Investigating and Experimenting Interference Mitigation by Capture Effect in LoRa Networks

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1 INTRODUCTION

Recently, Low-Power Wide Area Networks (LPWAN) play a key role in the Internet-of-Things (IoT) maturation process. Under the LPWAN broad term are a variety of technologies enabling power efficient wireless communication over very long distances. For instance, technologies based on ultra-narrow band modulation (UNB) – e.g. SigFox™ – or Chirp Spread Spectrum modulation (CSS) – e.g. LoRa™ [3] – have become de facto standards in the IoT ecosystem. Most of LPWAN technologies can achieve more than 20 km in line of sight (LOS) condition. In a typical long-range 1-hop connectivity scenario, the gateway is the single interface to Internet servers through cellular/ADSL/Ethernet/WiFi technologies depending on what is available locally. Devices typically communicate directly to one or more gateways, which removes the need of constructing and maintaining a complex multi-hop network. Recent deployment tests with LoRa gateways located on top of high building show more than 6km range in urban scenarios for smart city applications [5]. A large city can easily be covered with less than 10 gateways. Indoor smart building applications are also enabled by the easy coverage of buildings several stories high. Communication to high altitude balloons have also been realized successfully [1, 2] and tests with low-orbit satellites are on the way [4]. These very versatile technologies definitely provide a better connectivity answer for battery-operated IoT devices by avoiding complex synchronization and costly relay nodes to be deployed and maintained.

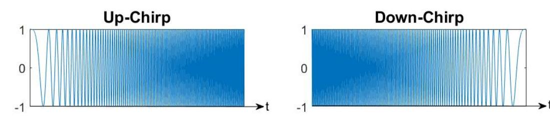

Figure 1: Up-chirp and down-chirp signal.

LoRa PHY uses CSS modulation as depicted in figure 1 which is a kind of frequency modulation that manifests capture effect (CE). In the past, many theoretical studies on CE have been performed to increase the packet reception rate (PRR) of a network, in the presence of a collision. But in context of LoRa, not much research has been done. Here we present our work on the interference mitigation by capture effect in LoRa networks. The article is organized as follows: In second section we present capture effect in LoRa networks and research done in this regard. In the third section, we present our previous work on capture effect simulations and in the fourth and final section we present our experimental settings. The results are also presented with the experimentation settings the fourth section.

2 CAPTURE EFFECT IN LORA

Practical studies in [6, 8, 10] have shown capture effect for LoRa based system. In [9], authors presented capture study on equal power collisions in the pure ALOHA based 802.15.4 system. In [12], authors state that their collision detection approach can differentiate between a packet collision and packet loss for 802.15.4 based system.

Figure 2 shows the packet structure used by LoRa. LoRa offers maximum packet size of 256 bytes. More details on the LoRa packet structure can be found in [3]. For the purpose of this paper, the main part of interest is the preamble which is a sequence of constant up-chirps, two down-chirps and a quarter of up-chirp.

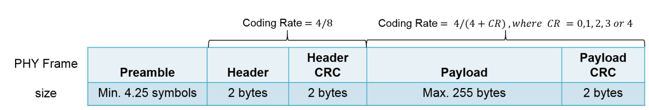

Figure 2: LoRa PHY frame format

The receiver uses the preamble to start synchronizing with the transmitter. The LoRa packet ToA can be defined as:

$$T_{air} = T_{preamble} + T_{payload} \quad (1)$$

where $T_{preamble}$ is the preamble duration and $T_{payload}$ is the payload duration which also includes optional header and CRC fields. Without going into the details of exact ToA computation which can be found in [3], one can say that SF and BW have direct influence on the ToA of the LoRa packet as these parameters typically define the symbol rate: higher SF increases ToA while higher BW decreases ToA at the cost of lower receiver's sensibility.

In general, the receiver keeps monitoring for the new potential preambles and if its SINR is above a given ratio, receiver stops ongoing reception and re-synchronizes with the new packet and demodulate the signal. We are going to characterize CE in the next section (the probability for a packet to be decoded despite the presence of one interferer). Note that for the sake of simplicity, we only consider 2-packet collision scenario. This analysis can be extended to 3 or more packet collisions. The capture characteristics of any radio transceiver depend on the modulation, decoding schemes and its hardware design and implementation. In a RF interference environment, a particular signal X can be successfully decoded if:

$$SINR_X = \frac{P_X}{\sum P_I + \sigma^2} > Th \quad (2)$$

where P_X is the source signal strength, $\sum P_I$ is the aggregate interference strength from the other active users in the network, σ is the channel noise coefficient and Th is the minimum SINR threshold required to successfully decode signal X. When two or more packets collide, with CE it is still possible to receive one of them. CE enables the receiver to decode a packet that satisfies Eq. 2, even if it arrives during the reception of an ongoing packet.

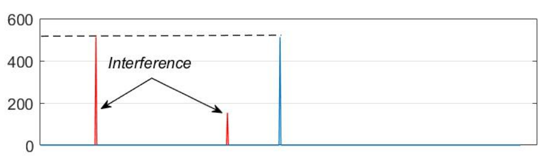

Figure 3: Coded chirps at 30, 100 and 128. Same TX power. $SF = 8$.

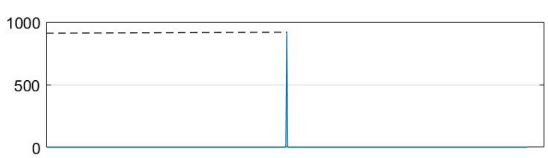

Figure 4: FFT of 3 Coded chirps at 128. $SF = 8$.

For a LoRa modulation, as shown in Figures 3 and 4, only the strength of the strongest interferer will matter as long as the simultaneous number of interferers is not too high and the probability to have interferers with a shift that falls at the same time remains low. So Eq. 2 will become:

$$SIR_X = \frac{P_X}{P_I} > Th \quad (3)$$

In the literature [7, 9–12], usually, two capture scenarios are taken into account. Both capture scenarios are shown in Figure 5.

- Decoding the First: During the reception of a packet, a second packet arrives and creates collision. In this case, receiver synchronizes with the first packet and tries to perform successful reception.
- Decoding the Last: Another scenario would be to decode the packet that arrives later. This necessitates to be able to detect the preamble of the second packet and then to correctly decode the packet.

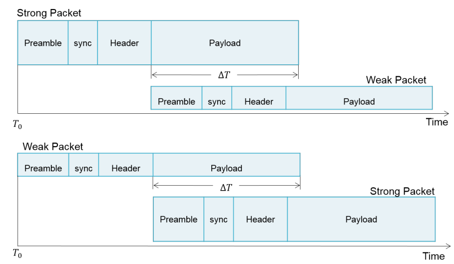

Figure 5: Capture Scenarios (top) Stronger First, (bottom) Stronger Last.

3 CAPTURE EFFECT SIMULATIONS

In earlier work of our team simulations were conducted and random collisions were generated at the receiver by generating two LoRa packets with time difference ($T_0 \leq \Delta T \leq T_{air}$). The first signal arrives at T_0 and second signal arrives after a random duration, within the T_{air} of the first packet. The transmission of an interfering packet can start at any time, and overlapping length ΔT of both packets varies randomly. The goal here is to identify under which power settings the collision detection and successful reception will work. In both cases, PRR is measured at the receiver, in simple steps as follows:

- Preamble detection: if preamble detection is valid, then it passes for sync word detection.
- Sync word detection: after the receiver detects the preamble it searches for the sync word and finds the starting of the header.
- Validation of Header and Payload: if header and payload data is not corrupted then it is considered as successful frame reception.

The packet structure used in these simulations is shown in Figure 2. The preamble consists on four up-chirps, two down-chirps and a quarter of an up-chirp. However, increase in preamble duration can improve the detection probability. An explicit header is used with a 2-byte CRC. The header is encoded with $CR = 4$. The payload is 20 bytes long, with no channel encoding $CR = 0$ and $SF = 8$. Channel coding is used to improve the reliability of the communication system by adding redundancy in the transmit data.

Figure 6 presents the capture results. The probability of successful reception is calculated with 1000 packets transmissions for each power setting on random overlapping lengths ΔT. The x-axis shows signal to interference power (SIR) and y-axis shows the probability

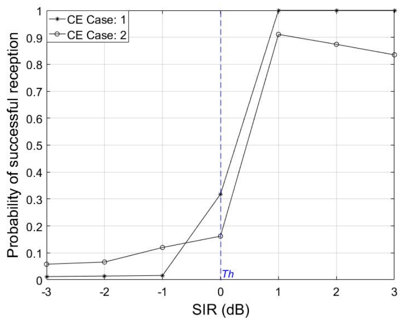

Figure 6: Capture Results with $SF = 8$, $CR = 0$ and $BW =$ 125kHz.

of successful reception with capture. Note that, we do not expect that the received power ordering is known a prior. From Figure 6 we can assume that if the received power difference between two interferers are around 1dB, the receiver can successfully decode the strong packet. Thus Eq. 3 can be expressed as:

$$SIR_X = \frac{P_X}{P_I} \geq 1\ dB \quad (4)$$

Successfully decoding one of the colliding packet can significantly increase the system throughput of any network. In the presence of CE, the total throughput of the system of N nodes can be expressed as:

$$\eta_{CE} = G \times [P(no\ collison) + P(collison) \sum_{i=1}^{G} P(SIR_i > Th)] \quad (5)$$

$P(no\ collison)$ and $P(collison)$ are probability of no collision and probability of collision at the receiver, respectively. Th is a threshold value set on signal to interferer i power ratio SIR_i of received signal.

In a pure ALOHA network, a node can successfully transmit a frame if no other node has a frame to transmit during two consecutive frame times (vulnerable time $2T_{air}$). The probability of a node having no frame to send is $(1-p)$. The probability that none among the rest of $N-1$ nodes have a frame to send will be $(1-p)^{N-1}$. The probability that none of the $N-1$ nodes have a frame to send during the vulnerable time is $(1-p)^{2(N-1)}$. Then the probability of being alone of a particular node will be: $P = p(1-p)^{2(N-1)}$.

4 EXPERIMENTATION SETTINGS AND RESULTS

In [6, 8], the authors experimentally proved the possibility of successful reception of concurrent transmissions using LoRa's modulation. They concluded that there are two important things to keep an eye on. First, the start time of the collision and second is the interfering signal strength. The authors concluded that when the RSSI from the interfering signal is same or lower than the signal being interfered, and that if the interfering transmission starts after the preamble of the transmission being interfered, then the interfered transmission will be received correctly. They found that to synchronize with a transmitting node, the receiver only needs 6 symbols of the preamble to be received without collision.

More detailed experimentations with very accurate timing has been performed in [8]. The authors also tested the case when the RSSI of the interfering transmission is higher at the receiver than the interfered transmission. They found that if the interfering transmission or interfering signal starts after the end of the preamble and header time, the transmission being interfered will be received with wrong payload CRC. However, in case the last six symbols of the transmitter's preamble can be received correctly, the receiver can synchronize with the transmitter and the reception can be successful. It is also important to note that the authors only used the 125-kHz channel bandwidth, and they think that additional experiments are required for other bandwidth channels.

In order to get accurate timing, authors in [8] experimented with devices placed close together and all connected to a timing unit. We performed additional experiments to get results in a real setting with more LoRa transmission parameters.

Capture Effect Setting

Our experimentation setting consists in 2 transmitters (1 master and 1 slave node) and 2 receivers (gateways) as depicted in Figure 7: the master node is at around 25 meters from the gateway and the slave node was placed at a distance of around 150 meters from the same gateway. Tests are performed outdoor in LoS conditions.

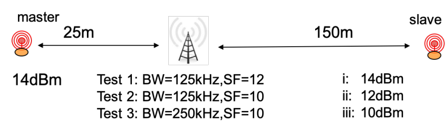

Figure 7: Experimentation setting

To synchronize the transmitter nodes, the master node continuously sends a message to the slave node. On receiving a message from the master, the slave acknowledges the reception of the message by sending an ack. The slave node synchronizes with the master's clock by taking the message reception time, and subtracting the ToA of the message from it. The master node on receiving the ack performs the same action: it takes the ToA of the ack and removes it from the time of reception of the ack, hence synchronizing with the slave clock. Once the nodes are synchronized, they start broadcasting a message every 25000ms. We switch on a LED at the beginning of a transmission to visually check that the nodes have successfully synchronized.

Once the nodes are synchronized, to analyze the capture effect, the nodes start transmitting at the same time. Then, every 10 messages we add a predefined delay at the slave node (the delay is approximately 1/8th of the ToA of the transmitted message): the first 10 messages (round 0) are sent at the same time by both nodes, the next 10 messages (round 1) are sent by the slave with a delay and so on. If t_master is the transmission time at the master, the slave will sent its message at $t_slave = t_master + r * delay$, where r is the round number. The delay is introduced after every 10 messages until there is no transmission overlap.

We tested 3 different LoRa settings by varying bandwidth *BW* and the spreading factor *SF*. We also performed the tests with different maximum power settings for each transmitting node. First with both the transmitters having the same maximum output power of 14dBm. Then we reduce the maximum output power of the slave node to 12dBm for the second test and 10dBm for the third test. Finally, we did a final test with both the transmitters having maximum output power of 10dBm. Code rate *CR* is kept same for all the experiments. Both transmitters have the same payload, which is 240 bytes, which will remain constant throughout the experiment. The master and slave nodes are Arduino Nano boards each equipped with a LoRa inAir9 radio module. All the communication took place at 868MHz frequency band. 2 gateways are used: one is an Arduino Nano with the same inAir9 radio module and one is a LoRaWAN RAK831 gateway with an SX1301 radio concentrator running a simple `util_pkt_logger` program.

Results Test 1

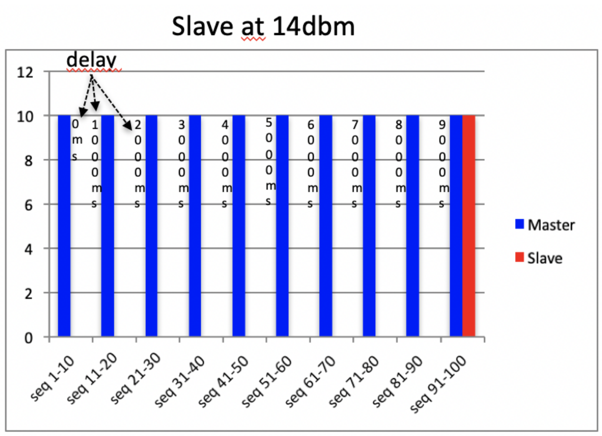

Figure 8: LoRa test 1 - Slave at 14dbm

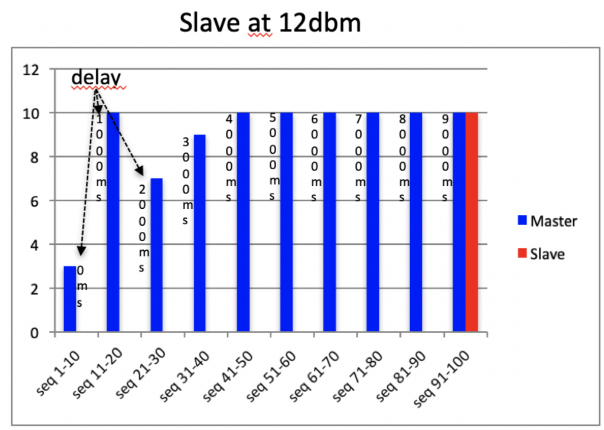

Figure 9: LoRa test 1 - Slave at 12dbm

Figure 10: LoRa test 1 - Slave at 10dbm

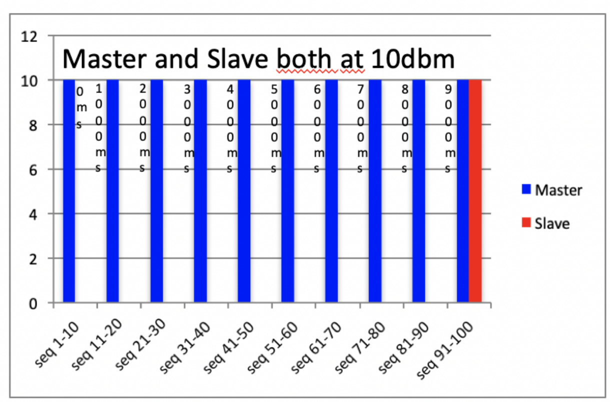

Figure 11: LoRa test 1 - Master and Slave at 10dbm

For first group of tests, we have *BW* set to 125kHz and *SF* to 12. For a payload of 240 bytes, the ToA is 8870 ms. The slave uses a delay increment of 1000ms every 10 messages. Figures 8, 9, 10 and 11 show the results when we put the slave node at 14dBm (same as master) then 12dBm and 10dBm. In these results we clearly see that we were able to receive most of the messages from the master hence proving the capture effect. When the slave reaches a cumulative delay of 9000ms, there is no overlap anymore and gateways receive from both transmitters.

Results Test 2

For second group of tests, *SF* is now 10 while *BW* remains at 125kHz. ToA is now 2206ms and the slave uses a delay increment of 300ms. Results are summarized in Figure 12, 13, 14, and 15 and they again confirm the capture effect as 89% of the messages were received.

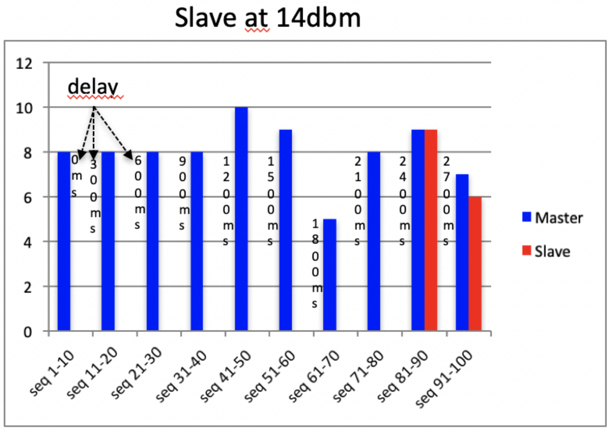

Figure 12: LoRa test 2 - Slave at 14dbm

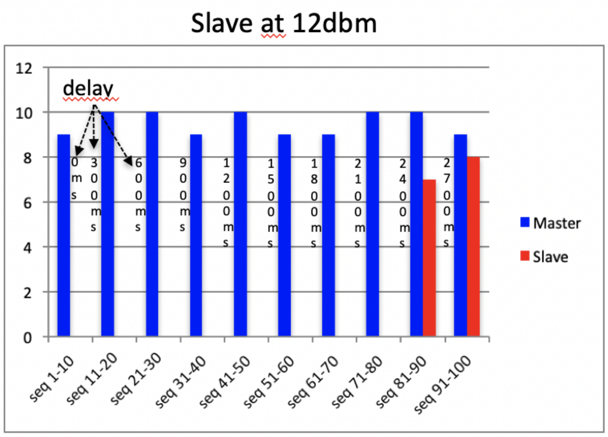

Figure 13: LoRa test 2 - Slave at 12dbm

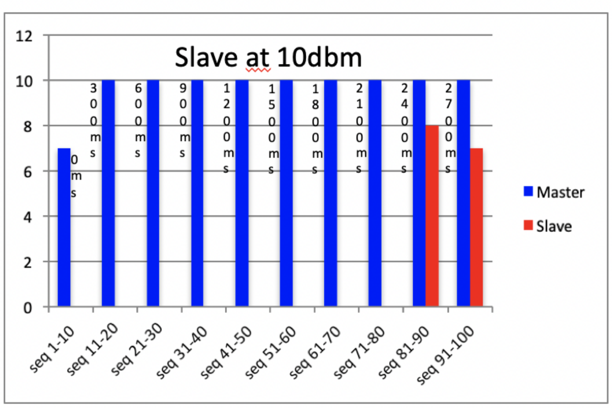

Figure 14: LoRa test 2 - Slave at 10dbm

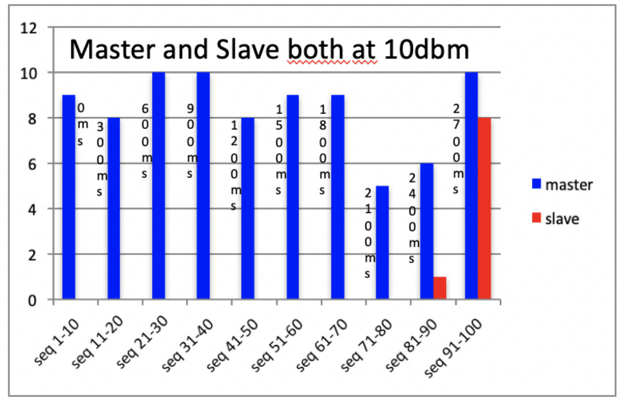

Figure 15: LoRa test 2 - Master and Slave at 10dbm

Results Test 3

For third group of tests, *BW* is now set to 250kHz and *SF* remains at 10. Toa is 1100ms and the slave uses a delay increment of 300ms. The results were found very similar to Test 1, with 94.5% of the messages received with no error.

Test in indoor conditions

We also performed the 3 previous described scenarios in indoor conditions. While the main results remain the same confirming the capture effect for the strongest and first transmitted messages, there are more instability in the results and no packets can be received in many cases.

CONCLUSIONS

In this article, we investigated the phenomenon of capture effect to see if we are able to recover some of the messages. We simulated and experimented on nodes in real world environment. The results confirmed that once two transmitters start transmitting in LoRa networks, it is possible that the receptors are able to receive the messages from one of the transmitters. A high percentage of messages were received in the outdoor conditions during our outdoor tests. The indoor tests probably have some other variables which come into play, e.g., deflective signals, which result in some instabilities in the results, and there are cases when many packets were completely lost. More research is needed in this regard to pinpoint the exact causes.

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