Smart and Very Distant Objects

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ABSTRACT

This work addresses the feasibility of extreme long distance links based on LoRa technology. We developed a specialized low-cost and highly sensitive hardware based on the LoRa chipset and deployed it in a 316 km long link. Received signal strength, signal to noise ratio, and packet reception rate were measured at two different frequency bands: 434 MHz and 868 MHz. Results clearly show that the link is feasible at both frequencies even with omni directional antennas. In addition, we provide details on the planning of the experiments, as well as procedure employed to find the suitable test bed for such a long distance link. These types of wireless systems are quite useful for disaster mitigation applications in sparsely populated areas.

CCS CONCEPTS

• **Hardware** → *Wireless devices*; • **Networks** → *Physical links*;

KEYWORDS

LoRa, extreme long distance, link planning, wireless, IoT, LPWAN, disaster prevention

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1 INTRODUCTION

Most work on IoT has been focused in the interconnection of a great number of devices at short distances. Yet there are applications in which very long links are required, for instance in natural disaster prevention and mitigation, specially in developing countries, where the data processing facilities may be far away from the sensor nodes. These applications share the following requirements: *(i)* nodes must be cheap, since they might be damaged or stolen because of its remote location, *(ii)* they must consume little power, to be able to operate for long time without maintenance, and *(iii)* they must be able to operate at long distances, since the gateway might be far away from some of the nodes. While recent analyses have reported more realistic forecasts about the number of devices that will be part of the Internet of Things, the number is still in the billions [3, 7, 13].

Most of the devices will be installed in domestic or industrial environments, since consumer and industrial automation are the two main areas of growth for IoT applications[1, 2, 6, 11]. Consumer devices require widespread, fast and secure wireless connections, so they will focus mostly on WiFi and Bluetooth Low Energy (BLE) solutions. Industrial devices are installed in RF noisy environments, so they demand reliable and interference resistant wireless protocols.

On the other hand, in natural disaster prevention and mitigation there are many IoT applications in which very long wireless links are required to transmit the sensors outputs to the places where they can be used for decision making. For example, in rivers to detect level and water flow; in forests to detect fires; in volcanoes [17] to detect eruptions often predated by gas emissions, and in mountain slopes to monitor early indications of landslides, avalanches or abnormal quantities of rain.

This is especially true in developing countries, where there is ample space for growth of IoT networks, with many applications that require very long links [8]. While the above requirements could be satisfied with the LoRa technology, the existing literature reports ranges of only a few tens of kilometers. Our previous experience in long distance wireless links motivated us to explore the range limits of reliable communication links with LoRa devices.

This work presents the hardware optimized for very long distance links that we developed using the Semtech LoRa chipset, and explores the feasibility of an extremely long wireless link of 316 km, yet unreported in peer reviewed literature. We describe each step in the link planning process, and give results for several different types of the antennas used in the experiments at two frequency bands: 868 MHz and 434 MHz.

2 LORA AND LONG LINKS

LoRa refers to a modulation technology that exploits the well known advantages of spread spectrum techniques to address the needs of low power, long range, wide area networks (LPWAN) using low cost end devices [5, 14]. This is done by leveraging chirp spread spectrum (CSS) modulation, widely used in radar, to build a frequency drift tolerant receiver that does not require precise synchronization with the transmitter while allowing the detection of very weak signals, even below the noise floor. Most communication systems require that the signal strength be well above the electrical noise and interference present at the receiver for error-less decoding of the signal.

LoRa can work at very low received signal levels by using a much wider bandwidth than the minimum required to carry the information. The ratio between the bandwidth of the modulated signal and that of the base-band signal is called the spreading factor (SF). LoRa has the flexibility of using spreading factors ranging from 7 to 12. The higher the spreading factor the longer it takes to transmit the same amount of information, thus occupying the channel for a longer time. This implies consuming more battery power, but allows for longer ranges since a high SF increases the energy per bit carried and consequently the detection accuracy.

So one can use a SF of 12 to reach very long distances, but carrying just a few bytes per packet, or a SF of 7 to carry more bytes per packet when the distance is lower thus saving battery power. This can be understood by considering the well known Shannon formula for channel capacity:

$$C = B \log_2 (1 + \frac{S}{N}) \quad (1)$$

where C is the channel capacity in bit/s, B is the bandwidth in Hz, S is the signal power and N is the noise plus interference power.

When the signal power is one hundredth that of the noise, the S/N ratio is 0.01 (−20 dB) and the capacity of a 125 kHz channel can be calculated as:

$$C = 125000 \times 0.14355 = 1794 bit/s \quad (2)$$

So, in principle, by using a 125000 Hz wide channel we can transmit 1.8 kbit/s even if the signal is one hundred times lower than the combination of ambient noise and interference.

LoRa based wireless systems do not transmit continuously in order to abide to spectrum regulations, and therefore the actual capacity is much less, depending on the duty cycle, spreading factor and coding ratio used. Those systems operate in several different unlicensed UHF bands, with different requirements according to the country of deployment, so the maximum transmitted power and maximum channel occupancy time (called duty cycle) must comply with different local regulations.

While LoRa is a proprietary technology developed by Semtech[14], the LoRa Alliance leveraged it to promote an open standard called LoRaWAN supported by a consortium of numerous vendors[5]. LoRaWAN provides all the functionalities to build a complete solution for IoT requirements by adding MAC and applications layers to the basic LoRa physical layer.

Several organizations have deployed LoRaWAN networks in many countries, with different approaches that range from closed commercial offerings that require a recurrent fee payment, to completely open initiatives like The Thing Network (TTN) [16]. LoRa has applications in transportation and logistics, smart buildings, smart cities and agriculture.

2.1 Bot for long link planning

One aspect that is paramount in the planning of wireless links is the determination of the attenuation introduced by the terrain between the transmitter and the receiver, which ultimately determines the feasibility of a given link. There are many commercial programs meant to solve this problem, most of them making use of digital elevation maps. Some of them are quite costly and others restrict their usage to the radios and antennas of a particular manufacturer.

We developed BotRf [18] as a link planning tool based on the Telegram bot technology. Built on open source tools, it can run on any smartphone or PC using Telegram. BotRf provides a simulation of the terrain profile for different atmospheric refraction index values, calculating the path loss in a wireless point to point link. It shows the results in an easy to grasp interface and gives a numerical value of the link margin in dB when the radio and antenna parameters are inserted. For the link calculation, it uses the popular Longley-Rice Irregular Terrain Model (L-R ITM) with SRTM1 digital elevation maps at a resolution of 30 meters.

It should be noted that electromagnetic waves occupy a volume in space called the Fresnel ellipsoid, extending from the transmitter to the receiver, with maximum girth at midpoint between the two. The radius of this ellipsoid is called the first Fresnel zone radius and is proportional to the square root of the wavelength and to the distance between the endpoints. In order to capture most of the power contained in radio waves, at least 60 % of the first Fresnel zone must be cleared. This means that the antennas must be raised above the minimum required to draw an unobstructed line from the transmitter to the receiver (the so called optical line-of-sight).

We used BotRf to find suitable sites for the long LoRa links, keeping in mind that if the model suggests that a link is unfeasible because of an obstruction or excessive attenuation, we accept this result at face value and search for an alternative. On the other hand, when the model finds an unobstructed path, we proceed to do a site survey at both ends before the actual deployment. This strategy has been quite successful over a number of links that we have simulated and later deployed [12]. Simulation outputs for the 316 km link using BotRf are given in Fig. 1 and Fig. 2. The first one tells us that the link is feasible since there is no obstruction due to terrain and shows the earth curvature readily apparent at this very long distance. The brown line in the figure represents the curvature of the earth, modified by the refraction index. The green line is the terrain profile as seen by the radio wave. The magenta line is the 60 % of the first Fresnel zone. The blue line is the optical line of sight. The second figure represents a "binocular" view as seen from one measurement point towards the other. This helps when trying to aim at the other site at such long distances. It is worth noting that using BotRf all the input data, as well as the results, are stored in the server under each user's account, so that they can be retrieved for future use.

2.2 Regulations

Frequencies allocations follow ITU recommendations and many countries impose specific requirements. The so called "unlicensed" bands must comply with certain limitations in order to share the common spectrum with other users. These limitations refer to the maximum effective irradiated power, duty cycle limitations and listen-before-talk (LBT) medium access techniques. In Europe the 868 MHz band access is dealt with in ETSI TR 103 055 version 1.1.1[4]. It specifies 3 sub-bands, shown in Table 1, with different power and duty cycle limitation for devices that do not abide to the LBT etiquette.

In order to save energy, a LoRa end device should abstain from monitoring the channel before attempting to use it. But, to allow the channel to be shared, the regulations impose a limitation on the time that a given user can transmit. If there is still pending traffic, regulations allow to switch to a different sub-band and start a new countdown to comply with the duty cycle limitation.

3 EXPERIMENTS

LoRa range evaluation was reported in [6, 9, 10]; the distance achieved in these experiments was in the tens of kilometers. We carried out experiments in Italy between two points that are separated by 316 km: Matajur (46.2121°, 13.5294°), elevation 1640 m above sea level, and Croce Arcana (44.13213°, 10.77892°), elevation 1677 m. Fig. 3 shows the geographical layout of the experiment.

3.1 Experimental LoRa board

To address the long range issues we developed a dedicated hardware platform using the Semtech $SX1276$ LoRa transceiver[15] and additional peripherals that enabled data logging during the tests. The block diagram of the board is given in Fig. 4, while its physical appearance is shown in Fig. 5.

As shown in Fig. 4, the board contains the Energy Micro $EFM32\text{-}GG990F1024$ micro-controller, which is connected to a 32 MB NAND flash and the Semtech $SX1276$ LoRa transceiver. The board has two RF ports: one for frequencies from 137 MHz to 500 MHz and the other for frequencies between 500 and 1020 MHz. There are also two LEDs for signaling and one push button. The port expander enables connection to other boards or sensors. The device can be powered directly from a Li-Poly battery.

The manufacturer's driver for the transceiver was adapted to be executed on our micro-controller. The porting of the driver encompassed rewriting the hardware abstraction layer (HAL) and replacing the packet reception polling mechanism with an interrupt based one, more amenable to our purposes. In our case, the test application on the transmitting motes sends packets consisting of an 8 bytes preamble, 9 bytes of payload and a CRC at two different frequencies: 434 MHz and 868 MHz. Transmitting is carried out with the following parameters: spreading factor $SF = 10$, coding rate $CR = 4/6$ and bandwidth $BW = 125$ kHz. Output power was set to 20 dBm for 434 MHz and 14 dBm for 868 MHz. Each packet has a unique number (ID) which is incremented by one in the subsequent transmission. The receiving motes do not send any acknowledgment to the transmitting ones, but log to the local NAND flash the received packet ID, received signal strength (RSS), signal-to-noise ratio (SNR) and the time stamp of the received packet. In addition, the packet reception rate (PRR) is calculated in post analysis of the recorded data.

Experiments were carried out in two trials with different sets of antennas. In the first trial we used Yagi 23 dBi antennas at both ends at the frequency of 868 MHz ; while at 434 MHz we used omni-directional 6 dBi antennas at both ends. In the second trial we

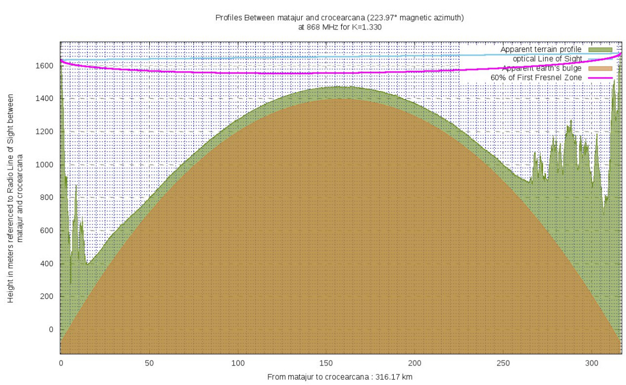

Figure 1: Earth curvature and terrain profile over the 316 km LoRa test link generated by BotRf simulation software

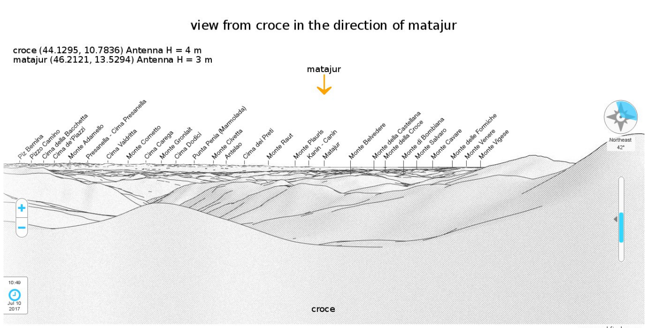

Figure 2: "Binocular" view of the 316 km LoRa link test bed generated by BotRf simulation software

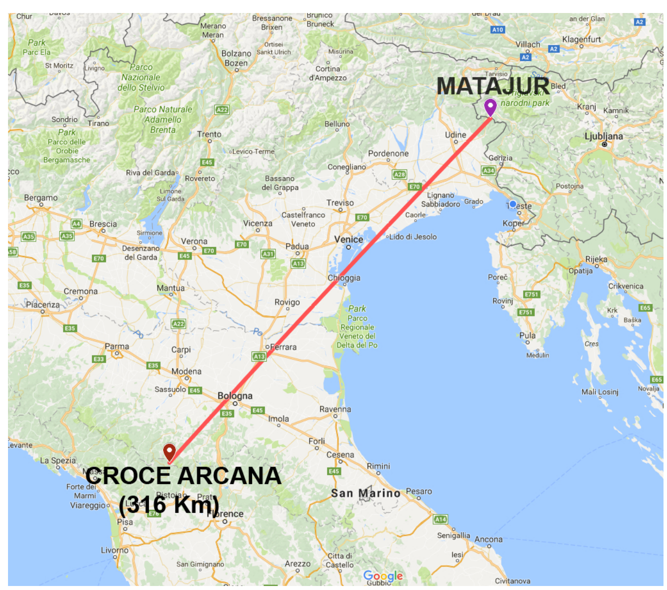

Figure 3: 316 kilometers LoRa test layout

Table 1: Three 868 MHz sub-bands with different power and duty cycle limitation

Sub-band	From frequency in MHz	To frequency in MHz	EIPR	Duty Cycle
G1	868	868, 600	25 mW (14 dBm)	1 %
G2	868.700	869.200	25 mW (14 dBm)	0.1 %
G3	869.400	869.650	500 mW (27 dBm)	1 %

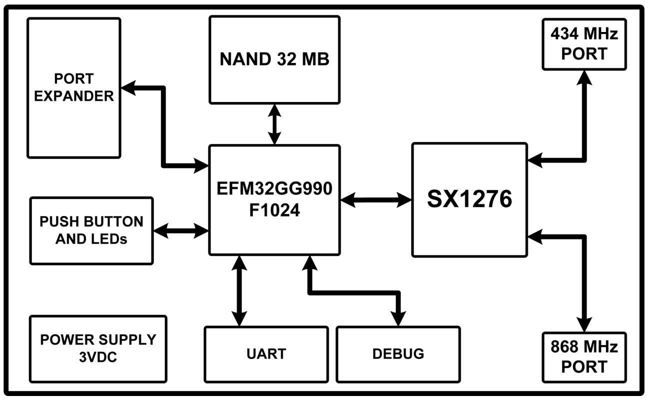

Figure 4: Block diagram of the developed board

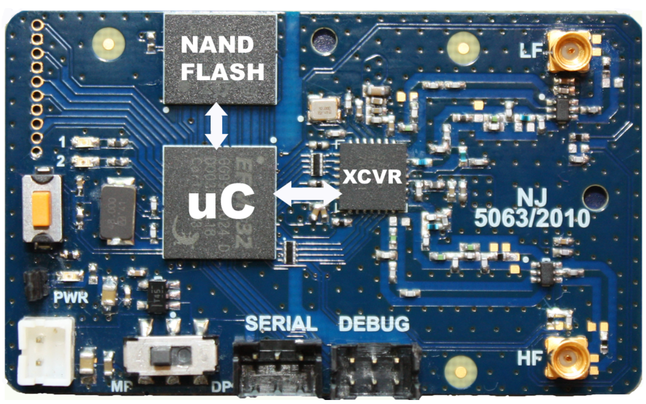

Figure 5: Physical appearance of the developed board. The board size is 35 mm x 58 mm

replaced the Yagis at 868 MHz with an omni-directional 6 dBi antenna at one end and a low-cost, stock rubber duck 4.5 dBi antenna on the other end. For 434 MHz, we used low-cost, stock rubber duck 0.7 dBi antennas on both ends.

3.2 Antenna alignment

The aiming of highly directive antennas represents a challenge. While one can use a compass in the field to establish the azimuth that had been previously calculated, for high gain antennas the compass method must be complemented by means of additional equipment. The standard procedure is to connect a signal generator that emits a stable continuous wave at a single frequency to antenna 1 at one end, and a spectrum analyzer to the antenna 2 at the other end. One then proceeds to leave antenna 1 pointed in

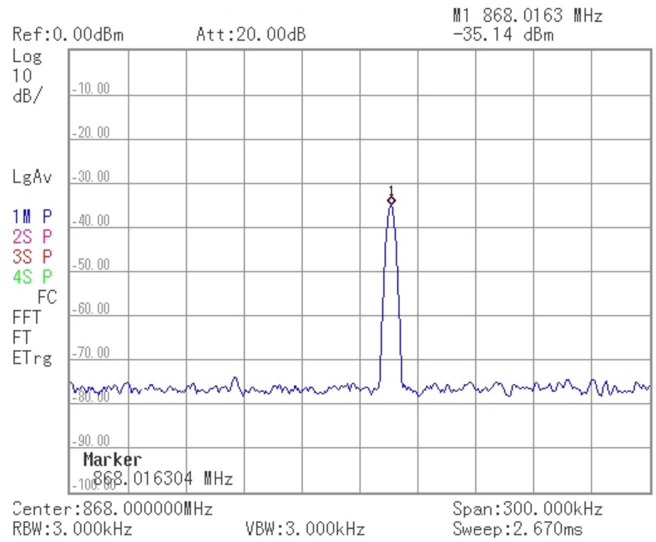

Figure 6: Narrow signal produced with FSK transmission mode to facilitate antenna alignment

the direction determined by the compass while antenna 2 is slowly swept horizontally continuously keeping track of the received signal strength on the spectrum analyzer screen. When a maximum is obtained, antenna 2 is fixed, and the procedure is repeated moving now antenna 1 until maximum signal is obtained again. One can then proceed to repeat the whole procedure at both ends in the vertical plane.

We leveraged the frequency shifting keying (FSK) capabilities of the Semtech transceiver used on the developed board to generate the single tone needed for antenna pointing. By setting the transmitting node to operate in FSK mode with a frequency deviation of 0 Hz, we produced a single tone signal, as can be seen in Fig. 6.

Although strictly speaking the result is not a continuous signal, since there are discontinuities in the transmission whenever the modulating signal changes, the interruption does not interfere with the alignment procedure since the frequency and amplitude do not change.

This spectrum can be compared with the much wider one of the LoRa signal depicted in Figure 7, which occupies a total of 125 kHz but on an intermittent basis and therefore is unsuited for antenna alignment purposes, since the span and resolution bandwidth setting on spectrum analyzer have to be as small as possible to increase the sensitivity of the analyzer to the required level.

On the receiving side we used a hand held spectrum analyzer to find the azimuth of the antenna position in which the received

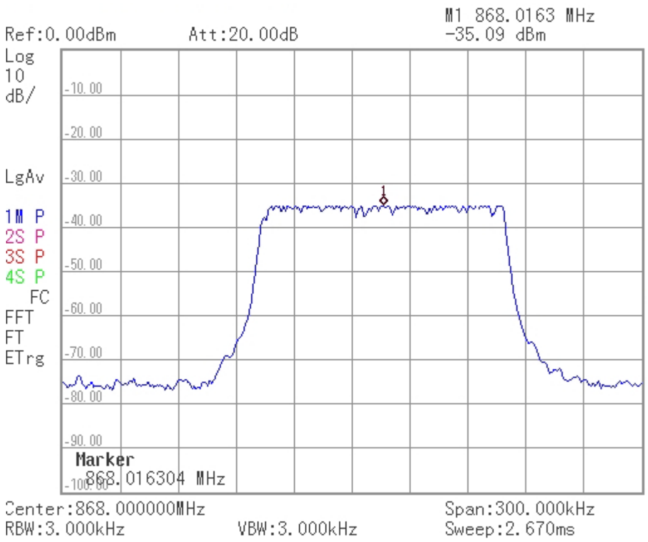

Figure 7: LoRa signal 125 kHz wide as measured in the lab

signal has the maximum power. The same procedure was then repeated at the other end. At such long distances the elevation angle is essentially horizontal, so no elevation adjustment was required.

It is interesting to note the use of the same developed board also as a very inexpensive and battery powered signal generator that replaces the expensive and bulky ones normally used for antenna alignment.

4 RESULTS AND ANALYSIS

In these experiments, we examined the received signal strength (RSS), signal to noise ratio (SNR) and packet reception rate (PRR). Received signal strength and signal to noise ratio were read by the micro-controller from registers in the transceiver and recorded in the NAND flash for post processing. Packet reception rate was calculated by measuring the fraction of correctly received packets out of the total number of transmitted ones. Figures 8, 9, 10 and 11 show the measurement results for both frequency bands and with different antenna combinations. A moving average on one-minute window to smooth-out short term fluctuations was applied to the RSS and SNR graphs, as well as to the PRR.

It can be observed that reception is almost flawless at both frequencies when Yagi antennas are deployed at 868 MHz and 6 dBi omni directional at 434 MHz. Since the RSS in the 868 MHz test scenario with Yagi antennas is relatively high we do not observe significant fluctuations of the measured received signal strength. On the other hand, when the RSS is approaching the sensitivity threshold, we observe significant fluctuations, both fast and slow. This observation is very important for link designing because it reveals slow fluctuation effects that are not easily observed on short distances. Slow term fluctuations at 434 MHz are around 25 dB when the received signal strength approaches the sensitivity threshold whereas they are bounded to 15 dB if the received signal is at least 10 dB above the sensitivity threshold. Packet reception rate decreases when RSS approaches the sensitivity of the receiver, as

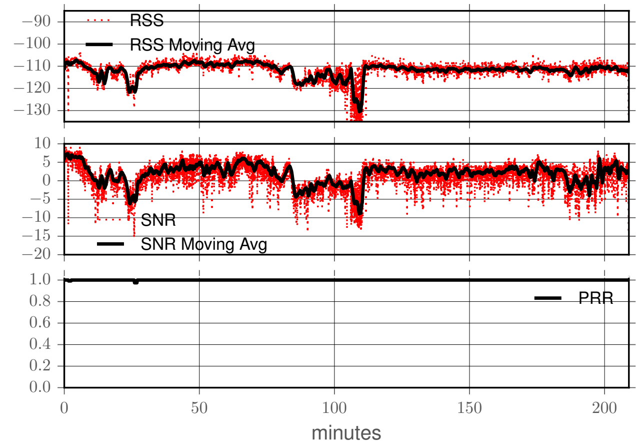

Figure 8: Experiment results at 434 MHz with 6 dBi omni directional antennas at both ends

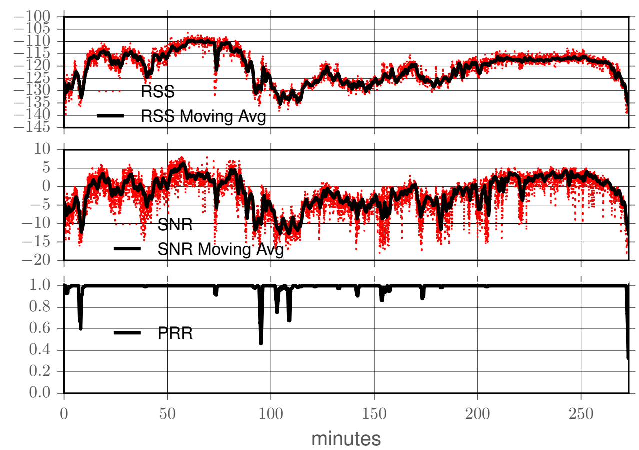

Figure 9: Experiment results at 434 MHz with 0.7 dBi omni directional antennas at both ends

expected. Reliable communication is possible even with low gain omni-directional antennas at 868 MHz, which proves that low cost, very long range links can be established even without expensive and bulky high gain antennas. In 434 MHz band, when omni 0.7 dBi low cost antennas are used on both ends, packet reception is still good, even when there are high fluctuations of RSS and SNR.

These results imply that it is possible to establish a reliable LoRa links at 434 MHz, even without using high gain antennas. In the 868 MHz band at least one antenna has to have a moderate gain, which in practical application could be at the Gateway node.

5 CONCLUSIONS

We built a low cost LoRa based board, optimized in terms of sensitivity, and successfully demonstrated transmission on an extreme long distance link, corresponding to typical scenarios in wireless applications in developing countries. Using BotRf, we were able to

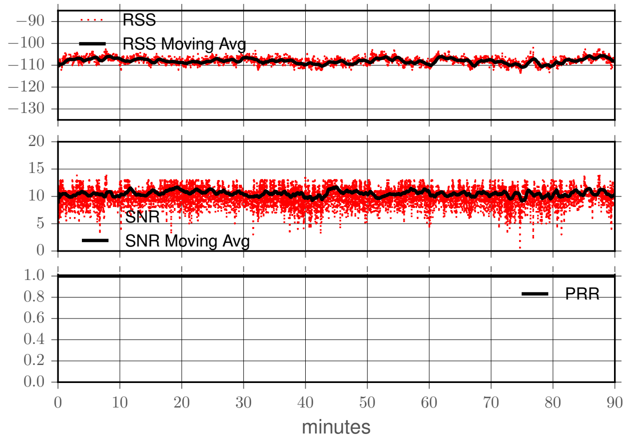

Figure 10: Experiment results at 868 MHz with Yagi 23 dBi antennas at both ends

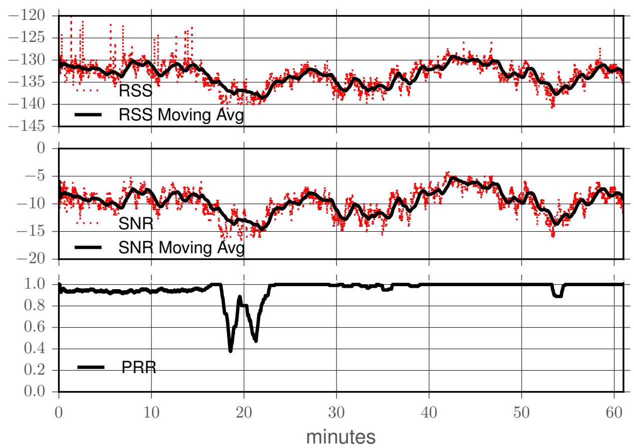

Figure 11: Experiment results at 868 MHz with 6 dBi omni directional antenna at one end, and 4.5 dBi at the other end

find a suitable test bed which offered complete clearance of the first Fresnel zone over a distance of 316 km at the standard atmospheric refraction index corresponding to a modified earth radius curvature factor of $k = 4/3$. We performed several measurements at both 868 MHz and 434 MHz and found that the packet reception rate was almost 100 percent when using the Yagi antennas and 6 dBi omni directional ones, respectively. Even when using the stock rubber duck antennas at each end the packet error was quite small at 434 MHz. The same applies at 868 MHz, when one end had an 6 dBi omni directional antenna and the other end a low gain rubber duck antenna. This proves the feasibility of very long distance links employing LoRa technology when there is a clear radio-electric line of sight between the transmitter and the receiver. It must be noted that over a 316 km distance the earth curvature intercepts (blocks) the line between the two end points and therefore the communication is only possible due to the bending of the radio waves as a consequence of the progressive reduction of the refraction index of the atmosphere with altitude under normal conditions. Therefore, in abnormal conditions (which happen very rarely), the communication would not be possible over this distance. We have also demonstrated the use of the same board as a lightweight, low cost, high power (14 dBm and 20 dBm), battery operated, single tone radio frequency generator that can be used for antenna alignment purposes as well as for cable testing and other applications. Future work will be aimed at performing long time experiments over a suitable long distance test bed to assess the performance over longer time periods and with variable spreading factors and different bandwidths. Our hope is that the work presented can elicit interest in applying this technology for disaster prevention and mitigation in remote areas.

REFERENCES

[1] Aloys Augustin, Jiazi Yi, Thomas Clausen, and William Mark Townsley. 2016. A Study of LoRa: Long Range and Low Power Networks for the Internet of Things. *Sensors* 16, 9 (2016). https://doi.org/10.3390/s16091466

[2] Martin Bor, John Edward Vidler, and Roedig. 2016. LoRa for the Internet of Things. In *Proc. 2016 Int. Conf. Embedded Wireless Systems and Networks*. Graz, Austria, 361 – 366.

[3] Alexandros-Apostolos A. Boulogeorgos, Panagiotis D. Diamantoulakis, and George K. Karagiannidis. 2016. Low Power Wide Area Networks (LPWANs) for Internet of Things (IoT) Applications: Research Challenges and Future Trends. *CoRR* abs/1611.07449 (2016). http://arxiv.org/abs/1611.07449

[4] ETSI 2011. ETSI TR 103 055 version 1.1.1. (2011). Retrieved July 13, 2017 from http://www.etsi.org/deliver/etsi_tr/103000_103099/103055/01.01.01_60/tr_103055v010101p.pdf

[5] LoRa Alliance 2016. LoRa Alliance. (2016). Retrieved July 13, 2017 from https://www.lora-alliance.org

[6] Andrea Zanella Marco Centenaro, Lorenzo Vangelista. 2016. Long-Range Communications in Unlicensed Bands: the Rising Stars in the IoT and Smart City Scenarios. *IEEE Wireless Communications* 23, 5 (2016), 60 – 67.

[7] Amy Nordrum. 2016. The internet of fewer things [News]. *IEEE Spectrum* 53, 10 (2016), 12 – 13.

[8] N.S.Miazi et al. 2016. The Internet of Things in Developing Countries: Opportunities and Challenges. In *proceedings of 5th International Conference on Informatics, Electronics and Vision (ICIEV) special session on Mobile Sensing*. Dhaka, Bangladesh.

[9] Juha Petajajarvi, Konstantin Mikhaylov, Antti Roivainen, Tuomo Hanninen, and Marko Pettissalo. 2015. On the coverage of LPWANs: range evaluation and channel attenuation model for LoRa technology. In *ITS Telecommunications (ITST), 2015 14th International Conference on*. IEEE, 55–59.

[10] Juha PetĂďjĂďjĂďrvi, Konstantin Mikhaylov, Marko Pettissalo, Janne Janhunen, and Jari Iinatti. 2017. Performance of a low-power wide-area network based on LoRa technology: Doppler robustness, scalability, and coverage. *International Journal of Distributed Sensor Networks* 13, 3 (2017), 1550147717699412. https://doi.org/10.1177/1550147717699412 arXiv:http://dx.doi.org/10.1177/1550147717699412

[11] Thomas Noel Pierre Neumann, Julien Montavont. 2016. Indoor deployment of low-power wide area networks (LPWAN): A LoRaWAN case study. In *IEEE 12th Int. Conf. on Wireless and Mobile Computing, Networking and Commun. (WiMob)*.

[12] Ermanno Pietrosemoli, Marco Zennaro, and Carlo Fonda. 2012. Low cost carrier independent telecommunications infrastructure. In *Global Information Infrastructure and Networking Symposium (GIIS), 2012*. IEEE, 1–4.

[13] Ramon Sanchez-Iborra and Maria-Dolores Cano. 2016. State of the Art in LP-WAN Solutions for Industrial IoT Services. *Sensors* 16, 5 (2016). https://doi.org/10.3390/s16050708

[14] Semtech 2016. LoRa. (2016). Retrieved July 13, 2017 from http://www.semtech.com

[15] Semtech datasheet 2016. SX1276/77/78/79 - 137 MHz to 1020 MHz low power long range transceiver. (2016). Retrieved July 13, 2017 from http://www.semtech.com/images/datasheet/sx1276.pdf

[16] The Things Network 2016. The Things Network. (2016). Retrieved July 13, 2017 from https://www.thethingsnetwork.org

[17] Geoffrey Werner-Allen, Konrad Lorincz, Mario Ruiz, Omar Marcillo, Jeff Johnson, Jonathan Lees, and Matt Welsh. 2006. Deploying a wireless sensor network on an active volcano. *IEEE internet computing* 10, 2 (2006), 18–25.

[18] Marco Zennaro, Marco Rainone, and Ermanno Pietrosemoli. 2016. Radio Link Planning made easy with a Telegram Bot. *arXiv preprint arXiv:1610.09248* (2016).