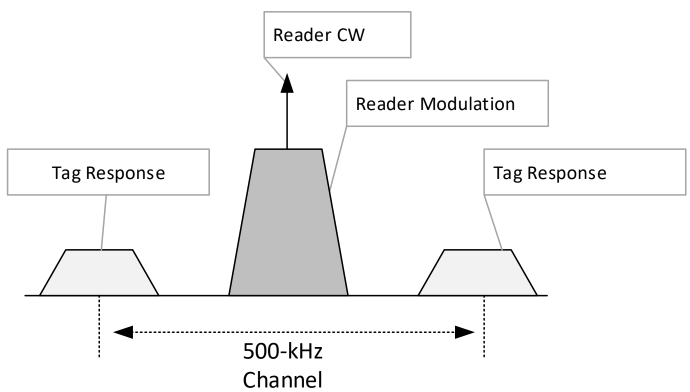

Figure 3: Passive RFID channel implementation

In the United States, passive RFID Interrogators are considered frequency-hopping devices, falling under the guidelines of CFR 47, Part 15.247[6]. Each single RFID Interrogator randomly hops among 50 channels. For the default 500kHz channel spacing, the RFID Interrogators used the spectrum from 902.75MHz to 927.25MHz, covering a frequency range of 24.5MHz. This allowed for a 750kHz guard-band at the band-edges.

Co-Existence of LoRaWAN and RFID

The Impact of RFID on LoRaWAN

A co-located RFID Interrogator emitting 4 W ERP and sharing the same space and frequency spectrum can impact the reception of LoRa packets under the following scenarios.

[6] "Operation within the bands 902MHz – 928MHz, 2400MHz – 2483.5MHz, and 5725MHz – 5850MHz", https://www.gpo.gov/fdsys/pkg/CFR-2013-title47-vol1/pdf/CFR-2013-title47-vol1-sec15-247.pdf

Co-channel Interference

As illustrated inFigure 4, the signal-to-interference-and-noise ratio (SINR) can be degraded when the RFID Interrogator carrier shares the same channel frequency as the LoRa signal. Typical LoRa-based chipset implementation requires -5 to -19.5 dB signal-to-interference ratio (SIR)[7]. When this occurs, filtering cannot be applied to increase the rejection of the interference.

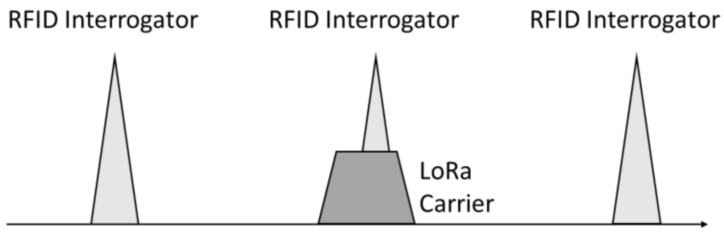

Figure 4: RFID Interrogator Co-channel with LoRa Carrier.

Adjacent-channel Interference

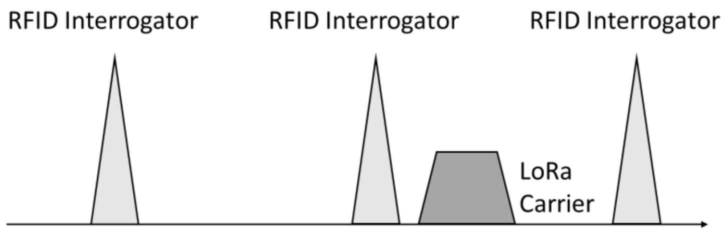

Figure 5: RFID Interrogator in adjacent channels of LoRa.

As illustrated in Figure 6, there can be interference when LoRa carriers are located between Interrogator signals. This situation can be due to power leakage from the RFID Interrogator into LoRa channels. In addition, the strong signal will also impact the AGC mechanism in the LoRa-based receiver. The Type A Reference Interval (Tari) in Figure 6 is 25 us in a dense Interrogator environment.

[7]"SX1261/SX1262 Datasheet", available at: https://www.semtech.com/products/wireless-rf/lora-transceivers/sx1261

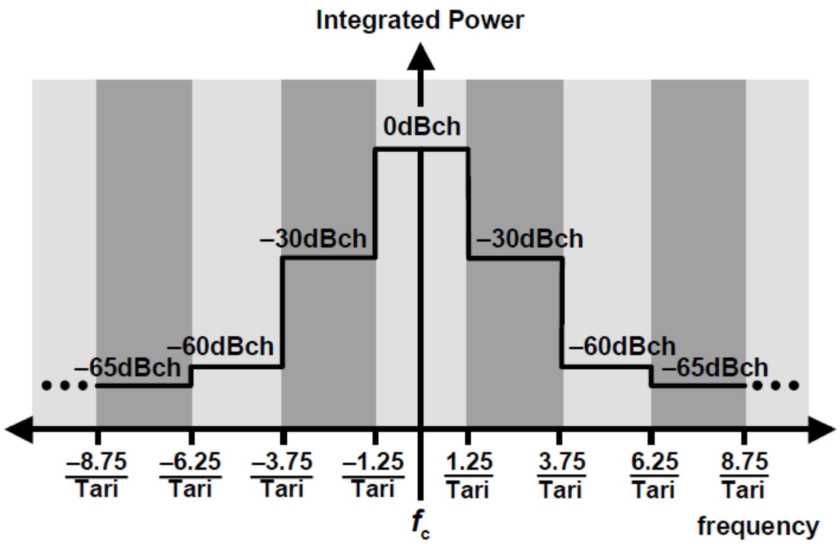

Figure 6: RFID Interrogator channel mask

Nonlinear Impairments (IM3, IM5)

The third- and fifth-order intermodulation products, due to nonlinearity of the front-end, could also cause an issue. As depicted in Figure 7, the potential impact is considerable, given a large number of co-located interfering sources and the ERP of the interfering signal.

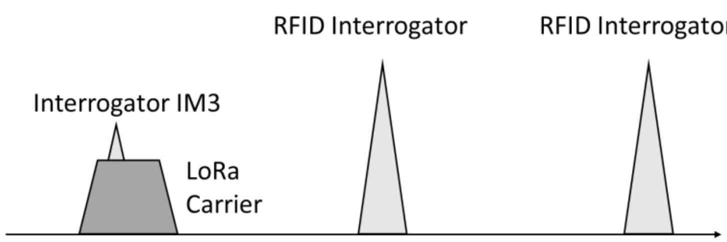

Figure 7: Co-Channel impairments of LoRa due to Interrogator IM3/IM5

The Impact of LoRaWAN on RFID

Given the relatively-low emitting power of LoRa-based end-devices and gateways, and the high density of RFID Interrogators, the impact of LoRaWAN transmissions on an RFID system is negligible.

Features for Better Coexistence

LoRaWAN Features

LoRaWAN includes features designed to be adaptive and to coexist with systems that generate frequency-selective interference, such as the UHF-RFID system.

1. LoRa modulation provides strong co-channel and adjacent-channel rejection: As noted in the SX1262 datasheet, the co-channel rejection with a single carrier interference is 5-19 dB, depending on the spreading factor (SF), and the adjacent-channel rejection is 60-72 dB.
2. As described in the LoRaWAN MAC protocol, an adaptive channel plan from the Adaptive Data Rate (ADR) command is mandatory. This feature allows the network server to disable channels that are known to have strong interference as a means of improving the overall packet transmission quality.

UHF RFID Features

1. UHF RFID Interrogators are all network-controlled and provide a configurable channel plan. Some high-end products support changing the RFID channel plan during operation without losing data.
2. The end-node (RFID tag) is a passive device and does not store the channel plan. This means that the tags can be adapted to any channel plan the Interrogator uses.

Blocking Performance of LoRaWAN-based System

Test Bench Information

This section presents the lab test bench for characterizing the LoRa-based receiver performance in the presence of simulated RFID Interrogator interference, in both co-channel and adjacent-channel scenarios.

Equipment and tools:

- Vector Signal Generator – SMBV100a
- RF enclosure
- The device under test (DUT) – LoRa-based PicoCell gateway
- The device under test (DUT) – SX1272 Nucleo shield and L152RE Mbed boards.
- Programmable Attenuator – RCDAT-6000-90
- RF cables
- Gateway HOST - Raspberry Pi

Waveforms:

- Waveforms of RFID Interrogators captured in a real retail store by SDR kits were used for Interrogator signal generation.

Figure 8 illustrates the test bench implementation:

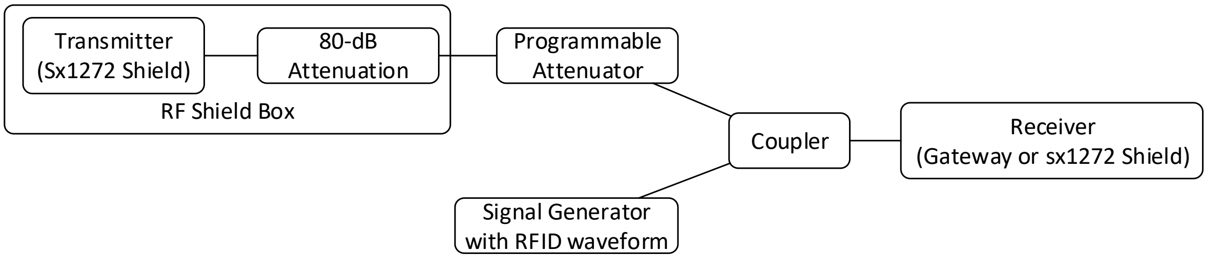

Figure 8: Test bench setup for lab measurements

Gateway Performance

The purpose of the uplink test is to quantify the rejection and robustness of the PicoCell gateway as the victim receiver.

The SMBV100a simulated a single RFID Interrogator transmitter by playing back a captured and post-processed Interrogator waveform. The waveform was extracted from the captured data in the retail stores, using an eight-tap Butterworth filter with 50kHz bandwidth and a carrier frequency of 912.25MHz.

The LoRa uplink packet had the following parameters:

- Bandwidth: 125kHz.
- Carrier frequency: 914.5MHz
- Spreading factor: SF7, SF10
- Code Rate: 4/5
- Packet length: 16 bytes in the physical layer payload.

The baseline performance was set by measuring the 10 percent Packet Error Rate (PER) for the device under test, without an RFID Interrogator. Next, the desired signal level was set at 6 dB, 26 dB, and 46 dB above this nominal sensitivity threshold. The Interrogator carrier was then injected into the PicoCell gateway at various frequency offsets. The interferer power was also changed until the LoRa PER was nominally 10 percent. The result illustrates the power level of an RFID Interrogator incident upon the PicoCell gateway that can be tolerated as a function of the frequency offset.

The relative rejection performance using SF7 is shown in Figure 9 below. With varying transmission power levels of LoRa signals, the relative interference signal level was constant in the same frequency offset point. It suggested a linear impairment depredating the SINR before analog-to-digital conversion (ADC) due to insufficient filtering

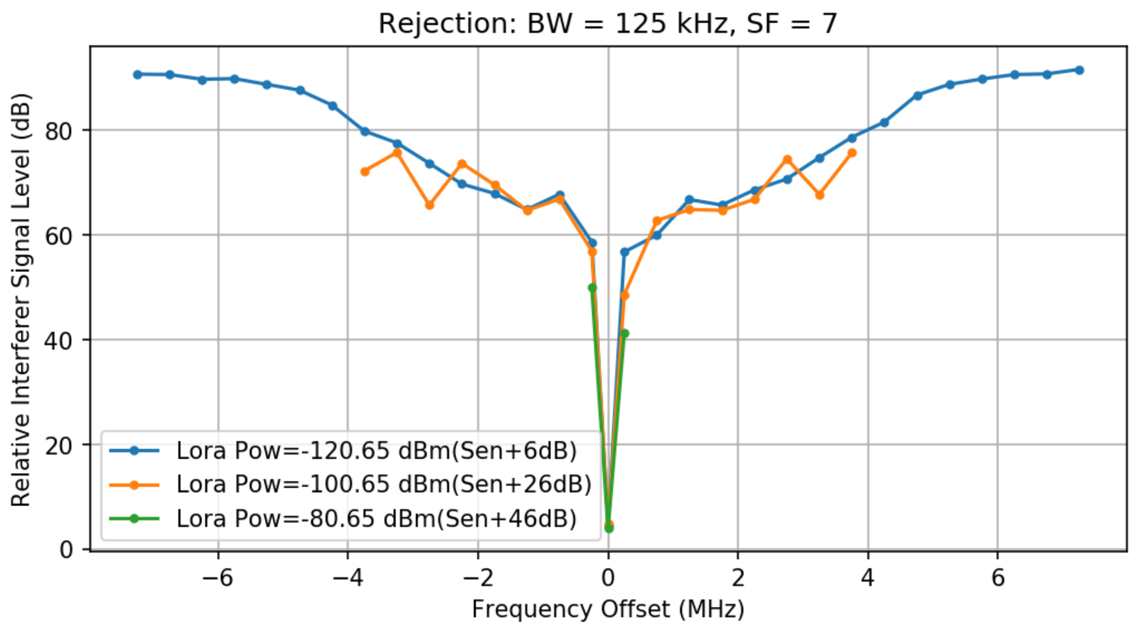

Figure 9: Co-channel and adjacent-channel rejection performance by Pico gateway receiver in relative interferer signal level, SF=7.

As illustrated in Figure 9, for an adjacent channel interferer at an offset of 250kHz, the PicoCell gateway could tolerate an RFID signal that is 55-60 dB higher than the desired LoRa signal. However, when the interferer is on the same channel, the rejection is typically reduced to 5 dB.

The PicoCell gateway receiver rejection performance was saturated when the received RF power of the interferer was -30 dBm to -20 dBm. This was due to the increased noise floor when the signal generator transmitted at high output power. This also applies to real-world scenarios in which the Interrogator transmits at high power.

The SF10 result is shown in Figure 10, with the relative rejection as the metrics:

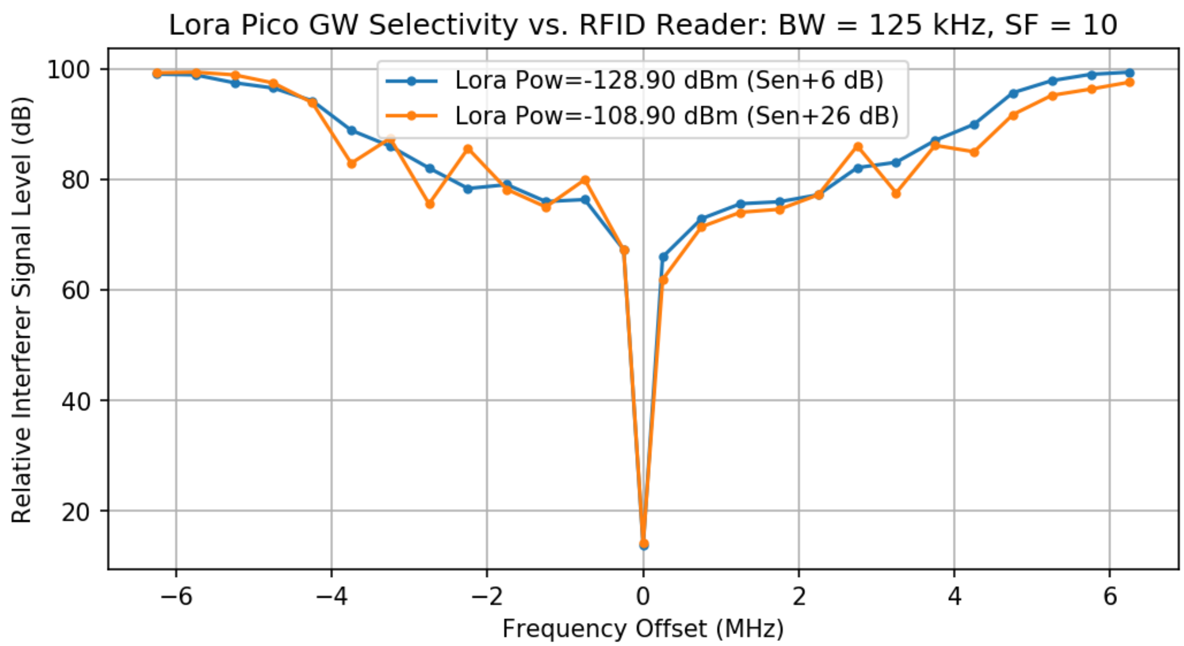

Figure 10: Co-channel and adjacent-channel rejection performance by Pico gateway receiver in relative interferer signal level, SF=10

End-Node Performance

The downlink receiver performance was conducted with two SX1272DVK1xAS development kits that were configured as the downlink packet transmitter and the target receiver, respectively.

Again, the purpose of this test was to measure the end node receiver performance in the presence of a nearby RFID Interrogator. In addition to all parameters considered in the uplink test, the receiver low-noise amplifier (LNA) gain was fixed, to demonstrate potential performance improvement by backing off the LNA gain at the expense of signal sensitivity.

The LoRa packets had the following parameters:

- Bandwidth: 500kHz.
- Carrier frequency: 923.3MHz
- Spreading factor: SF7, SF10
- Code Rate: 4/5
- Packet length: 16 bytes in the physical layer payload.

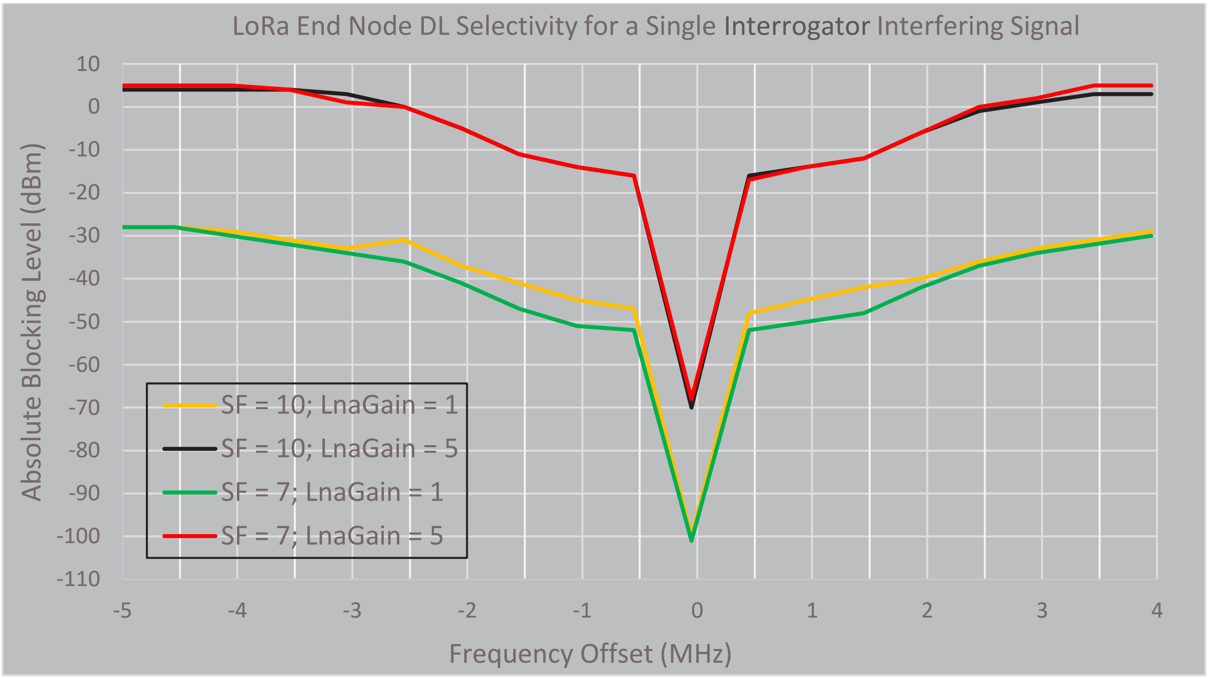

Figure 11: Co-channel and adjacent-channel rejection performance by an SX1272 receiver, in an absolute interferer signal level

The constant spacing between different LNA gains settings suggested that the RFID interference was a linear impactor that reduced the SINR. Thus, the receiver performance was a function of the signal-to-interference ratio (SIR) with a given frequency spacing.

The results indicated that the absolute level of blocking immunity increased as we backed-off LNA gain and lost some sensitivity. This suggested that a zoned or micro-cell gateway deployment would mitigate the impact of the multiple co-located interference sources.

Similar to the uplink results, adjacent channel rejection was typically 50 dB better than the co-channel rejection. The co-channel rejection was measured at about 5 dB for SF7.

Summary

From the lab measurements, the transceivers in LoRaWAN demonstrated great robustness against interference (>50 dB difference in rejection) when the interference and the LoRa signal did not share the same frequency. It also showed that the absolute rejection performance can be improved at the cost of sensitivity; hence, reduced gateway spacing is preferred in a deployment where LoRa and UH-RFID signals coexist.

Channel Plan Optimization

Based on the results from the lab measurements noted in in the Summary above, and the system features described in Features for Better Coexistence, it is clear that an optimized channel plan could help mitigate the impact of adjacent and co-channel interference from high-power RFID systems.

Default RFID Channel Plan

The default 500kHz RFID channel plan uses 50 channels, with a spacing of 500kHz. The first channel is 902.75MHz, and the last channel frequency is 927.25MHz.

Four LoRaWAN uplink channels are selected, hence four downlink channels are used, in accordance with the LoRaWAN regional specification for the US902-928 region. The RFID channels and LoRaWAN uplink/downlink channels are listed in Table 1. The normalized spacing between LoRaWAN and RFID channels is also listed. The normalization is by LoRa channel bandwidth, which is 125kHz for uplinks and 500kHz for downlinks.

In principle, if the normalized spacing is greater than 0.5, the signal could be separated by filtering (if we do not consider the RFID Interrogator signal bandwidth), and the interference scenario becomes adjacent interference. Otherwise, the interference scenario is co-channel interference.

Table 1: Default RFID Channel Plan with 500kHz Spacing.

Channel (RFID/LoRaWAN)	Channel Frequency (MHz)	Spacing between LoRaWAN/ RFID (norm. by LoRaWAN BW)	Channel (RFID/LoRaWAN)	Channel Frequency (MHz)	Channel (RFID/LoRaWAN)	Channel Frequency (MHz)	Spacing between LoRaWAN/ RFID (norm. by LoRaWAN BW)
IM3	902.25		14	909.25	36	920.25	
LoRaWAN UL0	902.3	0.4	15	909.75	37	920.75	
LoRaWAN UL1	**902.5**	**2**	16	910.25	38	921.25	
LoRaWAN UL2	902.7	0.4	17	910.75	39	921.75	
1	902.75		18	911.25	40	922.25	
LoRaWAN UL3	**902.9**	**1.2**	19	911.75	41	922.75	
LoRaWAN UL4	**903.1**	**1.2**	20	912.25	42	923.25	
2	903.25		21	912.75	LoRaWAN DL0	923.3	0.1
LoRaWAN UL5	903.3	0.4	22	913.25	43	923.75	

Channel (RFID/LoRaWAN)	Channel Frequency (MHz)	Spacing between LoRaWAN/ RFID (norm. by LoRaWAN BW)	Channel (RFID/LoRaWAN)	Channel Frequency (MHz)	Channel (RFID/LoRaWAN)	Channel Frequency (MHz)	Spacing between LoRaWAN/ RFID (norm. by LoRaWAN BW)
LoRaWAN UL6	**903.5**	**2**	23	913.75	**LoRaWAN DL1**	**923.9**	**0.3**
LoRaWAN UL7	903.3	0.4	24	914.25	44	924.25	
3	903.75		25	914.75	LoRaWAN DL2	924.5	0.5
4	904.25		26	915.25	45	924.75	
5	904.75		27	915.75	**LoRaWAN DL3**	**925.1**	**0.3**
6	905.25		28	916.25	46	925.25	
7	905.75		29	916.75	**LoRaWAN DL4**	**925.7**	**0.1**
8	906.25		30	917.25	47	925.75	
9	906.75		31	917.75	48	926.25	
10	907.25		32	918.25	LoRaWAN DL5	926.3	0.1
11	907.75		33	918.75	49	926.75	
12	908.25		34	919.25	**LoRaWAN DL6**	**926.9**	**0.3**
13	908.75		35	919.75	50	927.25	
					LoRaWAN DL7	927.5	0.5

With this channel plan, LoRaWAN uplink channels 1, 3, 4, and 6 are suitable for transmission among the block A with a minimum spacing of 1.2 times the bandwidth between the LoRaWAN channel frequency and the RFID channel frequency. The other four channels experienced degraded performance due to co-channel impairment or nonlinear third-order inter-modulation (IM3). For the downlink, all eight channels were blocked by the RFID signal, and there was not enough separation from the closest RFID channel due to its larger signal bandwidth.

This channel plan is referred to as the 500kHz Channel Plan in the Field Measurement section.

Optimized RFID Channel Plan

By shrinking the space between RFID Interrogators from 500kHz to 450kHz, and carefully selecting four uplink channels and their corresponding downlink channels, we successfully avoided all co-channel interference, while maintaining full compliance with the LoRaWAN specification.

Table 2: Optimized RFID channel plan with 450kHz spacing, free up four uplink and four downlink channels.

Channel (RFID/LoRaWAN)	Channel Frequency (MHz)	Spacing between LoRaWAN/ RFID (norm. by LoRaWAN BW)	Channel (RFID/LoRaWAN)	Channel Frequency (MHz)	Channel (RFID/LoRaWAN)	Channel Frequency (MHz)	Spacing between LoRaWAN/ RFID (norm. by LoRaWAN BW)
IM3	902.2		15	909.4	35	918.4	
LoRaWAN UL1	**902.5**	**1.2**	16	909.85	36	918.85	
IM3	902.65		17	910.3	37	919.3	
LoRaWAN UL3	**902.9**	**1.6**	18	910.75	38	919.75	
1	903.1		19	911.2	39	920.2	
LoRaWAN UL5	**903.3**	**1.6**	20	911.65	40	920.65	
2	903.55		21	912.1	41	921.1	
LoRaWAN UL7	**903.7**	**1.2**	22	912.55	42	921.55	
3	904		23	913	43	922	
4	904.45		24	913.45	44	922.45	
5	904.9		25	913.9	45	922.9	
6	905.35		26	914.35	46	923.35	
7	905.8		27	914.8	**LoRaWAN DL1**	**923.9**	**0.7**
8	906.25		28	915.25	47	924.25	
9	906.7		29	915.7	48	924.7	
10	907.15		30	916.15	**LoRaWAN DL3**	**925.1**	**0.8**
11	907.6		31	916.6	49	925.6	
12	908.05		32	917.05	**LoRaWAN DL5**	**926.3**	**1.3**
13	908.5		33	917.5	50	926.95	
14	908.95		34	917.95	**LoRaWAN DL7**	**927.5**	**1.1**

We chose 902.5MHz, 902.9MHz, 903.3MHz, and 903.7MHz for the uplink channel plan. None of these channels overlapped with RFID channels or IM3/IM5 products.

The corresponding downlink channels were at 923.9MHz, 925.1MHz, 926.3MHz, and 927.5MHz. None of the RFID channels overlapped with LoRaWAN downlinks. However, IM3/IM5 products may collide with LoRaWAN downlink traffic.

The channel plan is referred to as the 450kHz Channel Plan in the Field Measurement section.

Compliance

Both channel plans should comply with the FCC regulation in North America, specifically the 47 CFR 15.247 federal regulation.

The RFID Interrogator runs in Frequency Hopping Spread Spectrum (FHSS) mode. The RFID Interrogator has passed FCC certifications with both channel plans.

The LoRaWAN gateway runs in digital transmission system (DTS) mode, and the LoRaWAN sensor runs in hybrid mode. Both gateway and sensor reference designs have passed FCC pre-certification tests. The channel plan proposed in this section complies with the LoRaWAN regional parameters for the US902-908 region.

Field Measurement

The purpose of this field measurement was to measure the LoRaWAN system performance in typical retail stores with a dense UHF-RFID Interrogator deployment.

Test Site Information

Test Site Description

Two large retail stores were selected to test the LoRaWAN performance. Both stores had a similar dense RFID system deployment.

Store-1
One large retail store was selected to perform the baseline test discussed in the Baseline Measurement and Result section of this document. The store size was about 410 feet by 330 feet, including both the open store floor and back stock areas.

For better efficiency and accuracy of RFID inventorying, there was additional RF insulation installed along the wall separating back stock and open floor areas. Additionally, some internal walls are concrete. This caused higher attenuation than is typical in drywall structures.

Store-2

Another retail store was tested with LoRaWAN deployment. More details can be found in the Evaluation with Optimized Channel Plan section. The size of the store was about 520 feet by 380 feet. An RFID system similar to that in use in Store 1 was deployed and running.

Device Location

LoRaWAN Gateway/Device

The potential locations of LoRa-based sensors included places such as cold storage in the refrigerators of the grocery section and (separate) liquor store, sensors/detectors in the server room, mouse traps in non-public areas, and motion detectors near the fitting rooms and liquor store.

In the long-term, this LoRaWAN network could also support LoRa Edge™[8] based long-range inventory and geolocation functionality.

Five gateways were deployed near the in-store Ethernet switches in the back stock area and in the fitting room area, typically at a height of 12 to 15 feet. The detailed locations are mapped in Figure 12 below.

RFID Devices

The RFID Interrogators were mounted on the ceiling, with 25-ft to 40-ft spacing horizontally, covering the whole shop floor. In the back stock area, they were also ceiling-mounted. Each one covered one stock aisle.

Hardware Configuration

The following LoRa-based hardware was used in the field measurement.

1. End nodes: SX1272 mbed shields and mbed boards, with 14 dBm output power.
2. End nodes: SX1276 mbed shields and mbed boards, with 20 dBm output power.
3. LoRa Pico Gateway.

Baseline Measurement and Result

The baseline measurement was conducted in Store-1, as described in the Test Site Description.

For this part of our investigation, we evaluated the performance degradation caused by the RFID system.

[8] https://www.semtech.com/products/wireless-rf/lora-transceivers/lr1110

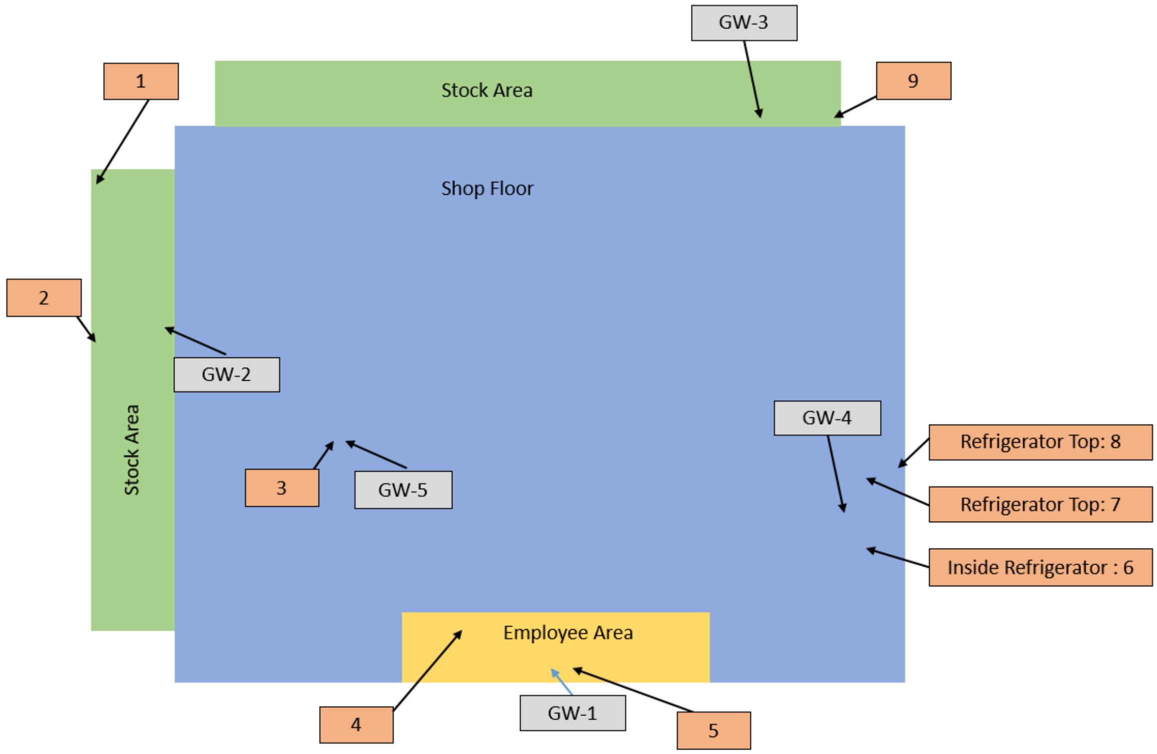

Figure 12: Map and sensor location of Store-1

A total of nine sensor nodes were deployed for the test, as illustrated by the orange boxes in Figure 12 Both uplinks and downlinks were tested.

Uplink Measurement

All 8 channels (channel 0-7) were enabled in this test.

We first turned off the RFID system and measured the uplink packet success rate (PSR/ FSR). Only a single gateway (GW-1) was enabled. All end-nodes generated uplink frames using circulated spreading factors between SF7 and SF10.

Table 3: Packet success rate in uplink with RFID system off

Location	PSR from GW-1
1	80%
2	84%
3	99%
4	95%
5	100%
6	99%
7	99%

Location	PSR from GW-1
8	99%
9	82%

The PSR performance was good; however, some nodes were separated by RF insulation. All nodes achieved beyond 80 percent PSR, with a single gateway placed on a table in the corner of the store.

Note: All measurements were based on circulating spreading factors. If ADR were enabled, we would expect to see further improvement in performance.

The PSR with different spreading factors is shown in Figure 13, along with a detailed analysis of the packet received by the node at location 1. Generally, better performance is expected when using a higher spreading factor, with the exception of SF10. (The long time-on-air for signals using SF10 increases the probability of collisions with transmissions from other end nodes.)

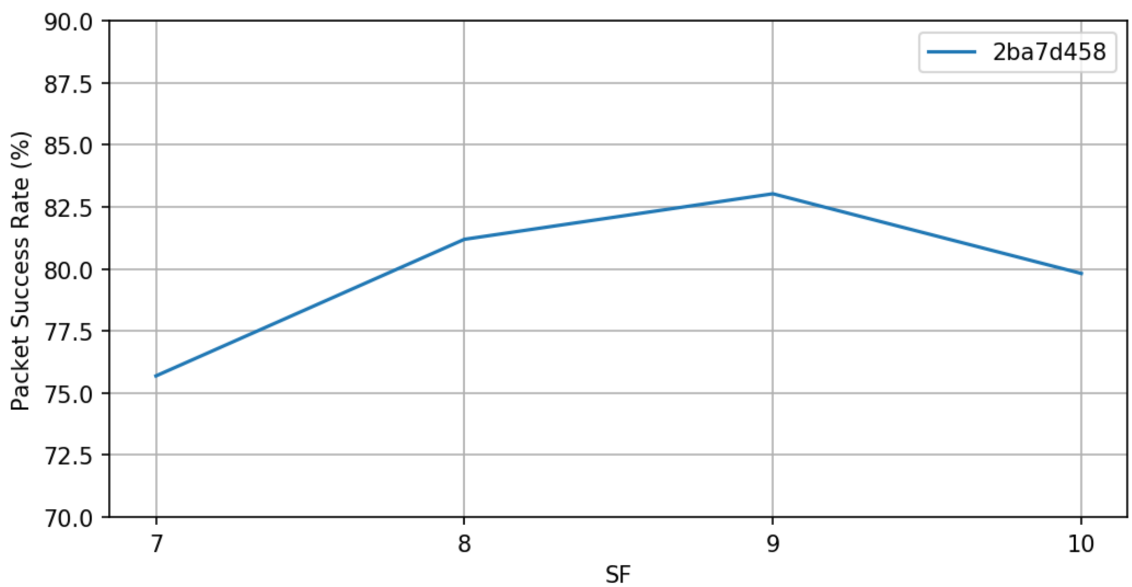

Figure 13: Packet Success Rate For Location-1 Node Grouped By Spreading Factors, with RFID Off.

We then turned the RFID system on, using the 500kHz (default) channel plan, expecting a large degradation due to the strong interference. To address this interference issue, we deployed multiple LoRa-based gateways to provide redundancy and diversity.

A multi-gateway scenario was evaluated with 5 PicoCell gateway locations in the stock area, loading bay, cold chain area, employee break room, and the clothing floor. The result is shown in Table 4.

Table 4: PSR with Single/Multiple Gateways in the Uplink, with Default 500kHz RFID

	PSR					
Location	GW-1	GW-2	GW-3	GW-4	GW-5	Minimal of multi-GW
1	0%	82%	1%	0%	2%	82%
2	6%	85%	0%	0%	42%	85%
3	95%	53%	36%	68%	98%	98%
4	90%	4%	16%	52%	80%	90%
5	97%	0%	27%	65%	54%	97%
6	53%	0%	22%	99%	13%	99%
7	92%	0%	69%	100%	68%	100%
8	79%	2%	62%	99%	42%	99%
9	11%	0%	92%	50%	1%	92%

While relying on a single gateway did not provide good performance, (for example, using only GW-1 can lead to 0% PSR for node location 1), the redundancy provided by deploying additional gateways, allowed the overall PSR to be maintained beyond 80 percent.

We analyzed one typical end node result in detail: location-8 with 79 percent PSR measured with GW-1. The result, grouped by spreading factors, is shown in Figure 14. With an increased noise floor, the transmission became an SINR-sensitive system that provided a better success rate with higher spreading factors.

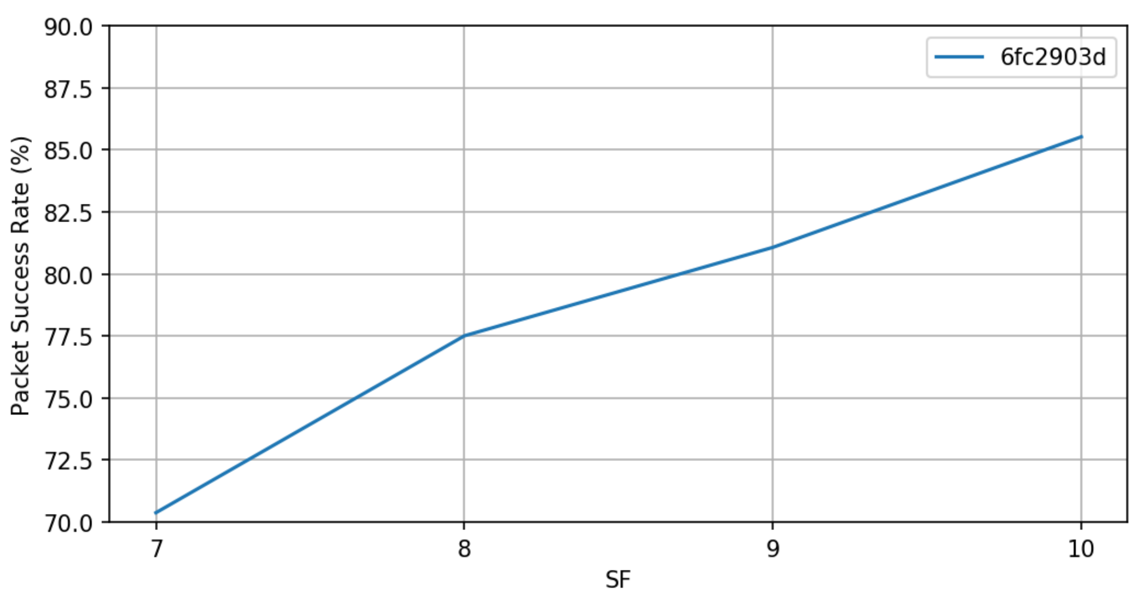

Figure 14: Packet success rate of location-8 node grouped by spreading factors in the uplink, with 500kHz RFID.

Downlink Measurements

A similar performance was expected in the downlink when the RFID was off, namely, that a single gateway could cover the whole store.

For this, we tested the downlink performance with the RFID system turned on. Performance with two channels were measured: 927.5MHz and 924.5MHz, with the RFID system on and running with default 500kHz spacing. The 924.5MHz downlink channel was impaired by two adjacent RFID channels at 924.25MHz and 924.75MHz. SF7 was used in the results shown in Table 5.

Table 5: PSR with a single gateway in the downlink, with the 500kHz RFID plan.

	PSR	
	GW-5, BW500SF7	
Location	924.5MHz	927.5MHz
3	96%	99%
7	32%	43%
9	0%	56%

We investigated the performance of the different spreading factors for the location-7 node, with the 924.5MHz channel, as illustrated in Figure 15.

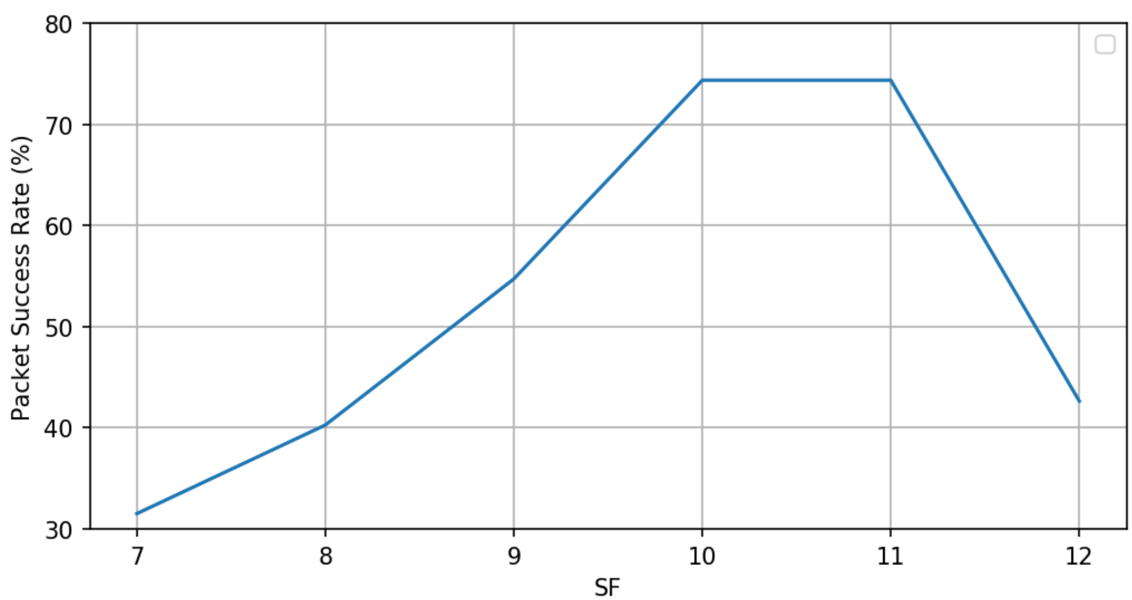

Figure 15: Packet success rate of location-7 node grouped by spreading factors in the downlink, with 500kHz RFID.

As we can see, increasing the spreading factor improved the robustness to noise/interference, which effectively improved the success rate from 32 percent using SF7 to more than 75 percent when using SF

10/11. However, it is significant to note that SF12 performance as degraded. This is primarily due to the long time-on-air, which increased collisions among LoRaWAN signals and RFID transmissions.

Evaluation with Optimized Channel Plan

The purpose of this test was to measure the performance of a LoRaWAN network in a retail store with a dense RFID Interrogator deployment.

A Semtech evaluation network server[9] was selected as the LoRaWAN network server (LNS) in this measurement.

This LoRaWAN measurement was generated in the larger retail store, as described in Test Site Description above. Four channels were used in this test: when testing with 500kHz RFID channel plan, we used channels 1, 3, 4, and 6; when testing with 450kHz RFID channel plan, we used channel 1, 3, 5, 7.

As illustrated in Figure 16, four gateways were mounted in the store: the bottom right gateway (GW-1) was mounted about seven feet high. The other three gateways were mounted higher than the RFID Interrogators, so that the interference from the RFID Interrogators could be minimized. The back stock area was located in the upper section, while the bottom section was the employee area.

On the map, we marked the node locations by the first four characters of their device EUIs.

[9] https://na.iot.semtech.cloud/

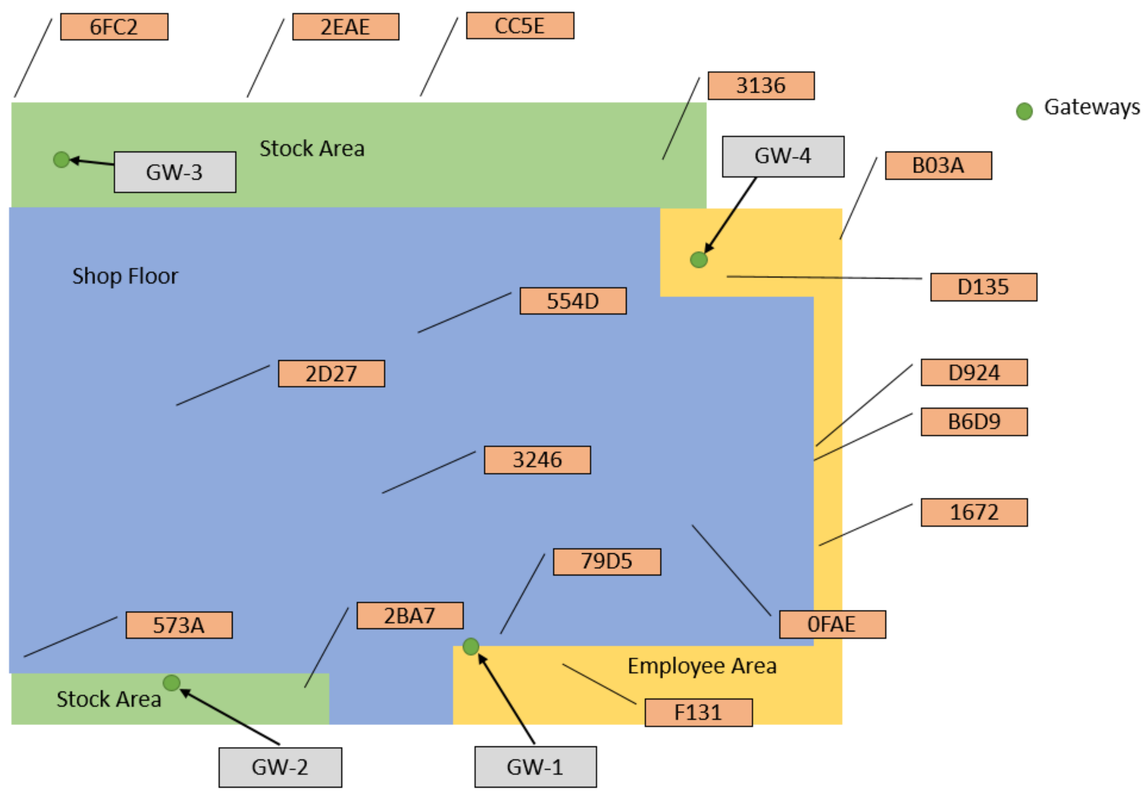

Figure 16: Map and sensor/gateway location of Store-2

Some nodes need special attention:

1. CC5E simulated a mouse trap close to an exit in the hallway. It was far from any gateways.
2. D135 sat in a walk-in refrigerator with a thick door that was covered by a metal structure.
3. D924 was placed in a freezer at a low temperature.

In the following result sections, each PSR/FSR value was generated by collecting the data in a four-hour window. More than 2,000 packets were measured.

Uplink Measurement

When measuring the uplink PSR, two RFID channel plans were implemented and compared, as described in Channel Plan Optimization.

Table 6: PSR in uplink using LoRaWAN.

	PSR	
Node ID	500k	450k
D92426DBD92426DB	42.74%	93.50%
CC5E33A1CC5E33A1	64.30%	94.67%

Node ID	PSR	
	500k	450k
0FAEF0510FAEF051	94.96%	97.52%
3246CDB93246CDB9	99.29%	99.49%
554DAAB2554DAAB2	98.96%	99.31%
3136CEC93136CEC9	97.25%	97.54%
6FC2903D6FC2903D	94.88%	96.69%
F1310ECEF1310ECE	97.53%	93.81%
573AA8C5573AA8C5	98.17%	97.80%
2BA7D4582BA7D458	98.29%	98.05%
B6D94926B6D94926	98.75%	98.40%
D1352ECAD1352ECA	91.04%	Not Measured
1672E98D1672E98D	99.08%	97.69%
79D5862A79D5862A	97.94%	94.29%
B03A4FC5B03A4FC5	93.04%	92.79%
2D27D2D82D27D2D8	99.80%	99.78%
2EAED1512EAED151	98.82%	Not Measured
Average	92.05%	96.76%

The 450kHz plan provided significantly better performance, improving the average PSR from 92 percent to about 97 percent.

We also measured the confirmed uplink with limited retransmissions. The maximum number of retransmission attempts is seven. Therefore, if either the uplink packet failed or the downlink acknowledgment failed for any given frame, no more than eight transmission attempts could be made

Table 7: PSR in uplink using LoRaWAN and confirmed uplink/retransmission.

Node ID	PSR	
	500k with Retransmission	450k with Retransmission
D92426DBD92426DB	66.23%	100.00%
CC5E33A1CC5E33A1	79.56%	100.00%
0FAEF0510FAEF051	100.00%	100.00%
3246CDB93246CDB9	100.00%	100.00%
554DAAB2554DAAB2	100.00%	100.00%
3136CEC93136CEC9	100.00%	100.00%
6FC2903D6FC2903D	100.00%	100.00%
F1310ECEF1310ECE	100.00%	100.00%
573AA8C5573AA8C5	100.00%	100.00%
2BA7D4582BA7D458	100.00%	100.00%
B6D94926B6D94926	99.71%	100.00%
D1352ECAD1352ECA	100.00%	100.00%

Node ID	PSR	
	500k with Retransmission	450k with Retransmission
1672E98D1672E98D	100.00%	100.00%
79D5862A79D5862A	100.00%	100.00%
B03A4FC5B03A4FC5	100.00%	100.00%
2D27D2D82D27D2D8	100.00%	100.00%
2EAED1512EAED151	100.00%	100.00%

Most of the nodes were error-free; only the back stock mousetrap and the one in the freezer experienced some frame loss with the 500k channel plan. We saw no frame loss with the optimized channel plan and confirmed uplink.

Downlink Measurement

The downlink performance is shown in Table 8. The average PSR was 60 percent for the default channel plan. This improved to 81 percent for the 450kHz optimized channel plan.

Table 8: PSR in downlink using LoRaWAN.

Node ID	PSR	
	500k	450k-2
D92426DBD92426DB	59.89%	74.06%
CC5E33A1CC5E33A1	43.05%	84.05%
0FAEF0510FAEF051	64.79%	82.43%
3246CDB93246CDB9	41.13%	84.13%
554DAAB2554DAAB2	39.96%	83.62%
3136CEC93136CEC9	54.81%	59.18%
6FC2903D6FC2903D	92.65%	94.26%
F1310ECEF1310ECE	87.06%	91.90%
573AA8C5573AA8C5	71.47%	95.25%
2BA7D4582BA7D458	69.45%	94.29%
B6D94926B6D94926	38.28%	66.65%
D1352ECAD1352ECA	70.17%	Not Measured
1672E98D1672E98D	44.00%	64.53%
79D5862A79D5862A	88.01%	94.40%
B03A4FC5B03A4FC5	63.54%	63.72%
2D27D2D82D27D2D8	34.60%	80.73%
2EAED1512EAED151	64.36%	Not Measured
Average	60.42%	80.88%

Result Summary

Using a practical gateway installation and four gateways in a retail store, we achieved greater than 95 percent FSR with respect to uplinks, and more than 80 percent FSR with respect to downlinks, as shown in Table 9.

Table 9: Summary of average FSR among multiple end-nodes

Average FSR	Uplink		Downlink
	Unconfirmed	Confirmed	
500kHz Default Channel Plan	92.05%	96.79%	60.42%
450kHz Optimized Channel Plan	96.76%	100%	80.88%

For mission-critical applications, it became clear that the 450kHz channel plan can provide very high service quality without significant frame losses.

LoRaWAN-based applications are generally focused on transmitting uplinks. Downlinks are predominantly used for provisioning and network control, with feedback enabled. Typically, failed downlink transmissions can be observed by the network (for example, a failed join accept message, or a failed ADR command) and downlink retransmissions can be easily scheduled.

The LoRaWAN network can operate normally with the transmission quality presented in Table 9.

Interestingly, there was no performance degradation from the RFID system when the channel spacing was moved from 500kHz to 450kHz when it coexisted with the LoRaWAN network.

Conclusion

In this paper, we have investigated the coexistence of co-located LoRaWAN network and UHF-RFID systems. Based on the datasheet and lab measurements presented in the section on Blocking Performance of LoRaWAN-based System we have proposed an optimized channel plan for both LoRaWAN and RFID systems, as described in the section on Channel Plan Optimization. Furthermore, we were able to demonstrate that LoRaWAN and high-power RFID systems can coexist with a good performance. The LoRaWAN success rate exceeded 96 percent for uplinks and 80 percent for downlinks, without any observed impact on the RFID system.

For applications in locations such as a large retail store, warehouse or airport, RFID and LoRaWAN are better suited for different applications. For example, RFID is well-suited for choke-point data capture, for instance, scanning a truck at a loading bay. For its part, LoRaWAN is great for ubiquitous coverage, both indoors and outdoors, to track and find an item in a yard or in a warehouse. In addition, LoRaWAN can support other sensor and monitoring applications. This investigation/demonstration illustrates that both system can work in the same location and frequency band, to better serve user needs.

Important Notice

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