Interference Analysis of LoRaWAN Systems

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1.1 LoRa and LoRaWAN

LoRa is a physical layer standard which is based on chirp spread-spectrum (CSS) modulation. In Chirp modulation, symbols are encoded into multiple signals with either increasing (upchirp) or decreasing (downchirp) frequency. While LoRa uses a fixed bandwidth of 125kHz, 250kHz or 500kHz, the data rate can be adapted by choosing a different amount of spread in time. Lora signals are very robust to fading, Doppler shifts and multipath interference because of the changing frequency.
The Long-Range Wide-Area Network (LoRaWAN) protocol is a protocol specially designed by the LoRa Alliance for the use on top of LoRa.

1.2 Chirp Spread Spectrum Modulation

The generation of the chirps in LoRa modulation is defined by the spreading factor (SF=7..12). The data signal is chipped at a higher data rate of 2^{SF} chips per symbol and modulated onto the chirp signal. The spreading factor defines the symbol duration and the amount of bits contained in one symbol. in figure 2 you can see a comparison of chirps with different spreading factors.

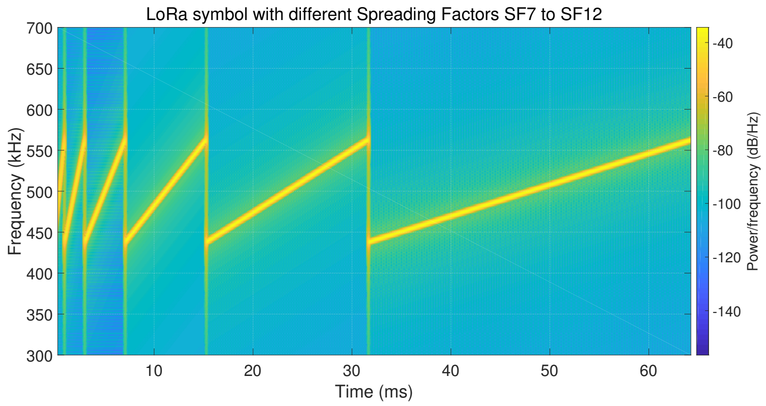


Figure 2: Lora Chirp

The symbol duration is defined as follows:

$$T_s = \frac{2^{SF}}{BW} \tag{1}$$

The information gets encoded with a Code Rate (CR=1..4), which brings us to an expression of the bit rate:

$$R_b = SF \frac{4}{4 * CR} \frac{BW}{2^{SF}} \tag{2}$$

with

- SF ... Spreading Factor (7..12)
- CR ... Code Rate (1..4)
- BW ... Bandwidth

Table 1 shows the different bit rates for specific spreading factors and bandwidths.

SF	BW $[kHz]$	$Bit\ Rate$ $[kbit/s]$
12	125	0.293
11	125	0.537
10	125	0.977
9	125	1.758
8	125	3.125
7	125	5.469
7	250	10.938
7	500	21.875

Table 1: Bit Rates

1.3 Message Format

The message format is depicted in figure 3 and is divided in the following parts:

- *Preamble:* consits of 10 downchirp symbols "0" followed by 2.25 upchirps which represent the synch word.
- *LoRa Physical Header (PHDR):* The header tells the receiving end about the length of the payload, presence of CRC and coding rate of the rest of the message. The header itself is encoded with a codie rate CR=4/8.
- *Header Cyclic Redundancy Check (PHDR_CRC)* The CRC is optional and is specified in PHDR.
- *PHYPayload:* the physical payload starts with the MAC header where the type of the message and the format are specified. It then continues with the MAC Payload and ends with a message integrity code.
- *Cyclic Redundancy Check (CRC):* used for error detection.

Figure 3: Message Format of a LoRa signal

2 Interference Measurements

The goal of this work is to evaluate the signal reception of LoRa signals with different interference sources. In section 2.1 a sensitivity analysis is performed to find the limits of LoRa communication. After that the impact of a continuous wave signal is shown in section 2.2 followed by an investigation of collision by multiple LoRa signals.

Measurement Setup:

For the setup of a LoRa communication, the open-source LoRaWAN Network Server stack called ChirpStack (`https://www.chirpstack.io/`, formerly known as Loraserver) is used. ChirpStack provides the following open-source components for LoRaWAN networks:

- *ChirpStack Gateway Bridge:* handles the communication with the LoRaWAN gateways
- *ChirpStack Network Server:* a LoRaWAN Network Server implementation
- *ChirpStack Application Server:* a LoRaWAN Application Server implementation
- *ChirpStack Gateway OS:* embedded Linux-based OS to run the full ChirpStack stack on a LoRa gateway

The architecture of the server is depicted in figure 4. LoRa messages are received by the gateways within reach of the sending node and forwarded to the Gateway-Bridge by the packet forwarder. The Gateway-Bridge transforms the messages into a data-format used by the network components (JSON or Protobuf). Via MQTT, the Network-Server receives the message by one or multiple gateways. The Network-Server has knownledge of the device activations in the network and can handle join-requests. The data, received by multiple gateways will be de-duplicated and forwarded to the Application-Server. This server provides web-interfaces and APIs for the managment of the communication system.

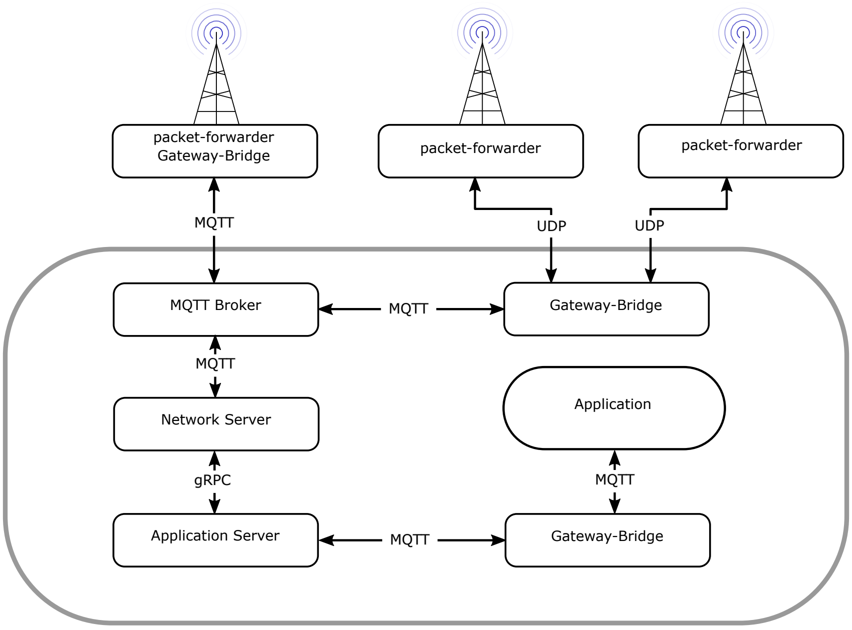


Figure 4: ChirpStack architecture

As gateway, a raspberry pi 3 is used with an iC880A - LoRaWAN Concentrator. For the end-node, several signals from a RN2483 tranceiver module were recorded with an signal analyzer for replay with a signal generator Rohde & Schwarz SMBV100a.

2.1 Sensitivity Analysis

A big advantage of the LoRa modulation technique is high sensitivity. As a trade off for a relatively low data rate, singnal reception is possible with extremely low receiving power. In figure 5 the sensitivity analysis for a 250kHz LoRa signal and different spreading factors is depicted. As can be seen, a packet delivery ratio of 100% can be reached with a receiving power of about 138dBm and a high spreading factor.

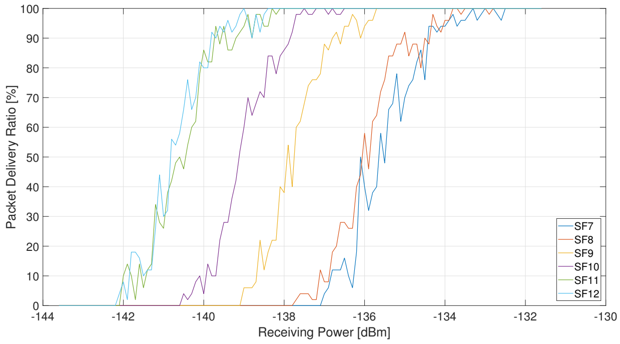
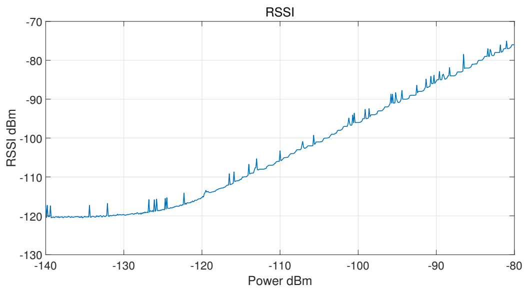
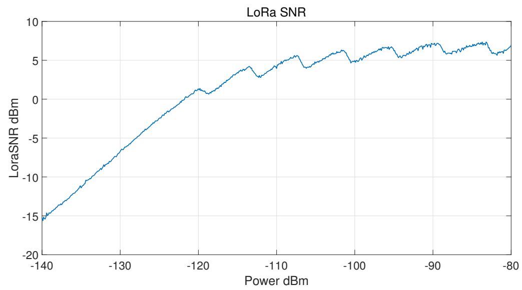


Figure 5: Sensitivity Analysis



(a) RSSI

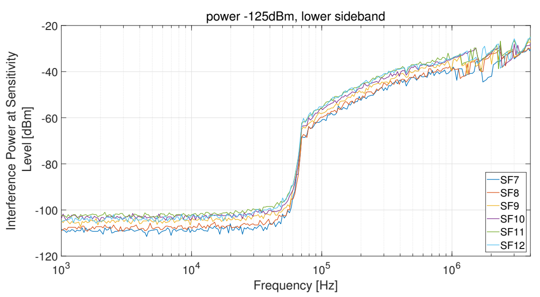


(b) LoraSNR

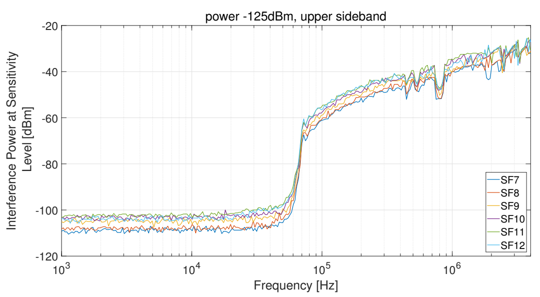
Figure 6: RSSI and LoraSNR of a signal with Spreading Factor 12

2.2 Interference with a continuous wave signal

Next step is to evaluate the impact of a continuous wave (CW) signal as interference source. As CW-source, a Rohde & Schwarz SME03 signal generator is used. The CW-signal is swept around the carrier frequency of the LoRa signal (868.1 MHz) and the sensitivity of the LoRa reception is measured.



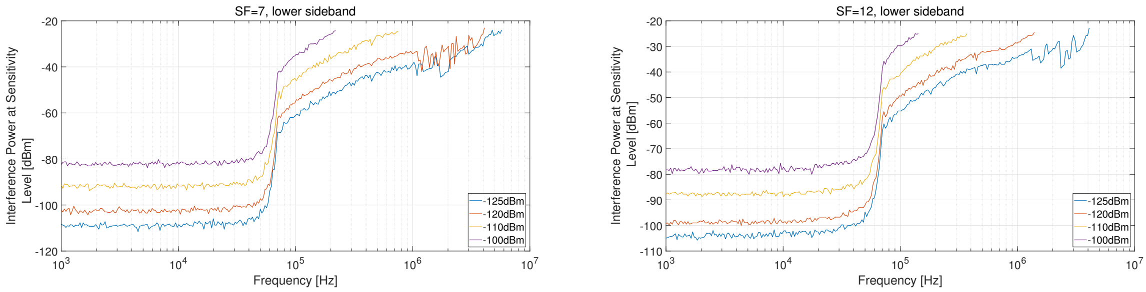
(a) Lower sideband



(b) Upper sideband

Figure 7: Frequency spectrum around the LoRa-carrier-frequency (868.1MHz) with a CW-interference and a LoRa signal receiving power of -125dBm (BW=125kHz)

Figure 7 shows the result for the 7a) lower and 7b) upper sideband of a LoRa signal with a receiving power of -125dBm and different spreading factors. It shows, that sensitivity level of the LoRa signal is very low with a CW-frequency inside the LoRa bandwidth. However, the power of the interference has to be about 15dBm to 25dBm higher than the receiving power of the LoRa signal to disrupt the communication.



(a) SF=7 (b) SF=12

Figure 8: Frequency spectrum around the LoRa-carrier-frequency (868.1MHz) with a CW-interference and different LoRa signal receiving power for a) SF=7 and b) SF=12 (BW=125kHz)

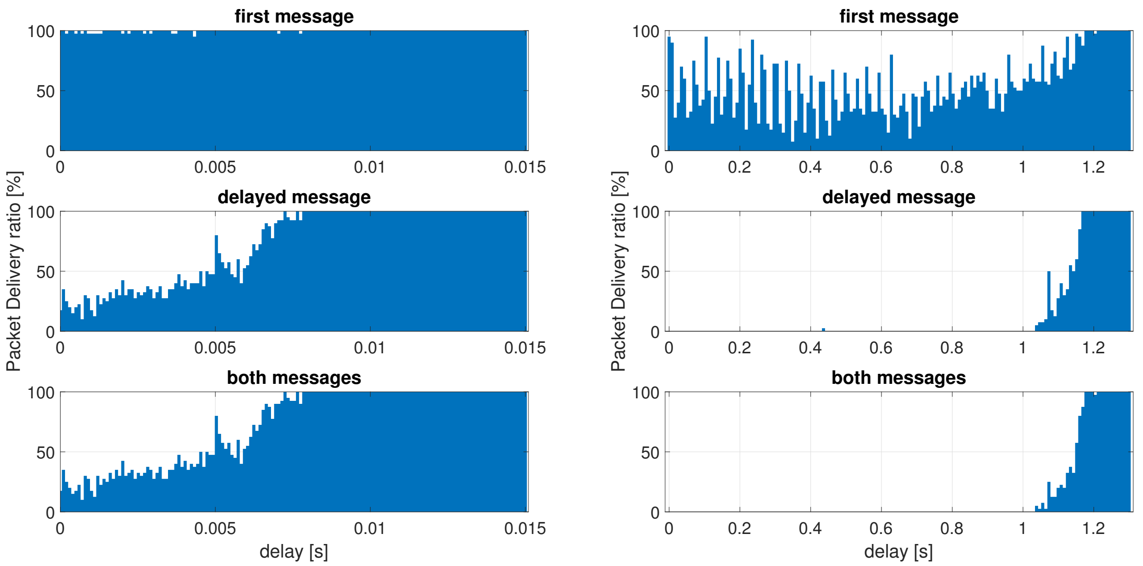
The sensitivity increases linear with the receiving power of the LoRa signal, as can be seen for the case of SF=7 in figure 8a and SF=12 in figure 8b.

2.3 Interference with multiple LoRa signals

In this section, the packet delivery ratio of two LoRa signals received at different times is investigated. Both signals were sent with different settings of spreading factor and transmit power at the carrier frequency 868.1 MHz.

2.3.1 Two messages with the same receiving power

The results of this measurement have shown, that signals with two different spreading factors have no impact on each other. The chirps are orthogonal the gateway receives them on on different channels.
Two signals with the same spreding factor lead to a decrease of the packet delivery ratio as can be seen in figure 9. Figure 9a shows the case for two messages with SF=7. The first signal is received with no impact of the delayed message. The delayed signal has a lower reception rate while the arrival overlaps with the preamble of the first message.
In the case with two signals with SF=12 depicted in figure 9b, the delayed message interferes with the first one and decreases its packet delivery ratio. The receiver is locked to the reception of the first signal during during its reception and the delayed message is unrecognised.



(a) Both signals with SF=7, $T_{signal} = 52ms$

(b) Both signals with SF=12, $T_{signal} = 1.3s$

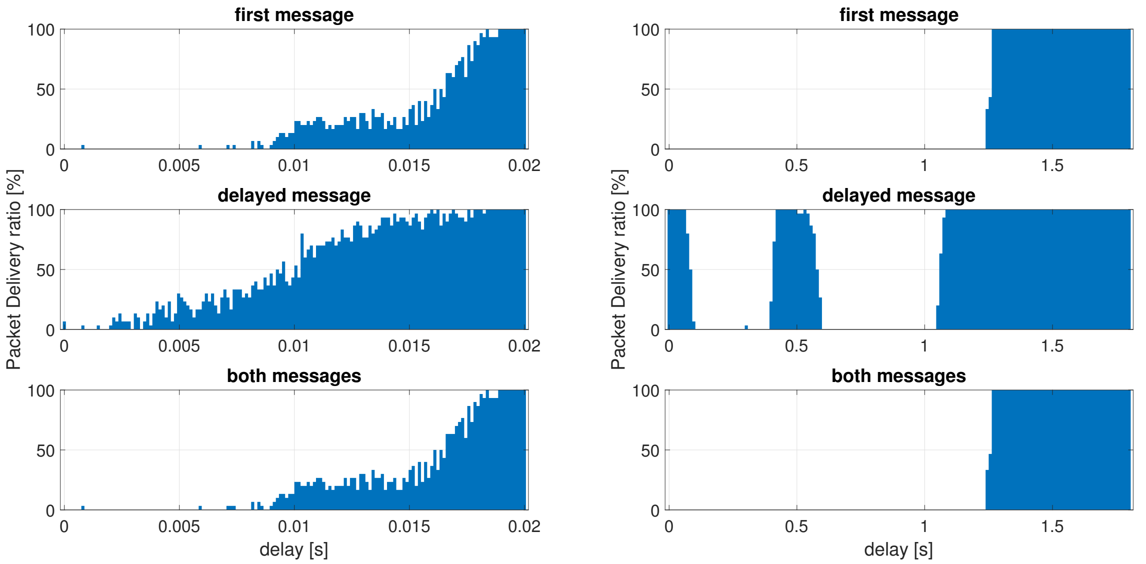
Figure 9: Collision detection with two delayed signals SF=7 and SF=12, each with 100dBm receiving power.

2.3.2 Two messages with different receiving power

Figure 10 shows the impact of a collison of two signals with different power. The case with SF=7 (figure 10a) shows, that in this case the stronger signal arriving during the reception of the first one, leads to a packet loss.

The interference of two sigals with SF=12 (figure 10b) shwos a different result. The first signal with lower power is unrecognized when a collision with a signal with higher power happens. The higher-power signal is received when it arrives at specific times during the reception of the lower-power signal. This situation is depicted in figure 11 in greater detail. The stronger frame survives the collision, wehen it arrives during the reception of the first 4 upchirps of the preamble of the first frame. Between the rest of the preamble and the header, the receiver is locked to the weaker signal and no frame gets received. During the header - which consists of the PHDR, PHDR_CRC and the MAC header, described in section 1.3 - the receiver releases the lock on the weaker frame due to a failed redundancy check and starts listening to the delayed signal. During the payload, the receiver is locked to the weaker frame again and both messages are lost again. At a some point during the reception of the payload of the first frame, the receiver starts to recognize the delayed message again. When the collision happens durion or afrer the redundancy check happens, both frames get received.

If the signal with a lower power arrives during the reception of one with a higher power, it gets lost almost everytime.



(a) Both signals with SF=7, $T_{signal} = 52ms$

(b) Both signals with SF=12, $T_{signal} = 1.3s$

Figure 10: Collision detection with two delayed signals SF=7 and SF=12, first message -125dBm and delayed message -90dBm receiving power

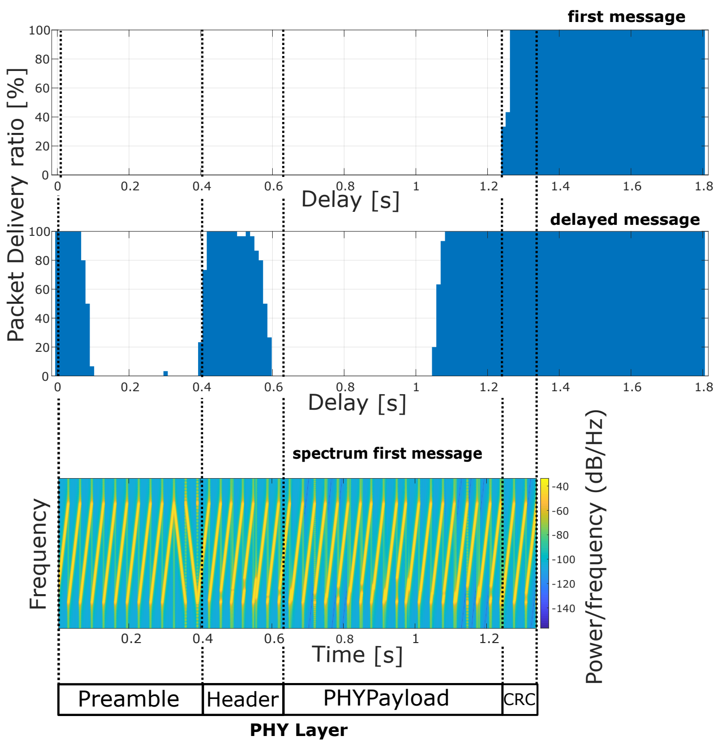


Figure 11: Impact on packet delivery ratio of a message with a delayed LoRa signal with higher power.

2.4 Packet Error Probability

With the results in 2.3 it is possible to define a packet error probability for which we make some assumptions. There are two different kinds of uplink messages:

- *unconfirmed message:* When a message is received by the gateway, no acknowledgement (ACK) wil be sent back.
- *confirmed message:* In this case, a successfull transmission has to be acknowledged by the gateway by sending an ACK message back. for this purpose, the LoRa node opens two receive windows after the transmission.

In the following calculations we assume, that only unconfirmed messages are sent. This simplifies the model, since retransmissions and windows for downlink transmission can be neglected. We also assume perfect orthogonality of the different spreading factors, no interference between the M=8 frequency channels and uniform distribution of the traffic load a over the given channels and spreadfing factors ($p_{SF} = \frac{1}{6}$):

$$a = \frac{p_{SF}\lambda}{M} \tag{3}$$

The packets are generated following a poisson process. For a specific package generation rate λ an symbol duration we get the following expression for the receiving probability:

$$P(successfull) = \exp^{-2aT} \tag{4}$$

With this equation we can derive the probability for the collision of two packets:

$$P_1(collision) = 1 - \exp^{-2a_1T_1}\exp^{-a_2(T_1+T_2)} \tag{5}$$

This can then be generalized to the case of N different nodes with transmission time T_i and arrival rate λ:

$$\begin{gathered} P_i(collision) = 1 - \prod_{k=1}^{N} \exp^{-2a_k(T_i+T_k)} \\ P(collision) = \frac{1}{N}\sum_{i=1}^{N} P_i \end{gathered} \tag{6}$$

In figure 12, the collision probability over the arrival rate λ for a different amount of nodes is depicted. The spreading factor is 12 and the signal duration T is uniformly distributed between 1 and 3 seconds.

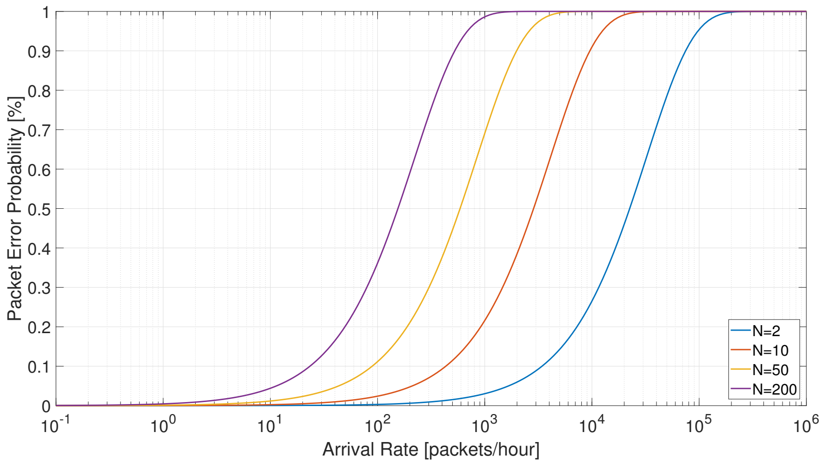
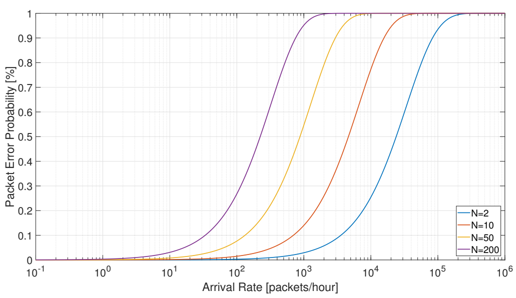


Figure 12: Collision probability of several nodes with SF=12

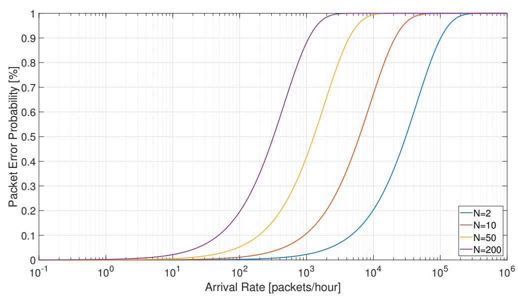
We have seen in section 2.3.1 and 2.3.2, that a collision does not mean that both packets are lost. To consider this in our calculations, we introduce a probability of a dropped frame during a collision p_j in equation 6:

$$P_i(collision) = 1 - \prod_{k=1}^{N} \exp^{-2a_k p_j (T_i + T_k)} \tag{7}$$

In figures 9b and 10b we can see a dropping rate of 65.27% for two signals with the same power and 48.19% when a higher power signal collides with a lower power signal.



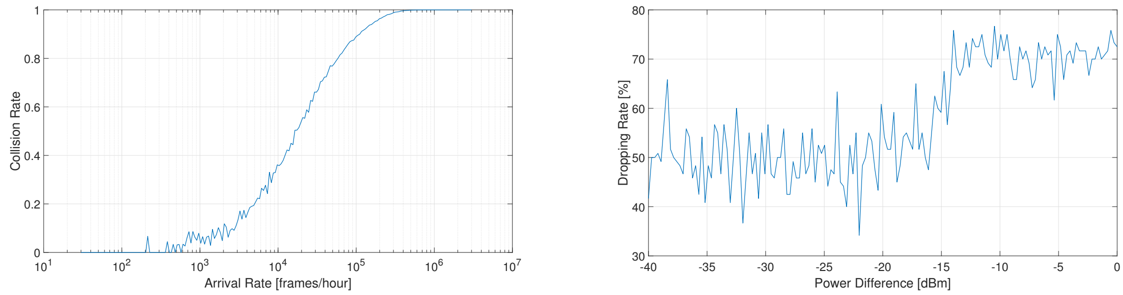
(a) Both signals with same power



(b) Signals with higher power

Figure 13: Packet error probability of several nodes with SF=12

A measurement of the scenario with two different nodes is depicted in 14. Figure 14a shows the collision rate over different arrival rates which shows similar results to the collision probability in 12. The dropping rate for a collision of two nodes with different receiving power is depicted in 14b. The first frame arrives with a receiving power of -90dBm and the second one with a random delay during the reception of the first one with the depicted power difference. It shows a dropping rate of 70% for equal power and 50% for a difference of 20dBm, which confirmes the dropping rate p_j used for the calculation of the packet error probability depicted in figure 13.



(a) Collison rate over arrival rate

(b) Dropping rate over power difference

Figure 14: (a) Measured collision rate of two nodes (b) and dropping rate for collision of two signals with different power

3 Summary

The measurements with a LoRa communication system in this project, show the effects of the highly resistant modulation technique. A interference of a CW signal needs to be about 15 to 25dBm higher than the power of the LoRa signal to cause an error. Reception of more LoRa frames with different spreading factors simultaneously has no impact on the packet error ratio due to the orthogonality of the chirps. Two or more signals with the same spreading factor, received at the same carrier frequency, cause some errors when they arrive at the same time. Section 2.3 shows that collision leads to a packet loss dependent on the receiving power and the time when the signals interfere. The models derived in this section can be used to predict the real life behaviour of a LoRa communication system, as shown in 2.4.