Evaluation of LoRaWAN's Static and Dynamic Capabilities and its Limitations for IoT Applications

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Abstract: This paper is a study of connection parameters of Long Range Wide Area Networks (LoRaWAN) for reliable and robust data communication. It also seeks to highlight the limitations and shortcomings of the LoRaWAN technology, with the goal of identifying areas for improvement. The primary goal is to investigate how particular network parameters affect communication and message transmission. The experimental setup consists of a gateway and two end nodes. The maximum range between the end device and the gateway was tested in a free field in which a stable communication is possible. Furthermore, the connection between the gateway and the endpoints was evaluated at various movement speeds. Additionally examined in a laboratory environment were the roundtrip time, the uplink, delay and downlink, and the received signal strength indicator according to the used transmission power, packet size and the spreading factor. The maximum packet sizes for each spreading factor were also tested.

1 INTRODUCTION

One of the currently widespread Low Power Wide Area Network (LPWAN) technologies is LoRaWAN (Long Range Wide Area Network). A LoRaWAN-enabled end device is a sensor or actuator that is wirelessly connected to a LoRaWAN infrastructure network using radio gateways [1]. All of the data gathered by the end devices is transmitted through the low power LoRaWAN network to a listening gateway, where it is then sent to the network server and the application server [2]. The aim of this investigation was to explore the possibilities of expanding possible areas for the use of wireless communication channels in industrial environments based on the LoRaWAN technology. To achieve this goal, the Round-Trip Time (RTT) was measured, which is the sum of the time it takes for a data packet to be delivered or uplink time and for its acknowledgment to be received or downlink time together with the delay [3] in dependence of various transmission parameters used for data transmission. he achievable range, which is the distance between gateway and the end device, as well as the Received Signal Strength Indicator (RSSI), which is the relative quality of a received signal to a client device [4] were also measured.

2 STATE OF THE ART

There are several areas in which LoRaWAN technology can be used, such as: metre reading, street lighting, smart buildings, smart parking, cargo tracking, water leakage detection, water level monitoring, alerting about the occurrence of emergency situations, traffic management, smart energy systems, waste management, smoke detection, etc.

Modern LoRaWAN technology has experienced rapid development in recent years. Numerous studies have been conducted to investigate the characteristics and performance of LoRaWAN technology [5, 6]. In this article, the operation range and packet loss rate have been tested by the authors using experimental measurements, but they have not investigated how parameter settings affect network performance of LoRaWAN.

Without changing complex network setups, the study in [7] examines the impact of modulation parameters on the connection between the end device and its gateway. The authors in [8] use a stochastic geometry model to obtain more trustworthy results. This allows the simultaneous study of time interference and frequency domain. It is found that the packet replay approach reduces the probability of failure while increasing redundancy, resulting in a decrease in average throughput.

The best combination of SFs to reduce the probability of frame overlap was determined in [9]. In addition, they have set up a plan to increase uniformity for endpoints that are far from the gateway by assigning the ideal SF value and increasing the transmission power across the endpoints to reduce packet error rates.

3 EXPERIMENTAL SETUP AND MEASUREMENT RESULTS

Two end devices and a gateway have been used in the experiments conducted in this research. The uplink, downlink, and round-trip duration were all evaluated using a LoRa Shield end-device as given in section 3.1. The end-device and the gateway were 10 metres apart during the laboratory testing for these measurements. The second group of measurements have been done in a free field with the second end-device and the gateway positioned also in a free field. So it shall be possible to see how the technology operates in a real-world environment and identify the dependencies between the parameters through testing in the laboratory. Measurements in the field made it possible to estimate the maximum distance at which a stable message exchange can be operated and how the distance between the gateway and the end device affects the transmission time.

3.1 Measurements of the Uplink, Downlink and Round Trip Time

For measurements in the laboratory, the MultiTech gateway [10] and an end-device based on Arduino UNO [11] and LoRa Shield [12] have been used. A host with the Ubuntu 20.04 operating system on which The Things Stack [13] was installed, was connected to the gateway. The end-device was connected to another laptop on which it was possible to see and collect information about uplink, downlink and RTT times using the Arduino IDE terminal. The settings of the end-device, namely the *size* of the transmitted packet, *transmission power* and *spreading factor* (SF) have been changed and performance parameters with different sets of those parameters have been measured.

3.1.1 Impact of the Transmission Power

In this section, the test results for round-trip time, and uplink/downlink transmission time changes, based on variations in transmission power are described. Four measurement sets have been performed with different transmission power on the LoRa Shield end-device. In all four cases, the end device sent 13-byte messages present an empty message with LoRaWAN service information attached [14]. In all cases, the device was located in the laboratory and the environmental conditions did not change. For these tests, only a spreading factor of 7 and a bandwidth of 125 kHz were used. The impact of power variation on the transmission time was investigated using transmit powers of 5, 10, and 14 dBm.

As expected, the performance parameter differences in this group of measurements in the laboratory are not noticeable, but during the measurement one message was missed and the spreading factor value was automatically changed to 8. Before switching to SF8, the message skips the first downlink window and then, after one second delay, the second downlink window. Figure 1 shows a spike in the measured time. This is due to the fact that the message transmission time for SF8 is longer.

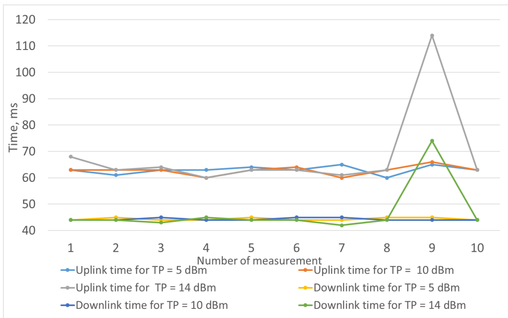

Figure 1: The relationship between uplink/downlink time and transmission power.

Also during the RTT measurement there were small changes, the graph behaves similarly to the uplink and downlink time graph at Figure 2. The message was sent again using SF8, adding extra time. The RTT measurements and the time jump is shown in Figure 2. During the tests in the laboratory, it was concluded that the transmission power does not affect the uplink, downlink time and RTT parameters.

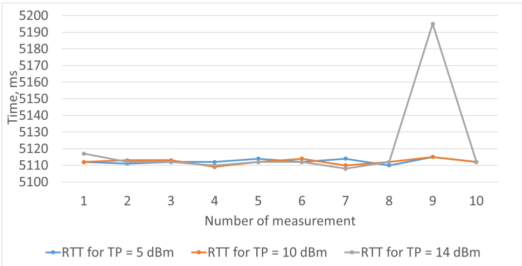

Figure 2: The relationship between RTT and transmission power.

3.1.2 Variation of Packet Size

In this part of the measurements, the *message size* has varied. The tests have been performed for three different message sizes from minimal to maximal possible sizes:- 13, 25 and 50 bytes which work with all spreading factors. These values were chosen to reveal the dependence of round-trip time on message size. Only a spreading factor of 7 and a bandwidth of 125 kHz were employed for these tests. The maximum permitted transmission power in the European Union, 14 dBm, was selected [15]. Increasing the packet size affected the message transmission time as expected. Values such as uplink time and RTT have increased. Figure 3 shows the dependence of uplink time on the packet size. It can be concluded that the time will increase in direct proportion to the packet size.

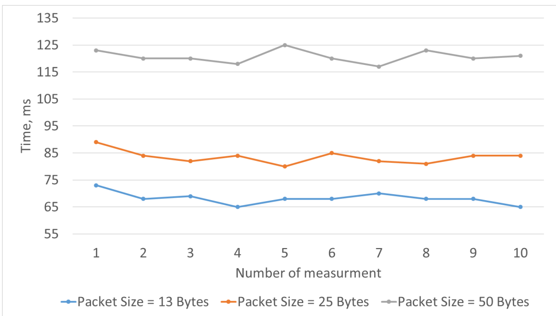

Figure 3: The relationship between uplink time and packet size.

The downlink time is unaffected by increasing the packet size since the acknowledgment packet's size is constant - 14 Bytes and independent of the transmitted packet size. downlink time ranges from 44 ms to 47 ms.

Although the difference in round-trip times between the three groups is small, it is noticeable, and as the size of the packet increases, the time gap tends to grow. A graphic in Figure 4 illustrates the measured data for better visualisation. Depending on the message that has to be transmitted to the gateway, the end node's data packet size may change when sending data. The results indicate that changes in packet sizes have no impact on message interference and collisions since there are relatively few messages.

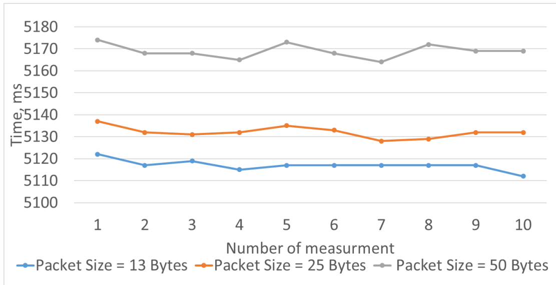

Figure 4: The relationship between RTT and packet size.

3.1.3 Variation of Spreading Factor

In this phase, there are six groups of measurements in which only the spreading factor is changed and all of the other parameters remain the same.

There is no doubt about the discrepancies between the six categories of measurements. The higher the spreading factor, the more time it takes for the message to reach the gateway and for an acknowledgment to be received by the end node. The uplink/downlink time measurements for the first four groups for spread factors 7, 8, 9 and 10 are closer to each other, compared to the measurements done on the last two groups for spreading factors 11 and 12. The last two groups of measurements show a significant increase in uplink/downlink time. This is because each spreading factor is associated with bits per second. For better visualisation the results are illustrated in Figure 5.

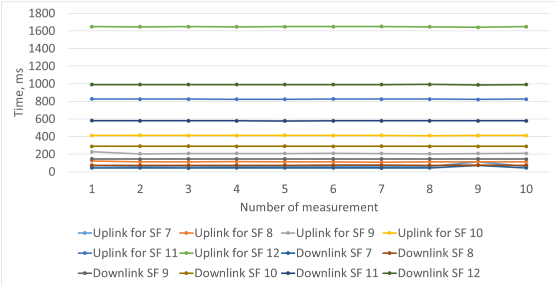

Figure 5: The relationship between uplink/downlink time and spreading factor.

For RTT the situation is similar to the uplink time measurements. The RTT significantly increases for the last two groups of measurements. The results are presented in Figure 6. The spreading factor affects the time of message transmission. By changing the spreading factor the transmission time of one symbol changes. The spreading factor affects the range of signal transmission. More details about this are described in paragraph 3.2.2.

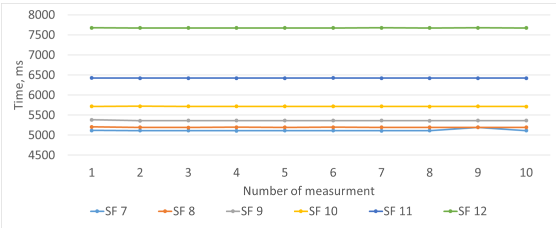

Figure 6: The relationship between round-trip time and spreading factor.

3.1.4 Variation of Spreading Factor with Respective Maximum Packet Size

The last group of laboratory tests were conducted to elaborate how other characteristics would change when the maximum message size is transmitted with different spreading factors. In these tests, the message size was maximally increased. Tests were performed for six different message sizes for all spreading factors. For spreading factors 7 and 8 a maximum message size of 248 bytes can be sent, which is 13 bytes more compared to the theoretical value of 235 bytes. But for SF 9 till 12 it was only possible to transmit a message less than the theoretical maximum value [16]. Maximum message sizes for spreading factor 9 till 12 of 113, 60, 57, 57 bytes can be sent, which is less compared to the theoretical values of 128, 64, 64, 64 bytes for each spreading factor respectively. For these tests, a bandwidth of 125 kHz and a transmission power 14 dBm were used since this is the maximum permitted power in that band for Europe. The maximum allowed transmission power for LoRaWAN for Europe is 14 dBm.

It is easy to see how the six measurement groups differ from each other. The larger the SF and the packet size are, the longer it takes for the message to reach the gateway and for the end-node to receive an acknowledgment. It can also be noticed that the transmission time at SF 8 and SF 10 look the same due to the fact that the message size was decreased. The results are shown in Figure 7.

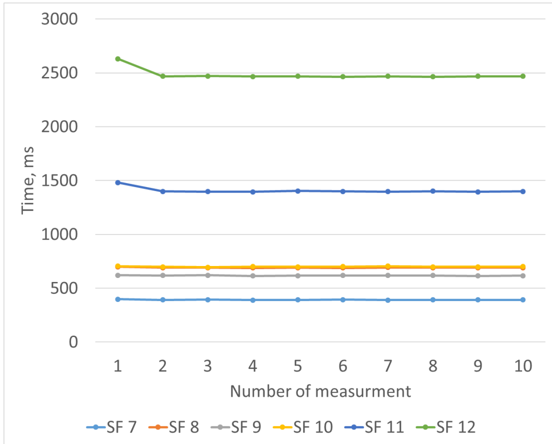

Figure 7: The relationship between uplink time and maximum packet size.

Because of the corresponding bits per second, the time needed for the last two groups increases drastically. A graph in Figure 8 illustrates the data.

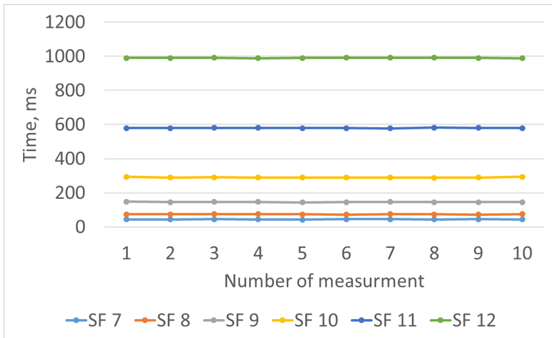

Figure 8: The relationship between downlink time and maximum packet size.

For RTT, the measurements are similar to the uplink time measurements. The difference between the transmission times at SF 8 and SF 9 is essentially undetectable. This is because when the message size and SF were dropped, the uplink time decreased but the downlink time increased, practically causing the RTT to remain unchanged. The results are presented in Figure 9.

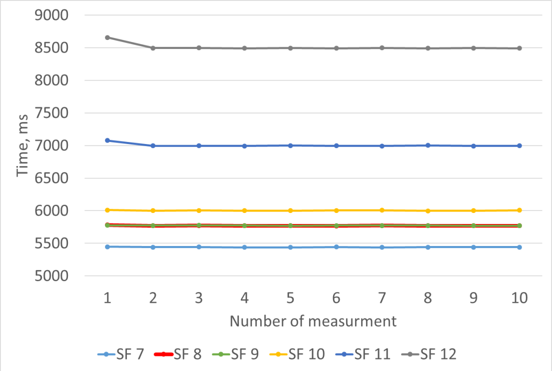

Figure 9: The relationship between round-trip time and maximum packet size.

3.2 Static Measurements of the Range in Free Field

Figure 10 shows the experimental setup used in this cycle of measurements. The gateway was placed on top of a 2.2 metre stick in order to maximise the range. The LoRa/GPS Shield was driven in a vehicle.

Figure 10: Free field device setup.

The end-device was plugged into a power bank and was being driven in a vehicle. A couple of car stops were chosen for all of the measurements. In each measurement series, the car stopped at nearly the same positions so the end-device can try to establish a connection with the gateway. Every 40 seconds, the end-device was sending LoRa signals that contained the end-device's most recent GPS coordinates. When the transmission power and spreading factor were changed, the behaviour of the range was observed. Only one parameter was altered at a time in each of these free field experiments, and the link between that parameter and the range may be seen below.

The gateway had two positions, chosen because of their higher ground compared to the surrounding area. The first position was on a small hill with free fields in front of it. The second position was on a higher hill compared to the first one. The only disadvantage of the second position was a couple of trees closely located to the gateway which were causing some link budget damage. There were a couple of small villages between the gateway and the end-device in some positions of the measurements, but because of their lower altitude they were not decreasing the link budget. The topology is explained in detail below, and can be seen in Figure 13 and Figure 16.

The range evaluation highly depends on the propagation environment. According to a LoRaWAN free field range calculator [17], if the gateway is placed on a position with a height of 30 metres and the end-device has a height of 1 metre, a range of 11100 metres should be possible for establishing communication between the gateway and the end-device.

3.2.1 Variation of the Transmission Power for the Static Measurements

The testing for the range's behaviour in relation to transmission power is covered in this section. Four measurements were conducted utilising four different transmission powers for the LoRa/GPS shield end device. In each of the four instances, the end-device was communicating with the gateway using 32-byte messages that contained the end-device's GPS coordinates. Since the device was always moved in the same direction, the environment wasn't radically changed. Only a spreading factor of 7 and a bandwidth of 125 kHz were employed for these tests.

The differences in the distances are clearly noticeable. Longer distances can be covered between the end device and the gateway for data transmission as the transmission power is increased. Figure 11 displays the greatest distances that were achieved. When comparing the urban environment results from the paper [18] and the measurements done in the free field, shown in Figure 8, a clear increase in the range can be noticed. This is due to the number of objects in the Fresnel zone. A maximum range of 6700 metres between the end device and the gateway was achieved in which data transfer is possible.

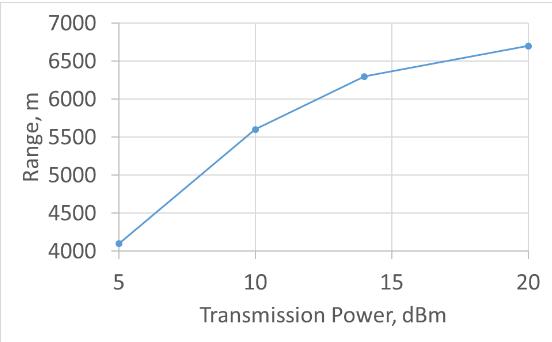

Figure 11: The relationship between the range and the transmission power in a free field.

In all these measurements the behaviour of the range according to the transmission power, the RSSI levels were also measured and noted. The chart in Figure 12 clearly shows the differences in the RSSI levels when the transmission power is changed. On each chosen car stop, the gateway receives a better signal when using a greater transmission power.

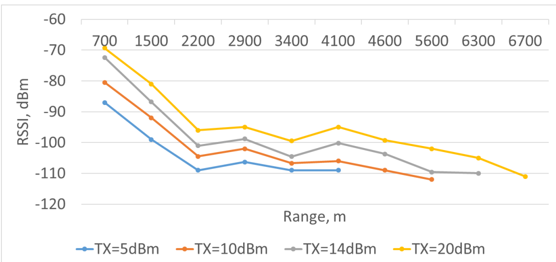

Figure 12: The RSSI levels when measuring the range with changing the transmission power in a free field.

The biggest distances reached with each tested transmission power are shown on the map in Figure 13. The gateway is represented with a red dot and the four biggest distances achieved with each transmission power are represented with blue dots. The gateway is located at an altitude of 94 metres. Additionally, it was placed on top of a 2.2 metres stick. This is beneficial for establishing better communication. The blue dots TX5, TX10, TX14 and TX20 which represent the last seen position of the gateway when using a transmission power of 5, 10, 14 and 20 dBm have an altitude of 75, 71, 73 and 70 respectively. The terrain between the gateway and TX5 has a low altitude dropping to 73 metres. Also, the terrain between the gateway and TX10 has a low altitude dropping to 61 metres. This is good for stable communication between the devices. The field between the gateway and TX14 has a lower altitude than the points at which the devices are loaded, dropping to 61 metres. In the middle between TX20 and the gateway there is a higher ground with an altitude of 73 metres compared to the position of TX20. This should not be a problem because of the higher altitude at which the gateway is located.

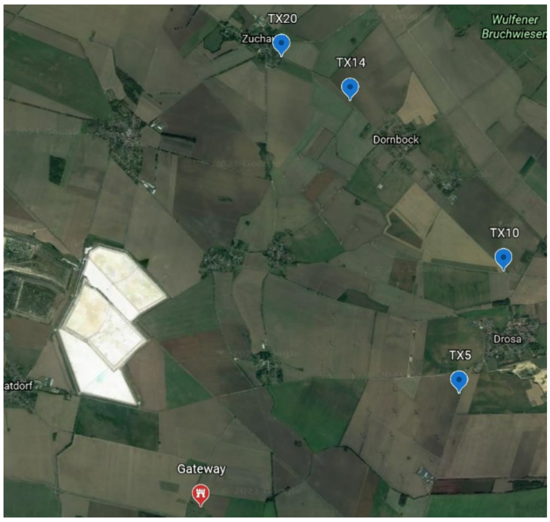

Figure 13: Map of static free field measurement of the range when changing the transmission power.

3.2.2 Variation of the Spreading Factor for the Static Measurements

Using spreading factors of 7 to 12, which correspond to data rates of 5469, 3125, 1758, 977, 537, and 293 bps, respectively, the behaviour of the range is investigated in this cycle of measurements. Only a transmission power of 14 dBm and a bandwidth of 125 kHz were employed for these experiments.

Figure 14 displays the biggest distances that were achieved on different spreading factors at which data transmission can be established between the end-device and the gateway. Data can be sent across bigger distances with raised spreading factors. So, in this cycle of measurements, a maximum range of 10950 metres was achieved with the spreading factor 12. When comparing the urban environment results from the paper [18] and the measurements done in the free field, shown in Figure 10, a clear increase in the range can be noticed.

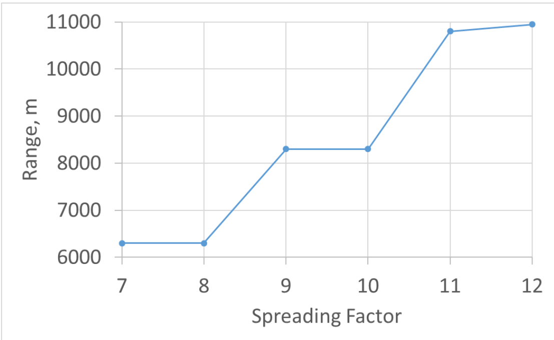

Figure 14: The relationship between the range and the spreading factor in a free field.

In all of these measurements of the behaviour of the range when varying the spreading factor, the RSSI levels of the received signals were also measured and noted. The chart in Figure 15 shows the RSSI level of each received signal when measuring the range. A clear decrease of the RSSI levels can be observed in the tendency with each increasing of the distance. However, there are a few points where RSSI is rising even on raised distance. This is because of the better line of sight in that particular position where the end device was located when transmitting the message.

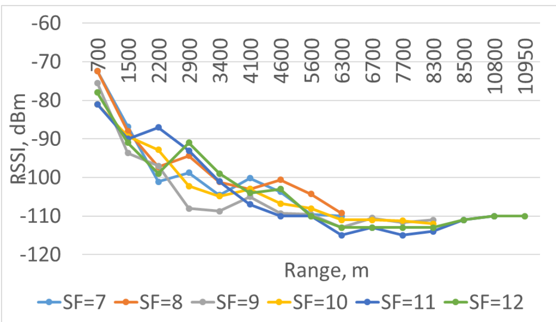

Figure 15: The RSSI levels when measuring the range with changing the spreading factor in a free field.

The biggest distances reached with each spreading factor are shown by the map on Figure 16. The first position of the gateway is again represented with a red dot, the second position with a yellow dot and all of the biggest achieved distances for each spreading factor is represented with a blue dot. The biggest ranges for the spreading factors 7, 8, 9 and 10 were measured when the gateway was located in the first position. Then the position of the gateway was changed and it was placed in the second position represented by the yellow dot. The biggest ranges for the spreading factors 11 and 12 were measured when the gateway was located in the second position.

The first position of the gateway has an altitude of 94 metres, and the second an altitude of 104 metres. Additionally to this, a 2.2 metres stick was used for the gateway. The points were specially selected because of their higher ground compared to the surrounding area. Dots SF7 and SF8 represent the last position of the end device when using a spreading factor of 7 and 8 have an altitude of 73 metres. The dots SF9, SF10, SF11 and SF12 representing the last seen position of the end device when using a spreading factor of 9, 10, 11 and 12 have an altitude of 69 metres. The altitude of the terrain between the dots SF7, SF8 and the first position of the gateway is lower than the altitude of their positions, with a minimum of 61 metres. There are two small villages in between SF9, SF10 and the first position of the gateway. The first village has an altitude of 63 metres and the second an altitude of 61 metres. The end device at dots SF9 and SF10 had an altitude of 63 metres. This can cause some link budget loss, but because of the height at which the gateway was located there with a line of sight. The altitude of the field between SF11 and the second position of the gateway reaches a maximum of 75 metres and the signal passes through one small village. The village has an altitude of 61 metres. The messages reach the gateway because of its higher position. The biggest accomplished range with this measurement was with spreading factor 12 and transmission power 14 dBm. The device was last seen at the position SF12. The altitude of the terrain between the second position of the gateway and SF12 reaches a maximum of 77 metres.

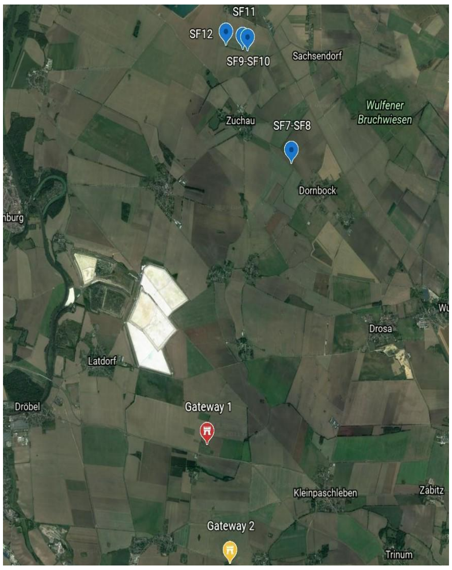

Figure 16: Map of static free field measurements of the range when changing the spreading factor.

3.3 Dynamic Measurements in Free Field

For the dynamic free field measurements, the LoRa/GPS shield end device was programmed to send messages every 20 seconds to the gateway. A 2.5 km straight road was chosen, so the car can reach the desired speed. The end device was located in a car, driven with speeds of 20, 50, 100 km/h respectively. The multitech gateway was placed at a height of 2.2 metre, in the middle of the road. The road together with the placement of the devices can be seen in Figure 17.

Figure 17. Map of the dynamic free field measurements.

3.3.1 Dynamic Measurements of the RSSI at Different Speeds

The RSSI behaviour was observed throughout this test cycle at selected speeds. The end device was communicating with the gateway in each case with 13 Bytes of data. Only a 14 dBm transmission power, a spreading factor of 7, and a 125 kHz bandwidth were used for these testing.

As shown in Figure 17 the car was following the road depicted by the yellow line. The gateway was placed in the middle of the route described by the red pointer. The end device was turned on for each group of measurements at the beginning of the road and switched off at the end.

Depending on the speed of the car, the end device reached the closest point to the gateway at a different moment. This is depicted with the peak of the three groups of measurements, shown in Figure 18. It can be clearly seen how the car started at a position that is further away from the gateway, came close to it and again moved away.

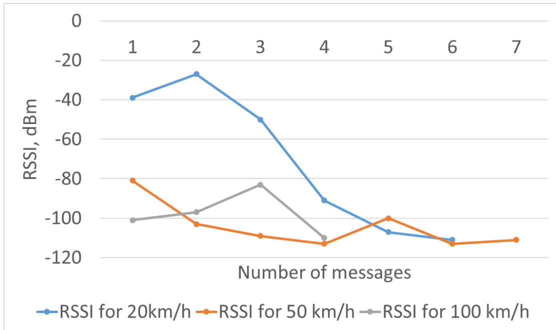

Figure 18. Dynamic measurements of the RSSI at different speeds.

3.3.2 Variation of the Transmission Power for the Dynamic Measurements

The tests for the behaviour of the RSSI according to the transmission power of 5, 10, and 14 dBm are covered in this section. Three measurements were made using three different transmission powers for the LoRa shield end device. In each of the three instances, the end device was communicating with the gateway using 13 Bytes of data. Only a spreading factor of 7 and a bandwidth of 125 kHz were employed for these testing. This cycle of measurements was only done with a constant speed of 100 km/h.

Figure 19 shows the RSSI levels while varying the transmission power. Because the starting point was the same for the three groups of measurements it can be clearly seen that the first message has a lower RSSI level compared to the other two. This is because of the lower used transmission power. When comparing the first messages for the other two groups, it can be seen that their RSSI levels are very close to each other. This can be caused by a change in the fresnel zone in that particular moment, compared to the other two groups, or by a slight change at the starting position of the end device.

Three peaks can be again spotted, depicting the message sent when the end device was at the closest position compared to the other messages in the same group. It can be seen that the end device in the first group of measurements, represented with the blue line in Figure 19, disconnects after reaching the peak. This is caused by the small transmission power of 5 dBm.

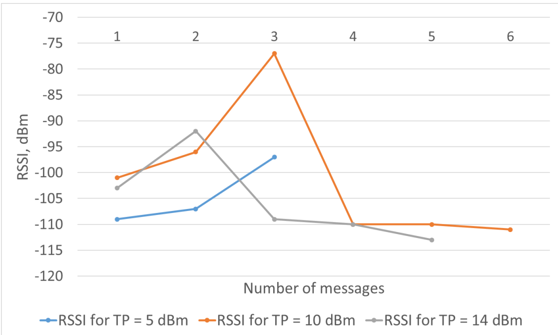

Figure 19. Dynamic measurements of the RSSI while varying the transmission power.

4 CONCLUSION

The advancements in the *IoT* field impose higher requirements for technologies that can provide long range and consume less energy. *LoRaWAN* is a good alternative to the technology of sensors and actuators that need to send and receive their data over long distances and don't require a lot of power.

The main goal of the paper is to evaluate the static and dynamic capabilities of LoRaWAN. The limitations of this technology were also tested in order to determine the best use cases for future IoT applications. The behaviour of the delay, uplink, downlink and round-trip time were tested according to the used transmission power, packet size and spreading factor. The maximum packet sizes were also tested for each spreading factor. This paper seeks to highlight the limitations and shortcomings of the LoRaWAN technology, with the goal of identifying areas for improvement.

With the help of the measurements a future user of the LoRaWAN technology can understand the influence of each parameter when changed, and its impact on the occupation of the channel and the time on air when creating a LoRaWAN end device for IoT applications. This knowledge should be implemented when following the strict limitations of the fair use policy [19].

The fair use policy limits the capabilities and use cases of LoRaWAN. For an actuator working as a Class C end device, the limitation of 10 downlink messages is strict. The uplink message policy is also very limited. In order to increase the applicability of LoRaWAN, the fair use policy should be modified. For limiting the data collision another method should be implemented. The devices should be also able to transmit the same message a couple of times, shortly separated known as time diversity and on different frequencies or frequency diversity. A third method, space diversity, or using a couple of antennas at a distance from each other can be also applied in order to ensure that the message reaches the gateway. In order to save the battery life of the end device, the space diversity should be implemented on the gateway.

LoRaWAN technology has a lot of potential applications where data needs to be collected. According to the results of the urban field tests conducted in [18], data transfer is feasible across short distances when necessary due to the presence of a large number of end devices. This will prevent the devices from interfering with one another and reduce the likelihood of data collision. The range can be restricted by lowering the transmission power and the spreading factor, which makes it ideal for applications in smart factories. The data collision can be also decreased by increasing the used unlicensed frequency bands as done recently in Europe.

The paper identifies the strengths and weaknesses of LoRaWAN. The study also highlights opportunities including the increase in battery life. By closely controlling the transmission power and the spreading factor, the life of the battery is extended. This is very useful for end devices located in remote places, which can not be often recharged. The battery life can be prolonged for a couple of years if the parameters are set right.

Data transfer is also possible on very big ranges as seen above in the free field measurements. The numbers can be controlled depending on the use case. As seen in the free field measurements in part 3.2.2, a maximum range of 10950 metres was reached with a spreading factor 12 and a transmission power of 14 dBm. This result is perfect for controlling sensors and actuators on big fields in smart farming or controlling a long street with smart lighting with LoRaWAN.

The stability of the communication was also tested at different moving rates. Stable communication is possible at 20, 50 and 100 km/h. Connection problems were encountered while testing the data transmission with a power of 5 dBm with a moving rate of 100 km/h. In this cycle of the measurements, the end device was able to establish communication but it was quickly disconnected. With a higher transmission power, there were no connection problems. The device was able to establish communication while the vehicle was moving at the tested speeds. The results of the dynamic measurements point out the opportunity for this technology to be used for predictive maintenance for industrial vehicles. With the increase of the amount of public gateways, this technology can also be used for tracking vehicles and goods as they travel to the end user.

There are many possibilities for future uses of the LoRaWAN technology that still need to be explored. Despite being quite young, this technology has a lot of potential. When discussing the wireless connection of sensors and actuators, it can become irreplaceable as the number of public gateways increases.

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