Ranging Capabilities of LoRa 2.4 GHz

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***Abstract*—Ranging is the act of measuring distance between two points. In this project, the aim was to determine the ranging capabilities of LoRa 2.4GHz and the optimal settings for the SX1280 transceiver, depending on the distance. This was done by carrying out three experiments. The first experiment was testing the number of ranging requests per packet. The study found that a higher number of requests yielded better results, although with diminishing returns. Thus, 100 requests per exchange were used for additional experiments. The second experiment tested the settings recommended by Semtech. It was found that the recommended settings, bandwidth 1.6MHz and spreading factor 6, could provide good ranging measurements at distances from 0-400m. The aim of the third and final experiment was to determine the optimal settings for ranging at different distances. It was found that the highest reliable bandwidth at a given distance combined with the lowest, reliable spreading factor, would be the optimal settings at a given distance. It was also discovered that the longest reliable range was somewhere between 1700m and 2500m. Therefore it is not recommended to use the SX1280 transceivers at distances above 1.7km with the transceiver configuration used in these experiments. It was found that LoRa SX1280 transceivers could accurately measure distances up to 1.7km with a difference in accuracy to the ground truth of at most 0.6%.**

I. Introduction

IoT devices and their different technologies are being used increasingly, with several billion IoT devices in use at the time of writing, and even more are expected to be in use in the years to come[1]. This makes IoT a crucial area where it's especially important to apply the appropriate technologies in different use cases to decrease cost, increase effectiveness, and limit the environmental impact of these devices and networks. LoRa in the 2.4GHz spectrum is discussed in this paper along with its ranging capabilities. LoRa is a physical layer technology using a proprietary modulation technique[2]. LoRa modulation is a version of Chirp Spread Spectrum modulation (CSS). The signals sent with CSS either increase (up-chirp) or decrease (down-chirp) in frequency over time. This increases the resistance to interference of the signal. LoRa also utilises Forward Error Correction, to further increase the robustness of the signal[3][2]. Ranging technologies are used in many applications, e.g., mapping of buildings, localisation indoors, Simultaneous Localisation and Mapping(SLAM), tracking applications, radio-controlled devices, etc[4]. LoRa 2.4GHz technology could prove to be a viable alternative solution to a range of these applications. This paper presents the results of some experiments testing the ranging performance of the SX1280 transceiver. The increased usage of IoT technologies and devices, as well as the expected growth of the number of theses devices, makes it vital for manufacturers and developers to apply the appropriate technology for their given use cases. Applications where distances between devices can vary from 0-1700m, LoRa 2.4GHz could provide a viable low power alternative to existing technologies in these areas such as WiFi, Bluetooth, GNSS, and ATLAS[5].LoRa fills a gap between current technologies, more specifically in applications where low power, long range, resistance to interference and ranging are priorities. More refinement of the SX1280 transceiver firmware is necessary if localisation should be implemented, since it would require trilateration calculations and several base stations in order to calculate the positions of devices. The highest power consumption of this transceiver is 8.2mA in high sensitivity receiving mode and 24mA in transmit mode[2][6]. The price and power consumption of the LoRa 2.4 GHz devices make them an attractive option when choosing a transceiver for communicating and ranging at distances below 1.7km. The Semtech SX1280 transceiver has several settings that impact the performance greatly e.g., spreading factor (SF), bandwidth (BW), number of ranging requests, etc. Therefore the optimal combination of these settings is crucial to explore in order to operate the transceivers optimally. Combinations of some of these settings have been tested and the results is a primary point of discussion in this paper. The experiment was carried out using the 'Outdoor Ranging Demo' function on the SX1280 transceivers, which were on the 1.6.1 version of the provided firmware. It should be noted that the BW and SF are limited in the ranging mode. For regular non-ranging communication the SX1280 can use BW 203, 406, 812, 1625kHz and SF5, 6, 7, 8,9, 10, 11, 12. However, in ranging mode, only SF5-10 and BW 400-1600kHz can be used. It should also be noted that the optimal settings might vary depending on application-specific priorities, e.g. if high accuracy is not necessary, it might be possible to decrease power consumption.

The SX1280 LoRa 2.4GHz transceivers implements *ranging*, i.e. measuring of distance between two transceivers. This is achieved by having the master transceiver send a ranging request to the slave. The slave will then synchronise itself to the signal, note that this process takes a fixed amount of time and is known by the master. The slave then sends a message back to the master. This process still leaves room for timing errors and clock frequency offset errors, which can impact the ranging calculation. This error is minimised by switching the roles of the master and slave, such that the error received from measurement master-slave will be reversed in the measurements of slave-master. The average of both these measurements is then calculated, which cancels the errors out. The calculation for the round trip time will therefore be

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$RTT = \frac{T\_slave-master+T\_master-slave}{2}$. In order to obtain even higher precision and accuracy, the temperature of the devices should be similar, as large temperature differences can result in a clock frequency offset[7].

Accuracy and *precision* are discussed in this paper according to their definitions[8].

II. Experimental setup

A. Experiment parameters and conditions

The experiments discussed in this paper, were carried out with the goal to determine the best combination of SF and BW, depending on the distance. The number of ranging requests per measurement was set to 100. As it was found from the first experiment, in which different numbers of ranging requests were tested at a single distance. From the results of this first experiment, 100 ranging requests was chosen as the setting[9]. The number of measurements per BW per SF per distance was 10, i.e., at each combination of these 3 parameters, 10 measurements were taken. The methodology behind the testing was that the combination of settings needed to be reliable, i.e. if 50 attempted measurements were taken at a certain combination of parameters, without a single successful measurement, that setting was considered too unreliable. The increase between distances in the final experiment was chosen from the results of the second experiment, which tested the maximum range of a single setting. The second experiment tested a single setting at different distances, in order to obtain the working range for a single setting. It was found that the working range of a setting is around 400m[9]. Therefore, for the third and final experiment, testing the optimal settings at given distances, increases of around 400-500m were chosen. However, it was not always possible to increase the distance with exactly this range, due to location availability. It should be noted that some other parameters might impact the measurements, such as temperature, humidity, rain, etc[10]. The humidity and temperature on the days of measurements are unknown, however it was not raining. The angles of the devices were pointing towards each other but the exact angles were not measured. The physical devices were held above the ground to avoid too much reflection. The ground truth of this experiment is the distance measured using Google Earth, any difference between the actual ground truth and the measured ground truth caused by the height difference between the devices is considered negligible. This is due to the relatively small size of these compared to the precision of the results since the locations of the master and slave generally had very little height difference. An example of this can be calculated from measurements where the slave was 6.64m above the master and 1135.7m away. The difference is $\sqrt{1135.7^2 + 6.64^2} = 1135.72$ i.e. 2cm difference at 1km.

B. Experiment plan and measurements

The distances for the measurements are found in Table II. All combinations of SF and BW were used to measure each individual distance. In essence, at each distance, a total of 180 measurements were taken. This was done to separate the settings, such that the impact of each individual setting could be investigated.

III. Results

The results from the third and final experiment are presented per distance, since there is not a single optimal combination of BW and SF that can optimally perform at all measured distances. The measurements at 100m will be used as an illustrative example in order to provide insight to the process of evaluating and finding the optimal setting at a single distance. In Fig.3, the results of the different settings at 100m can be seen. More specifically, the means of the 10 measurements per combination of settings are illustrated in Fig.3. The preference of a higher BW correlates with the theory of LoRa modulation, since $T_s = \frac{2^{SF}}{BW}$. From this formula it is seen that the symbol time T_s at constant SF, will be halved by doubling the BW, which in turn equates to double the transmission rate. Lower time on-air means that the signal and the receiver is less exposed to interference. The preference for higher BW is seen in Fig.3, which shows the absolute mean error of all the combinations of SF and BW at 100m, which is generally lower at BW 1600kHz. A lower SF generally seems preferable, this is due to the relationship between the symbol time T_s and the BW and SF, $T_s = \frac{2^{SF}}{BW}$. From this it is seen that an increase of SF by one, will double the symbol time, resulting in longer exposure to interference and reflections. The mean error provides some insight to the possible optimal setting at the measured distance. In order to further investigate the results, parameters of stability and standard deviation were also analysed. This analysis provides an enhanced understanding of the results and provides more developed arguments for a chosen optimal setting. However, tt should be noted that the optimal settings might vary depending on the use case, since lower BW and higher SF will result in higher transmission time and therefore require more power, which might be a deciding factor in a given use case. The optimal settings presented in this paper are based on accuracy, precision, and reliability being the important performance indicators. Accuracy is considered how close the measurements are to the ground truth, i.e., this can be quantified by the mean value. Precision is considered to be how close together the measurements are, i.e., the spread of the measurement values, which can be quantified by the standard deviation and the confidence interval of the measurements. Reliability, in this paper, is quantified as the number of successful measurements per number of attempted measurements. In this paper, these parameters are considered the key performance indicators for the combinations of settings.

Looking at the confidence intervals in Fig.1 and the standard deviations in Fig.2, the confidence intervals are observed to be smaller at higher BW. Likewise, the standard deviation are generally observed to be lower at higher BW.

Fig. 3 displays the absolute mean error for each combination of settings at 100m as well as the ground truth. This provides an overview of the accuracy of the settings, which gives insight to patterns in the results. BW 800kHz and SF5

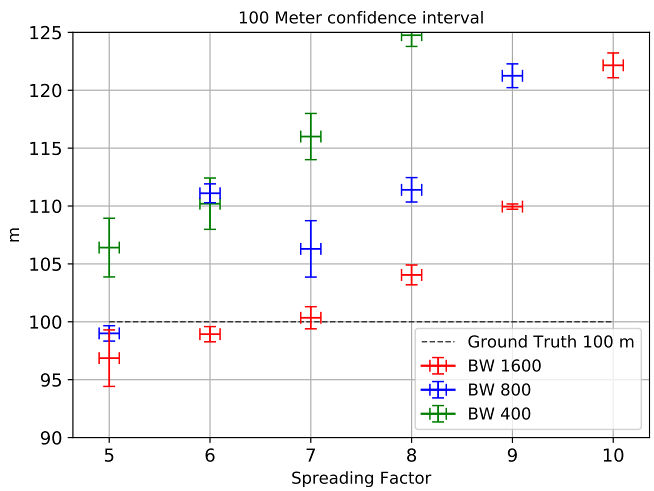

Fig. 1. 100m measurements confidence interval

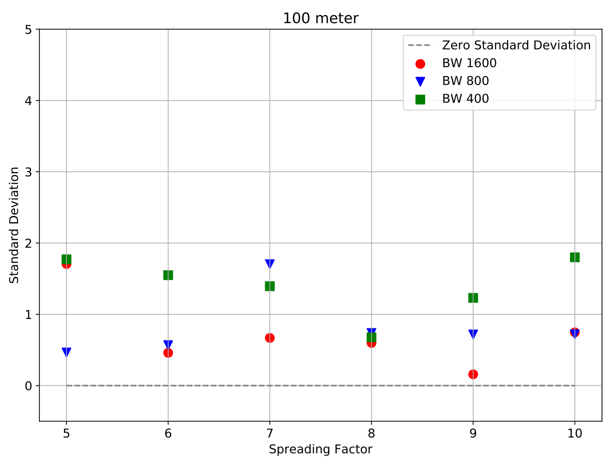

Fig. 2. 100m measurements standard deviation

or BW 1600kHz and SF7, are both possible candidates to being the optimal setting. However, further analysis needed to investigate the performance of these. From Table I, it is observed that BW 1600kHz and SF7 has a mean of 100.35 m, which is the most accurate combination of settings.

100m	400kHz	800kHz	1600kHz
SF5	106.41	99.00	96.86
SF6	110.20	110.10	98.93
SF7	116.00	106.30	100.35
SF8	124.75	111.40	104.05
SF9	145.75	121.25	109.95
SF10	182.23	143.71	122.15

TABLE I
100M MEAN VALUES

Considering the precision of the settings, both the standard deviation and the confidence interval are analysed. The standard deviations, presented in Fig.2, show BW 1600kHz as a suitable BW for this distance. The combination of BW 1600kHz and SF9 has the lowest standard deviation. From Table I it is seen that this combination is not adequately accurate. Considering the most accurate setting BW 1600kHz and SF7 in Fig.2, it is seen that it has a standard deviation of less than 0.75, considered adequately precise. Fig.1 shows that BW 1600kHz and SF7 is adequately accurate and precise. Most settings were observed to be reliable at 100m, with 10 successful measurements per 10 attempted measurements. At BW 400kHz and SF10, 10 succesful measurements were gathered from 150 attempted measurements, meaning that that specific combination of settings is not considered reliable at the tested distance of 100m.

Considering these findings, BW 1600kHz and SF7 is found to be the optimal setting for measurements at 100m. This analysis process was repeated for all distances. The findings of these analysis are presented in in Table II, which contains the optimal setting, along with the calculated link budget, confidence interval and mean difference from ground truth in percent, for each optimal setting. The link budget was calculated using the SX1280 calculator[11]. The link budget is used to illustrate the correlation between link budget and distance. The link budget helps illustrate the pattern that longer distances require higher link budgets and vice versa, that a higher link budget allows longer range communication.

The results of the experiment which measured each distance using all combinations of BW and SF are presented from in Table II The application of the previously described method to the results in Table II led to the findings of the optimal setting at each measured distance. The Table II displays the optimal BW and SF combination for a given distance, along with the calculated link budget for these settings. Furthermore, the mean and 95% confidence interval are included, since these describe the accuracy and precision of the chosen optimal settings. The percent wise difference between the ground truth and the mean is also included, showing the relative accuracy of the measurements. It should be noted that the transceivers are not considered reliable above 1.7km, since at 2.6km the number of attempted measurements required to achieve 10 successful measurements were at minimum 100. The accuracy at 2.6km varied from the ground truth with 3.67%. Looking at only the distances, which the SX1280 can be considered reliable, i.e. all distances except 2.6km, the accuracy of the measurements vary from the ground truth with at most 0.56%.

IV. Discussion

Operating in the 2.4GHz spectrum usually means interference and noise, since this frequency band is populated by several technologies such as WiFi and Bluetooth. Despite of this, LoRa is able to function in this spectrum, due to its interference and noise tolerances. These tolerances are due to the characteristics of LoRa modulation since it incorporates chirp spread spectrum modulation (CSS) and forward error correction (FEC) with interleaving. This makes it possible to correctly receive signals with negative Signal to Noise Ratio

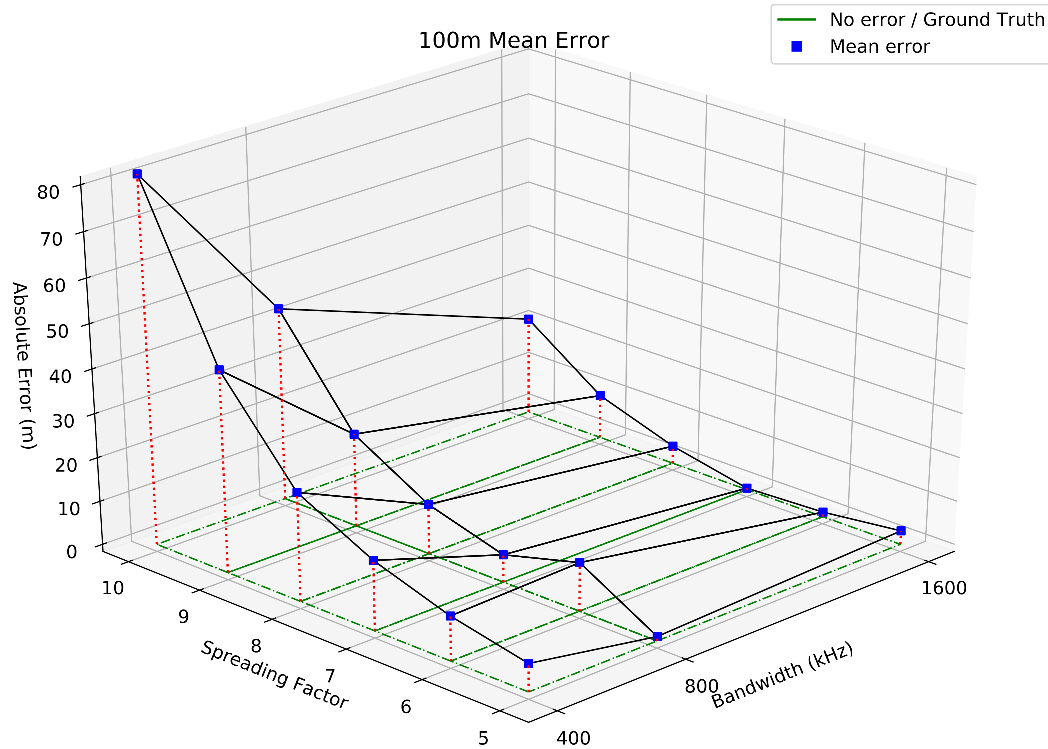

Fig. 3. Absolute mean error of combinations of BW and SFat 100m

Distance	BW	SF	Link Budget	Mean	Confidence Interval 95%	Mean % difference from ground truth
25m	1.6MHz	7	118.5dB	25.14m	24.86m - 25.42m	0.56%
100m	1.6MHz	7	118.5dB	100.35m	99.87m - 100.83m	0.35%
511.5m	1.6MHz	7	118.5dB	512.34m	511.48m - 513.20m	0.16%
1135.7m	400kHz	6	122.5dB	1135.10m	1132.78m - 1137.42m	0.05%
1693.6m	800kHz	8	127.5dB	1688.70m	1685.98m - 1691.42m	0.29%
2608.3m	400kHz	10	134.5dB	2512.50m	2506.62m - 2518.38m	3.67%

TABLE II
OPTIMAL SETTINGS WITH THEIR RESPECTIVE MEANS AND CONFIDENCE INTERVAL

(SNR) i.e., signals can be received below the ground noise or while stronger interfering signals are being sent[3]. This is an advantage, since the 2.4GHz spectrum is highly populated. For this reason, LoRa 2.4GHz can be used in applications where there already is a lot of interference. Choosing LoRa 2.4GHz in such a scenario can decrease the interference and noise compared to a WiFi or Bluetooth solution and ensure a reliable connection. Furthermore, the range of LoRa 2.4GHz makes the requirement for number of base stations low. For example, LoRa 2.4GHz could be used in the car industry to measure ranges to other vehicles, buildings, lights, etc. LoRa 2.4 GHz could also be used in automated factories by robots for mapping and localisation purposes. It is also a possibility to use LoRa 2.4 GHz in agricultural applications such as animal tracking.

In order for LoRa to be used for localisation purposes, a localisation algorithm would need to be implemented as this is not included by default in the standard or in the SX1280 transceivers. This could be achieved by utilising the ranging of the SX1280 and performing trilateration calculations. LoRa 2.4GHz technology and its features make it an interesting prospect in the field of IoT technologies. LoRa 2.4GHz could be an interesting option for indoor tracking applications and SLAM (Simultaneous Localisation And Mapping) technologies. However, to get high resolution maps or highly accurate distance measurements, e.g., for automated robots in factories, LoRa 2.4GHz could be combined with a near field technology to ensure high accuracy. LoRa 2.4GHz could be combined with e.g., an ultrasound sensor or RFID tags, further enhancing accuracy at shorter ranges.

The features of LoRa 2.4GHz are summarised in Table III, which highlight the main features of LoRa 2.4 GHz. Considering these features, LoRa 2.4 GHz is a technology applicable in use cases where high BW (>250kbps), low latency ($\sim$1ms), or mm accuracy is required. LoRa 2.4GHz can have quite high latency due to the time on-air of LoRa 2.4GHz packets easily which can exceed several ms. The time on air can be calculated using the SX1280 calculator[11]. This leaves LoRa 2.4GHz as a viable option in applications where long range ($\sim$1km cell size) is desired or there already is a lot of interference in the 2.4GHz spectrum, since LoRa 2.4 GHz has resistance to interference and noise. Since LoRa 2.4 GHz signals can be received below the noise floor, it could also be used for secretive communication e.g., in military applications. The findings about LoRa 2.4GHz technology can be found in Table III

Feature:	**LoRa 2.4GHz**
Operating frequency:	2.4GHz
Throughput (theoretical max):	250kbps
Ranging (max):	1700m
Signal BW:	200 - 1600kHz
Frequency band regulations:	Unlicensed
Ranging method:	Time of flight and RTT
Modulation:	Chirp Spread Spectrum
Power Consumption max (transmit):	24mA
Power Consumption max (receiving):	8.2mA
Price:	$\sim$ 7 USD

TABLE III
LoRa 2.4GHz feature set[6]

V. Conclusion

From the results and the analysis of these, it was found that the optimal settings correlates with the link budget. However, a higher SF is not necessarily the preferred setting, even though it theoretically offers the best measurements. From the results, it is seen that the SF rises as the distance is increased, and the BW decreases. From the results, a ”sweet spot” seems to appear for the SF at most distances, this is presented in Fig.3. The findings discussed in this paper are summarised in Table II. The maximal reliable distance that the SX1280 LoRa 2.4 GHz transceiver can measure distance is around 1.7km, which makes it an interesting technology for many ranging applications. Examples of ranging applications could be maritime ranging for autonomous sailing, where the ship could have LoRa 2.4 GHz transceivers in order to measure distances to docks, nearby ships etc. Another example of a ranging application could be smart traffic lights which could use LoRa 2.4 GHz transceivers to measure distances to cars and optimise traffic flow by minimising the number of cars waiting at the traffic light.

The low power consumption, the noise, and interference resistance of LoRa modulation are valuable features in many IoT applications. In applications where battery size is limited, long range is needed, or a high presence of noise, the LoRa 2.4 GHz ranging technology could be a valuable asset.

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