How Would Emergency Communication Based On LoRaWAN Perform? Empirical Findings of Signal Propagation in Rural Areas

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ABSTRACT

Low Power Wide Area Network (LPWAN) technologies are typically promoted for Internet-of-Things (IoT) applications, but are also of interest for emergency communications systems when regular fixed and mobile networks break down. Although LoRaWAN is a frequently used representative here, there are sometimes large differences between the proposed range and the results of some practical evaluations. Since previous work has focused on urban environments or has conducted simulations, this work aims to gather concrete knowledge on the transmission characteristics in rural environments. Extensive field studies with varying geographic conditions and comparative tests in urban environments were performed using two different hardware implementations. Overall, it was found that the collected values in rural areas are significantly lower than the theoretical values. Nevertheless, the results certify that LoRaWAN technology has a high range that cannot be achieved with other common technologies for emergency communications.

Keywords

LoRaWAN, Emergency Communication, Range Test, Empirical Evaluation, Dataset

INTRODUCTION

Low Power Wide Area Network (LPWAN) implementations are continuously gaining interest in practice and research, especially for usage in Internet of Things (IoT) devices. Therefore, the Long Range (LoRa) Alliance invented the Long Range Wide Area Network (LoRaWAN) standard. Advantages in using LoRaWAN for device connection are primarily the low energy consumption and the high range that can be achieved (Bardram et al. 2018). LoRaWAN has also gained attention in the crisis informatics community, based on the high peer-to-peer range and rather cheap and available devices and development boards. Use cases for this technology are mainly (1) establishing communication capabilities after infrastructure breakdowns (Höchst et al. 2020; Sisinni et al. 2020; Kuntke, Baumgärtner, et al. 2023), or (2) environment monitoring as part of early warning systems, e.g., to warn in case of flooding events (Huyeng et al. 2022).

However, contrary to the proposed range of up to more than 10 km (Queralta et al. 2019), recent studies show a broad range of maximum communication distances depending on the setting: 50-90 m in a dense forest environment (Iova et al. 2017) to 3km in urban area with high buildings (Mdhaffar et al. 2017) in practice. While a communication range of 50 meters does not seem very useful, communication up to several kilometers distance would be a good means of communicating many concerns in emergency situations. Therefore, it can be concluded that further research is needed to examine the effects of the geographical conditions on the transmission characteristics. Thereby, the information on the achievable range could be used to derive the maximum distance between devices to achieve an optimal distribution and reliable communication. For this research, different infrastructure areas like groups of trees and houses need to be assessed. The results of this research can then be used to adjust the technical implementation regarding real-life conditions. Therefore, this work addresses the following research question: *What concrete values for the LoRaWAN transmission characteristics can be achieved regarding geographical conditions?*

By answering this research question, the paper makes several contributions for further development of LoRaWAN based emergency communication systems.

First, Section Foundations and Related Work provides a short technical introduction on LoRaWAN and presents use cases of LoRaWAN in the crisis informatics community and works that investigate on wireless transmission range. Our own test methodology and the used hardware is described in Section Methodology. Afterwards, Section Results presents concrete test results, and Section Discussion presents implications of these empirical determined data. Finally, a brief conclusion is drawn in Section Conclusion, which also discusses limitations and opportunities for future research.

FOUNDATIONS AND RELATED WORK

This section explains the theoretical foundations of LoRaWAN, as well as later used software and hardware for the empirical evaluations, and also describes related work.

LoRaWAN

LoRaWAN is a popular Low Power Wide Area Network (LPWAN) technology, that was first released in 2015 (LoRa Alliance 2015). It is said to allow for a high transmission range of up to several kilometers along with a relatively low energy consumption. Because of the long range, LoRaWAN is often used in large-area IoT applications in combination with sensors, for example soil moisture or temperature sensors in agriculture. Since such sensors are often battery powered and distributed over a wide range, LoRaWAN is one of the rather appropriate technologies. Although LoRaWAN has some security considerations in the protocol itself, there remain security issues that must be taken into consideration when building resilient network setups (Kuntke, Romanenko, et al. 2022). A LoRaWAN network consist of end devices, gateways and servers and follows a stars-of-stars topology. All data arriving at the gateway are forwarded to a network server, which in turn forwards them to an application server to present it to users. LoRaWAN is partially based on the LoRa physical layer, which specifies the wireless data transmission between gateways and end devices (see Figure 1).

The spreading factor (SF) controls the amount of signals (chirps) per transmitted data. It allows to adjust the tradeoff between speed and robustness of a LoRa data transmission, with values between 7 (fast) and 12 (robust). The gateway and network server as well as the network server and the application server communicate over a conventional network connection via TCP/IP. To join a LoRaWAN network, new end devices must conduct over-the-air-activation (OTAA) or activation by personalization (ABP). The difference here lies in the key exchange protocols. The end devices can be of one of three different types. End devices of type A wait for the reply package for two windows after sending information. End devices of type B wait for an additional interval and end devices of type C listen continuously for incoming data frames. Our study uses type A and type C end devices. The Received Signal Strength Indicator (RSSI) and Signal-to-Noise-Ratio (SNR) values can be examined to check the connection quality of LoRaWAN. These indicators are especially suitable since they allow for a quantification of the transmission characteristics. The RSSI value represents the reception strength in dBm with a higher value representing a better reception strength. The SNR represents the ratio of signal to noise in dB, where a higher value is preferable.

Related Work

Despite a multitude of studies investigating the influence of the geographic conditions on LoRaWAN range, most of them focus on urban areas (Petrariu 2021; Petrić et al. 2016; Cattani et al. 2017) or test the range mainly by simulations (Khan and Portmann 2018).

Khan and Portmann (2018) only simulated a LoRaWAN network to gain knowledge about the transmission characteristics. Two different scenarios were tested. In scenario 1, an end device moved away from the gateway

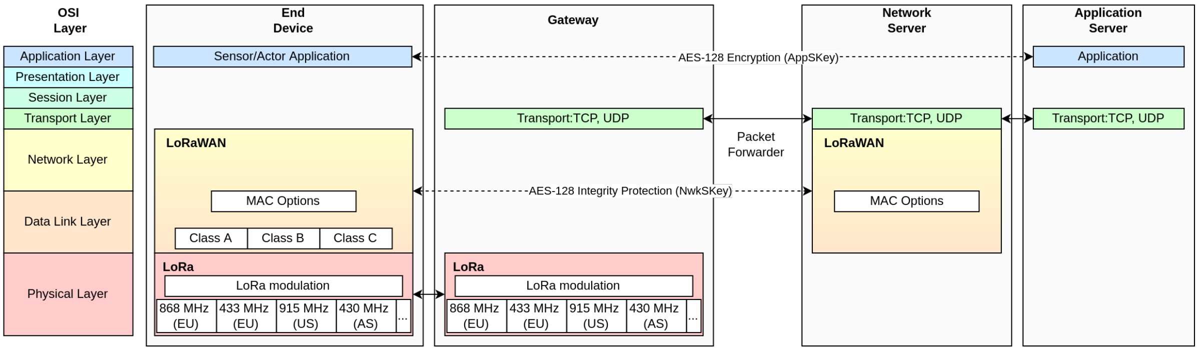

Figure 1. Simplified illustration of the LoRaWAN technology stack in the OSI model

with a constant direction on a distance of 1-7 km. In scenario 2, multiple end devices were positioned at different places in a 5 km radius around the gateway. The authors concluded that in scenario 1, adjusting the transmission rate would benefit the performance and in scenario 2, a higher quantity of maximum transfers would impair the performance. Most other works conduct field tests comparable to the ones executed in this work. However, some of these focus mainly on urban areas.

Petrariu (2021) focuses on urban areas and test Longley-Rice and ITU-R on the LoRa network coverage, choosing a communication interval of 10 seconds and a fixed communication channel (868.3 MHz). They also tested different SF from SF7 to SF12. In 200 measurements on a radius of 2 km, they focused on examining the Global Delivering System (GPS) Position, the RSSI values, the Signal-to-Noise Ratio (SNR) values, and the elevation. The maximum communication distance was 500 m. Similarly, Petrić et al. (2016) performed range tests on LoRa FABIAN with mobile end devices around a gateway and a measurement with fixed and devices in an urban area. Their findings were that position has an impact on transmission. Cattani et al. (2017) tested the reliability of LoRaWAN communication in three different locations, namely indoors, outdoors and underground on a university campus and concluded that temperature and humidity can influence the reliability. Other works have executed tests in more rural areas. Marfievici et al. (2013) conducted tests on Wireless Sensor Network (WSN) technology in different vegetation environments and at different times of the day. The conclusion was that all of these factors have an impact on the transmission characteristics for WSN, especially the Packet Delivery Ratio (PDR). Iova et al. (2017) investigated the effect of different types of vegetation in rural environments on the LoRa signal quality. In four different environments, they positioned the sender at a fixed point and the receiver at changing distances. Line-of-Sight (LoS) connections achieved a range of 450-550 m. A range of 50-90 m was achieved when the connection was blocked by vegetation. It was concluded that transmitter power had no effect on range, but temperature could affect the quality of the connection.

Ojo et al. (2021) focused on the usage of LPWAN for Smart Agriculture. The authors used 433 MHz and 868 MHz bands and varying SF values between 7 and 12. The gateway was placed at a height of 3 m and the end devices at different places with different vegetation between gateway and end device. Ranges of up to 860 m in dense forest and 2050 m in less dense forest areas were achieved. Mdhaffar et al. (2017) consider the usage of LoRaWAN networks to gather medical data. A coverage of 33 km2 with the gateway on a height of 12 m in rural environments was achieved. Also, a range of 2 km in dense urban environments and 3 km in less dense urban environments was recorded. Höchst et al. (2020) use LoRa capable micro-controller boards as companion devices for smartphones. A specific chat application allows the smartphone to connect via bluetooth to the LoRa board and let a user send SMS-like messages as LoRa signals to other users. A real-world evaluation for the device-to-device communication allows a range of up to 2.89 km.

Most of those results show that the environment can affect the LoRaWAN transmission characteristics and that further studies are needed to gain accurate values regarding the impact of geographical environment in rural areas on the RSSI/SNR values. With correspondingly more concrete empirically determined values, more precise expected ranges could be predicted in the future, systems could be planned accordingly, and recommendations could be made in the use of emergency communication and environment monitoring systems.

METHODOLOGY

The goal of this work is to determine typical ranges of LoRaWAN by means of empirical measurement series. For this purpose, test series with different hardware setups are to be carried out in order to compensate for the peculiarities of individual hardware and to be able to represent a certain range if there are differences in the hardware.

(a) Setup H: Two Heltec Wireless Sticks, each connected to a smartphone

(b) Setup A: Adeunis FTD

(c) Setup A: LoRaWAN Gateway on a tripod, connected to a laptop

Figure 2. The used hardware setups of our empirical tests. (source: own pictures)

Table 1. Used hardware of both setups.

Setup H *(Heltec)*	Setup A *(Adeunis)*
• 1x Heltec Wireless Stick (RF95 Modem, ESP32 dual-core Microprocessor, IPEX-1 Spring Antenna 2) • 2x Android smartphone	• 1x Adeunis Field Test Device LoRaWAN EU863-870 (LoRaWAN V1.0 Protocol) • 1x DLOS8N Outdoor LoRaWAN Gateway • 1x Notebook with ChirpStack v3 (LoRaWAN network server)

Two different hardware setups were used for the field tests (see Figure 2 and Table 1): Setup H with two smartphones and two small companion LoRa boards for sending/receiving LoRa signals and setup A with an outdoor LoRaWAN gateway and a commercial signal test device.

Setup Description

The Heltec Wireless Sticks in setup H communicated with two Android smartphones to establish the data transfer over the BlueRa app (Höchst et al. 2020). For the field tests, one smartphone (the sender) stayed at a fixed position and sent a message at an interval of 15 seconds to the receiver smartphone, which moved in varying distances and with varying obstacles around the sender. The data was saved on the smartphones and was later evaluated with DB Browser for SQLite.

In setup A, the Adeunis Field Test Device (FTD) offers the IoT-Configurator interface to configure the different communication variables. The gateway was equipped with an open-source embedded Linux system and was connected to a ChirpStack v3 network server instance. The Adeunis FTD was registered in ChirpStack as a regular LoRaWAN end device, and a payload encoder allowed translating the received bits into human-readable data fields like the position (latitude, longitude) and SNR/RSSI values. ChirpStack stored its data in a PostgreSQL database, that allowed to export data for external processing and evaluation. The resulting data sets are uploaded for further processing by thirds (Kuntke, Bektas, et al. 2022).

Field Tests

During all field tests, protocols were made to document the results and circumstances, e.g., the weather and geographical setting. This ensures the reproducibility and comparability of all tests. The first tests focused on single-object obstacles to estimate if the impact of a single object on the transmission quality would be sufficient to calculate an obstacle's repeated impact. Setup A was used to test this assumption, since this implementation

Table 2. The conducted field tests in regard to the used hardware setups, and its location. Three conditions (weather/area) were tested with both setups simultaneously for comparison.

Tests with setup H	Tests with setup A
H1 (Frankfurt am Main, urban)	
H2 (Frankfurt am Main, urban)	
H3 (Darmstadt, urban)	
H4 (Hofgut Neumühle, agricultural)	
H5 (Hofgut Neumühle, agricultural)	A1 (Hofgut Neumühle, agricultural)
	A2 (Frankfurt am Main, forest)
	A3 (Frankfurt am Main, urban)
H6 (Frankfurt am Main, forest)	A4 (Frankfurt am Main, forest)
H7 (Frankfurt am Main, urban)	A5 (Frankfurt am Main, urban)
	A6 (Darmstadt, agricultural)

provides more detailed information on the transmission characteristics like RSSI and SNR. The test was conducted by placing the sender at a fixed point in front of the obstacle and then placing the receiver at two fixed positions, one with the obstacle between the devices and one without the obstacle between them. Since it could be concluded that the collected data wasn't accurate enough for this procedure, the following tests did not follow this procedure. In the other tests, the effects of different geographical surroundings were tested by placing the gateway at a static position and moving away from the gateway with the end devices with varying distances and obstacles. During the tests, packets were sent by the end device at regular intervals. The tests were conducted in different environments with varying degrees of vegetation, namely (1) urban areas, (2) dense forests, (3) less dense forests, and (4) agricultural fields with smaller hills, hedges, and groups of trees. The GPS data of end device and gateway as well as a description of the surroundings was recorded for later evaluation. Additionally, the meteorological data was collected from the Deutscher Wetterdienst (DWD, *German Weather Service*), since Cattani et al. (2017) detected that weather conditions could influence transmission characteristics. While this is not the focus of this work, this also allows for better comparison. In the test with setup A, the RSSI and SNR values were documented as well. A depiction of the conducted test with corresponding location can be found in Table 2.

RESULTS

In the following, the field tests will be explained in detail with the respective achieved results.

Setup H

Test H1 was conducted in Frankfurt am Main, thus a more urban area. This was the first test and mainly aimed at collecting a first test record. This mainly enabled an estimation of the achievable degree of detail as well as range. Test H2 was executed in a similar environment and was meant to deliver results on whether single obstacles would influence the transmission. For this reason, houses, trees and bushes were used as obstacles.

The results showed that trees or bushes did not have a sufficient effect on the transmission to be noticeable with the used hardware. Houses, on the other hand, could impede and block the transmission. It was therefore concluded that further tests should examine these results in urban areas as well as rural areas with varying degrees of foliage. Similar to Test H2, Test H3 was also executed in an urban environment, however this time in Darmstadt, to gather data that is not just based on one location. The same obstacles as in Test H2 were chosen, with one part of this test focusing on trees and bushes and the other focusing on rows of houses. In the first part, the highest range in general for setup H, with 412 m, could be achieved. Hofgut Neumühle, an agricultural environment with slight hills, single bushes, and forest, was chosen as the location for Test H4. The receiver was surrounded by fields, which enabled a range test without many obstacles. Noticeable was that whenever a small elevation difference, i.e. a small hill, blocked the direct LoS connection between sender and receiver, the transmission failed.

In a second test, a small group of trees was used as an obstacle between the two devices. Here, transmission was possible as long as a direct LoS connection was ensured, meaning, only until the transmission was blocked by trees. Lastly, a range test was conducted, whereby an LoS connection was ensured but only a slightly higher range than in the test before could be achieved. Test H5 was executed simultaneously with Test A1 again at Hofgut Neumühle. Another range test was conducted which showed setup A could achieve a much higher range than setup H. In a second part of this test, the connection in a near forest should be tested, but the transmission broke off again when

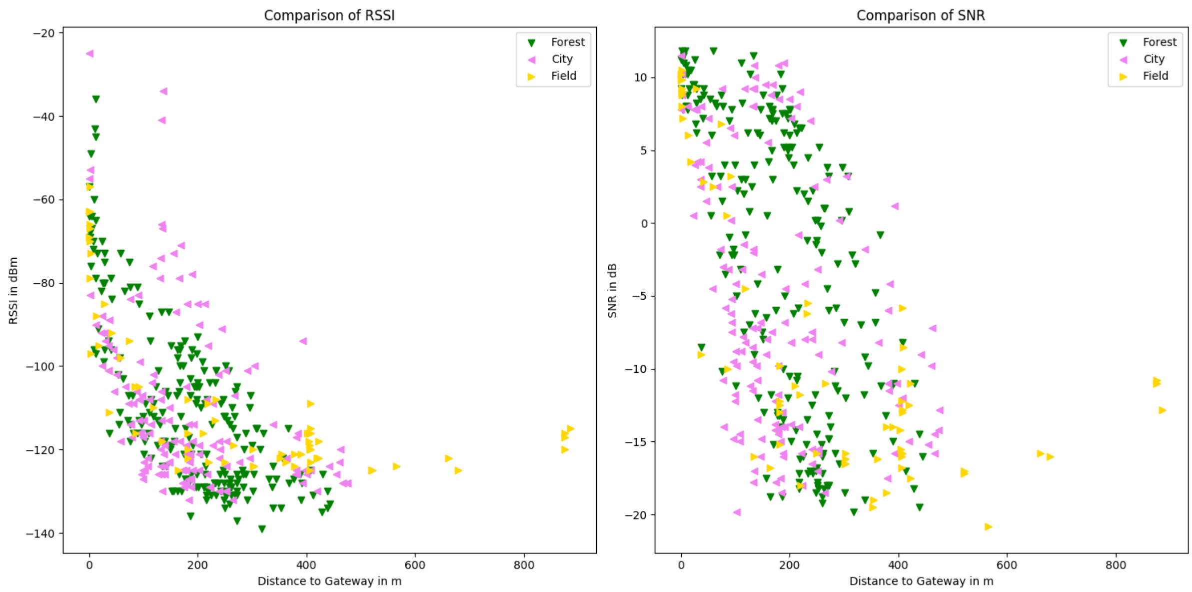

Figure 3. Comparison of RSSI and SNR as a function of distance with the Adeunis Tests A1-A5.

a slight elevation difference blocked the transmission. To again test the range in a dense forest, a forest area in Frankfurt am Main Oberrad was chosen as the location for this test. Test H6 was also simultaneously conducted with Test A4 (setup A). First, an area of the forest with small buildings like a playground was tested and it was found that this did not result in different ranges for the setups. Secondly, an area only consisting of forest was tested, where setup A could achieve much higher ranges. Lastly, in Test H7 an urban area was tested again with both setups (Test A5 for setup A), to gain comparable data of both setups. As soon as some buildings blocked the connection, the transmission broke off again. In an area with more buildings, the setups performed similarly but in an area with less building and more park areas, setup A achieved the higher range.

Setup A

Test A1 was conducted simultaneously with Test H5. During this test, setup A achieved a range of 885 m in a small valley. It was also evident that in this case, the RSSI and SNR values no longer worsened. To conduct a first test in a forest area, a forest in Frankfurt am Main Louisa was chosen for this test. This area is characterized by having little undergrowth. In a second part of this test, allotments were also tested as an obstacle. In both parts the RSSI as well as the SNR values decreased with increasing distance between sender and receiver. Test A3 was executed in the city center of Frankfurt am Main. In a first part of this test a maximum distance of 500 m could be achieved. However, a few minutes later only a distance of 160 to 170 m could be measured in the same environment. Similarly, the values for RSSI and SNR worsened. The only noticeable difference was a change in weather conditions. Test A4 was executed simultaneously with Test H6. In the dense forest area, a range of about 250 m and in the last part of the test a range of 300 m could be achieved. The main difference here were two buildings that additionally blocked the transmission in the first part. In test A5, the same area as in Test A3 was tested to further investigate the changing values. This Test was also conducted with setup H. The range was only slightly higher than in the last part of Test A3 with 250 m, but still much lower range compared to the beginning of Test A3 where a range of 500 m could be achieved. A comparison of some of the RSSI and SNR values in the conducted tests A1-A5 can be seen in Figure 3.

Test A6 was executed in an agricultural used area in the north of Darmstadt. This test had the purpose of conducting a rather maximum-distance evaluation (but with real-world conditions) by performing tests in a known wireless transmission friendly area. The positioning of the gateway allowed for several hundred meters of LoS and up to 3 km with just a few obstacles. We got a maximum distance of about 3.3 km in this test for setup A. This is also shown in Figure 4.

DISCUSSION

Several observations can be made from the recorded results. First of all, both hardware configurations can be compared based on their usability for the given use case and test setups. For this purpose, the five field tests where both setups were used simultaneously can be considered. Especially in the tests H5a and A1a as well as H6b and

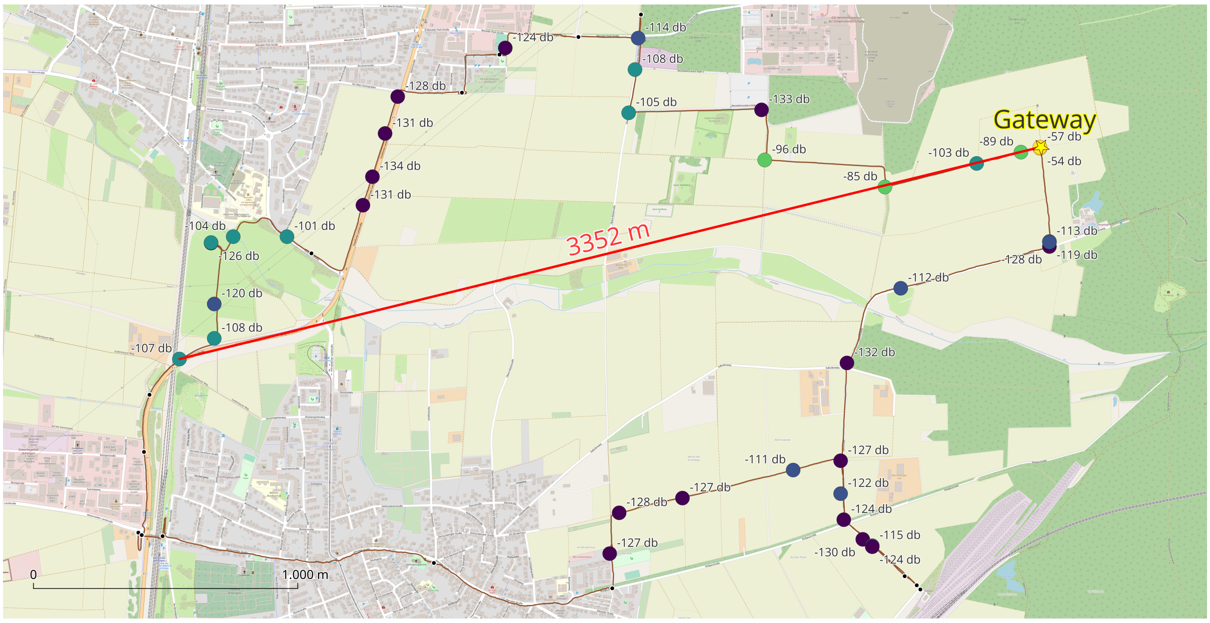

Figure 4. Test A6 (agricultural used area) with just a few obstacles achieved a range of 3352 m. Smaller black dots on the track mark failed transmission attempts. The gateway is on an elevation of 190 m NN. At the maximum distance, the sender is on an elevation of 175 m NN. This comes to an elevation difference of 15 m.

A4c, setup A achieved better results than setup H, which in the first case might be explained by the high elevation difference that occurred just after a few meters and affected both setups equally. Another explanation could be that setup H partially could not hold a stable connection. In tests H5b and A1b as well as H6a and A4a, both setups performed similarly. In the urban environments in test H7 and A5, both setups could achieve similar maximum ranges as well. Especially the high range by setup A in test A1 (885 m) could not be reproduced by setup H (test H5), which achieved a maximum range of 412 m. Setup A, in particular, enabled the collection of detailed RSSI and SNR values. Regarding the RSSI and SNR values, as shown in Figure 1, several observations can be concluded.

The lesser dense forest can achieve better results in RSSI and SNR as the agricultural field with a distance of up to 400 m. In the environments urban-day 1 and less dense forest, better RSSI and SNR values could be achieved than in urban-day 2 and the denser forest. The difference in the two forest locations shows that the density of the obstacles can influence the transmission characteristics. Additionally, the transmission in the dense forest is generally worse with no connection beyond a range of 300 m. The difference in the transmission quality on the different days in the urban environments can be explained by the different weather conditions, which will be examined later.

Lastly, the open field achieves the highest range with 3352 m. Mdhaffar et al. (2017) could achieve a similar range of 3 km even in an urban setting, which can be explained by them placing the gateway at an elevation of 12 m compared to 1.3m - 2.0 m in this work. The results of Ojo et al. (2021) also could not be reproduced, as their higher placed gateway at 3 m and the fixed position of the end devices most likely enabling the higher range. However, our tests were conducted with mobile emergency communication systems in mind, like those described by Höchst et al. Such systems will be used at rather low heights of maximum 2 m, as they are typically used as handheld devices. It is also possible that the motion of the end devices could have influenced the connection. The simulations of Khan and Portmann, P. 3 (2018) with a range of 5 - 7 km can't stand as realistic compared to our field test results. In our most optimistic (but realistic) setting in test A6, 3.3 km between sender and receiver could be achieved. Based on our test results, we can confirm the approximate range of 500 m achieved by Iova et al. (2017) and Petrariu (2021) for area characteristics that potentially negatively impacts the LoRaWAN range, like many obstacles or mountain areas.

Although not the primary goal of this work, the meteorological data was collected as well. This enabled comparing the tests A3 and A5, which although conducted in the same environment resulted in different transmission characteristics. Test A3a conducted from 15:46 to 16:25 and test A5 conducted from 15:27 to 16:27 vary especially regarding the temperature, degree of coverage and vertical visibility. This suggests a correlation between the weather conditions and the transmission quality. These conclusions are supported by Cattani et al. (2017), who also deduce an effect of the weather conditions on the transmission characteristics. The differences in tests A3a and A3b/c, however, can't solely be based on the weather since technical difficulties occurred in this case that could have an effect on the range. Future works could focus more on the influence of the meteorological conditions specifically.

CONCLUSION

Two of the use cases of LoRaWAN based transmission in crisis informatics are environmental monitoring and digital emergency communication. By conducting field tests in varying environments (urban, forest, agricultural) this work could collect thorough data on the LoRaWAN transmission characteristics dependent of geographical circumstances. These results should help the design of developments for rural area LoRaWAN based systems, based on real world data. Consequently, the real values for the LoRaWAN range in urban and rural areas are significantly lower than the suggested theoretical values. Thereby, an impact of obstacles, the elevation and the meteorological conditions on the transmission characteristics could be recorded. Regarding the obstacles, it could be concluded that the density of the respective obstacles influences the transmission quality. To measure the effects of single objects, the used devices could not provide results that were detailed enough. The conclusion that a higher range can be achieved in valleys can also stand as one of the results of this work. Lastly, an influence of the meteorological conditions could be derived. The highest achieved range over all tests was 3352 m, with a good antenna, but not optimized location. We suggest to take this value as a real world maximum distance with current consumer grade electronics. For areas with a rather high obstacle density, like forests, this value goes down to about 800 m, which is also considered as a worst-case value for regular situations. In case of low-end equipment, the real world values are significantly lower, and achieved a maximal distance of 412 m in our test setup. This result is not convincing, and the use of such low-end boards for critical operations needs to be reconsidered strongly.

The results are obviously restricted by the limited number of conducted test, which were also only conducted in a limited time span and a limited area (all tests were conducted in Hesse or Rhineland-Palatinate, Germany). Additionally, the weather conditions were very similar in all field tests. Although two different hardware setups were used, a multitude of different configuration possibilities to implement a LoRaWAN network exists. Lastly, the field tests are limited by the assumption that multiple factors such as obstacles, distance, elevation, weather conditions and other circumstances could have influenced each one of the test results, thereby hindering a clear derivation of correlation. For a better generalization, further test should be conducted based on the results of this work. This would also serve the further collection of data to gain an empirical dataset. Additionally, further tests in different regional areas and with different meteorological conditions should be executed.

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REFERENCES

Bardram, A. V. T., Delbo Larsen, M., Malarski, K. M., Petersen, M. N., and Ruepp, S. (Apr. 2018). "LoRaWan capacity simulation and field test in a harbour environment". In: *2018 Third International Conference on Fog and Mobile Edge Computing (FMEC)*, pp. 193–198.

Cattani, M., Boano, C. A., and Römer, K. (June 2017). "An Experimental Evaluation of the Reliability of LoRa Long-Range Low-Power Wireless Communication". en. In: *Journal of Sensor and Actuator Networks* 6.2, p. 7.

Höchst, J., Baumgärtner, L., Kuntke, F., Penning, A., Sterz, A., and Freisleben, B. (2020). "LoRa-based Device-to-Device Smartphone Communication for Crisis Scenarios". en. In: *Proceedings of the 17th International Conference on Information Systems for Crisis Response and Management (ISCRAM)*, p. 17.

Huyeng, T.-J., Bittner, T., and Rüppel, U. (2022). "Examining the Feasibility of LoRa-based Monitoring in Large-scale Disaster Response Scenarios". In: *Proceedings of the 19th International Conference on Information Systems for Crisis Response and Management (ISCRAM)*, pp. 541–550.

Iova, O., Murphy, A. L., Picco, G. P., Ghiro, L., Molteni, D., Ossi, F., and Cagnacci, F. (Feb. 2017). "LoRa from the City to the Mountains: Exploration of Hardware and Environmental Factors". In: *Proceedings of the 2017 International Conference on Embedded Wireless Systems and Networks*. Uppsala, Sweden.

Khan, F. H. and Portmann, M. (Nov. 2018). "Experimental Evaluation of LoRaWAN in NS-3". In: *2018 28th International Telecommunication Networks and Applications Conference (ITNAC)*, pp. 1–8.

Kuntke, F., Baumgärtner, L., and Reuter, C. (2023). "Rural Communication in Outage Scenarios: Disruption-Tolerant Networking via LoRaWAN Setups". In: *Proceedings of Information Systems for Crisis Response and Management (ISCRAM)*, pp. 1–13.

Kuntke, F., Bektas, M., Buhleier, L., Pohl, E., Schiller, R., and Reuter, C. (2022). *LoRa Signal Loss in Rural Areas Dataset*. URL: https://doi.org/10.48328/tudatalib-975.

Kuntke, F., Romanenko, V., Linsner, S., Steinbrink, E., and Reuter, C. (2022). "LoRaWAN security issues and mitigation options by the example of agricultural IoT scenarios". en. In: *Transactions on Emerging Telecommunications Technologies* n/a.n/a, e4452.

LoRa Alliance (2015). *LoRaWAN™ Specification V1.0.*

Marfievici, R., Murphy, A. L., Picco, G. P., Ossi, F., and Cagnacci, F. (Oct. 2013). "How Environmental Factors Impact Outdoor Wireless Sensor Networks: A Case Study". In: *2013 IEEE 10th International Conference on Mobile Ad-Hoc and Sensor Systems*, pp. 565–573.

Mdhaffar, A., Chaari, T., Larbi, K., Jmaiel, M., and Freisleben, B. (July 2017). "IoT-based health monitoring via LoRaWAN". In: *IEEE EUROCON 2017 -17th International Conference on Smart Technologies*, pp. 519–524.

Ojo, M., Adami, D., and Giordano, S. (Apr. 2021). "Experimental Evaluation of a LoRa Wildlife Monitoring Network in a Forest Vegetation Area". In: *Future Internet* 13, p. 115.

Petrariu, A. I. (Nov. 2021). "A Study on LoRa Signal Propagation Models in Urban Environments for Large-scale Networks Deployment". English. In: *Advances in Electrical and Computer Engineering* 21.4, pp. 61–68.

Petrić, T., Goessens, M., Nuaymi, L., Toutain, L., and Pelov, A. (Sept. 2016). "Measurements, performance and analysis of LoRa FABIAN, a real-world implementation of LPWAN". In: *2016 IEEE 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, pp. 1–7.

Queralta, J. P., Gia, T., Zou, Z., Tenhunen, H., and Westerlund, T. (2019). "Comparative Study of LPWAN Technologies on Unlicensed Bands for M2M Communication in the IoT: beyond LoRa and LoRaWAN". en. In: *Procedia Computer Science* 155, pp. 343–350.

Sisinni, E., Carvalho, D. F., and Ferrari, P. (2020). "Emergency Communication in IoT Scenarios by Means of a Transparent LoRaWAN Enhancement". In: *IEEE Internet of Things Journal* 7.10, pp. 10684–10694.