LoRa from the City to the Mountains: Exploration of Hardware and Environmental Factors

Oana Iova[1], Amy L. Murphy[2], Gian Pietro Picco[1], Lorenzo Ghiro[1], Davide Molteni[1],
Federico Ossi[3], Francesca Cagnacci[3]
[1] University of Trento, Italy, {oanateodora.iova, gianpietro.picco, lorenzo.ghiro, davide.molteni}@unitn.it
[2] Bruno Kessler Foundation, Italy, murphy@fbk.eu
[3] Edmund Mach Foundation, S. Michele all'Adige, Italy, {federico.ossi, francesca.cagnacci}@fmach.it

Abstract

LoRa technology is an increasingly popular option for applications that can exploit its low power and long range capabilities. While most efforts to date have studied its characteristics for smart city environments, we take LoRa outside the city limits, exploring how the environment affects its core communication properties. Specifically, we offer two novel parameter explorations to understand first how vegetation affects communication range and second how antennas change radio behavior. Our results provide insight into LoRa in non-urban environments, specifically showing that vegetation dramatically reduces the communication range and that the antenna selection can have a profound effect.

Categories and Subject Descriptors

[**Networks**]: Network performance evaluation

General Terms

LoRa technology, communication range, experiments

Keywords

LoRa, communication range, Internet of Things, LPWAN

1 Introduction

Recently, LoRa [6] has received much attention for its low power and long range communication, ideal for many smart city applications. A typical LoRa network is formed by connecting a powered, stationary gateway to a cellular/ethernet backbone network that relays data collected from static and mobile nodes to a network server. While this makes sense in a city scenario, we take a step back, considering scenarios where the gateway may not be connected to a backbone, and even more, a stable power supply may not be available.

Our reference application is in rural or forest environments, using LoRa for communication between a point of interest and nodes that are within several hundred meters. For example, biologists are interested to know when non-domestic animals get within the range of a point of interest, e.g., a feeding station. In this case, information collected from devices attached to the animals can be offloaded to a stationary node and collected later when the feeding station is replenished, as neither wall power nor a stable cellular communication connection can be assumed. Hence, instead of the typical, power-hungry LoRa gateway, we consider the option of a standard LoRa node that is battery powered.

The first goal of this paper is to explore LoRa's communication capabilities in these application scenarios. We are interested in finding how the communication range changes when LoRa devices are moved from a city scenario to mountainous areas (Section 4). Our exploration follows a first breadth, then depth approach: first exploring a wide set of parameters, then selecting one parameter setting and exploring it in detail in several scenarios. Specifically, we consider a valley near a river (similar to an open field), and two forest environments with varying vegetation, detailed in Section 3.

Second, the embedded devices (containing the LoRa radio chip) that can be attached to animals or people need to be small and light, hence using a dipole antenna is not an option. Therefore, we tested several antennas with different characteristics and sizes, evaluating both their connectivity, and their suitability to be used in small embedded devices (Section 5). We follow again the first breadth, then depth approach: first exploring a set of antennas, then selecting the most suitable one for small embedded devices and testing it further in the aforementioned scenarios.

To the best of our knowledge, we are the first to present LoRa data outside the city limits in a mountainous scenario, showing the severe impact that vegetation has over the communication range. Also, we are the first to systematically study the impact of different antennas in the same conditions.

2 LoRa in a Nutshell

LoRa [6] is a new technology that uses a spread spectrum modulation at the physical layer. This technique represents each bit of the payload data by multiple chirps of information. These are then spread over a wide band, below the noise level, resulting in communication that is resilient to interference and inherently secure. LoRa has a set of specific configurable parameters that offer a tradeoff between the range of communication, the data rate, and energy consumption:

International Conference on Embedded Wireless
Systems and Networks (EWSN) 2017
20–22 February, Uppsala, Sweden

ISBN: 978-0-9949886-1-4

- *Bandwidth (BW)* represents the frequency range occupied by the signal. LoRa allows the use of three different bandwidths: 125 kHz, 250 kHz, and 500 kHz. A higher value permits the use of a higher data rate, reducing transmission time, but achieving smaller transmission range.
- *Spreading Factor (SF)* represents the number of chirps per symbol used in the treatment of data before transmission of the signal. It can take values from 6 to 12. The larger the spreading factor, the more the receiver will be capable to recognize the right symbol. However, a larger spreading factor also increases the transmission time to send a packet.
- *Coding Rate (CR)* is used in LoRa to improve the robustness of the radio link by performing forward error detection and correction. Each message is encoded in a redundant way, allowing the receiver to detect and correct a limited number of errors. LoRa allows four values for the coding rate: 4/5, 4/6, 4/7, and 4/8. Smaller values increase redundancy, and thus the data overhead, but the result is also more robust.

Existing studies on LoRa are very few, and are focusing on experiments performed in smart city scenarios [2, 3], indoor [5], or over water (with the end-device attached to the radio mast of a boat) [7]. None of them however, recorded or took into account during analysis the impact of environmental factors (e.g., temperature, wind, altitude, vegetation), or the use of small antennas suitable for embedded devices.

3 Experiment Design

We present here the general setup for our experiments: the hardware we used, the environmental sites, and the metrics that characterize the connectivity between LoRa devices.

3.1 Platform

We used the SX1272 evaluation kit from Semtech, which allows the user to test every aspect of the radio, all configuration parameters being easily accessible from a touch screen. The kit offers two portable devices equipped with an SX1272 radio module that works in the 868 MHz European band, and a 1/2 wave dipole antenna.

Considering the number of LoRa parameters that can be configured, we define here a configuration notation that we use throughout the paper: $< BW, SF, CR >$, where the abbreviations correspond to the LoRa parameters: bandwidth, spreading factor, and coding rate.

3.2 Sites

Our experiments were performed in four different sites, with different environmental characteristics. Two of them are situated in the valleys around the Italian city of Trento, providing the setup for our Line-of-Sight (LOS) experiments. The other two are mountainous areas with different vegetation characteristics. We present next each of them.

AIRPORT. This site is situated in the Adige valley next to Trento, on a bike lane that lies parallel to the runway of the regional Mattarello airport, where the lack of buildings, vegetation, and other obstacles provided LOS conditions for 1.5 km to test the connectivity range. During the experiments, there was some interference due to helicopters landing or taking off, but that data was discarded.

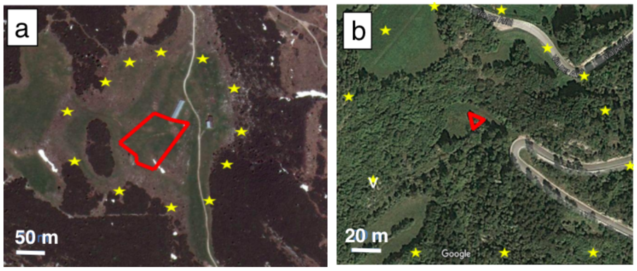

Figure 1. MOUNTAIN (a) and FOREST (b) environments. The red lines denote the area of interest. The yellow stars indicate the positions from which radio connectivity was assessed.

BIKE. Due to the interference present in the previous setting, we chose another site with LOS conditions: an 800m long bike lane, outside Trento, still in the Adige valley.

MOUNTAIN. The first mountainous site is Malga Covelo (Figure 1a), located at an altitude of ca. 1700 m a.s.l., in an open field. This area is slightly hilly, with a 10 - 15 m height difference separating the top of the site from the bottom. The site is surrounded by open fields, although on one side some shrubs (*Pinus mugus*) are present. While this area provides mostly LOS communication, its hilly configuration make it an interesting case study.

FOREST. The second mountainous site, Maso Ariol (Figure 1b), located at an altitude of ca. 650 m a.s.l. has a small flat area in the middle, but the surroundings are hilly and rocky, and presenting a prevalently flat meadow of width ca. 20 - 30, beyond which a dense and steep forest is present. This setting is very characteristic for a mountainous area, where the dense vegetation prevents LOS communication.

3.3 Metrics

During our experiments we used different metrics to characterize the connectivity between transmitter and receiver:

- *Packet Delivery Ratio (PDR)*, which provides information on the reliability of the communication; the PDR is computed as the ratio of valid received packets over the number of transmitted packets;
- *Received Signal Strength Indication (RSSI)* and *Signal to Noise Ratio (SNR)* are two PHY-level indicators available on the radio chips, which we used to characterize the quality of the LoRa signal;
- *Connectivity range* represents the measured distance between receiver and transmitter. Our goal was to study the connectivity range when the PDR was above 90%.

4 Exploring LoRa's Communication Range

In this section we aim to explore the communication range of the LoRa technology outside the city scenario. We make this exploration in three steps: *i)* search the lower bound of the transmission range in open space, and find out how this changes in the presence of vegetation; *ii)* study which of the parameters influences the communication range and how; *iii)* asses how consistent the quality of the signal is when tested in different environments.

Table 1. Maximum distance at which LoRa can communicate while using the minimum range setup. Experimental results at the AIRPORT.

TX Power (dBm)	Connectivity range (m)	PDR
7	450	95%
13	550	93%
14	550	93%

4.1 What are the Limits of Communication?

As a first experiment, we set out to find a lower bound for the transmission range (by keeping both transmission and reception as short as possible), as until now LoRa has been tested only for its *maximum* transmission range.

Experimental setup. We set the transmitter in a fixed position that was kept the same for every measurement. Then, we placed the receiver at different distances from the transmitter, to identify the ranges within which the LoRa devices operated with good performance. For each distance, we computed the PDR over 100 packets. We used the settings that would keep both transmissions and receptions as short as possible: $< 500\text{ kHz}, 6, 4/5 >$, and we repeated the test at various transmission powers (7, 13 and 14 dBm). The payload size was set to 9 Bytes, and the packet delay to 100 ms. These tests were run in sunny conditions, with a temperature of 24° C and a lack of wind.

Results. The first tests were conducted at the AIRPORT, which gave us a LOS environment. The results are presented in Table 1. We found that even at a transmission power of 7 dBm the radios manage to communicate at a distance of 450 m, with a PDR of 95%.

However, during our tests in FOREST we noticed that at 90 m there was no communication at all for any of the transmission power tested. We even used the power boost mode present on the evaluation kit (which makes use of a second amplifier) at 20 dBm. We managed to get some connectivity at this point, but the PDR obtained was 80%. Our conclusion is that the drop in range/quality induced by vegetation is substantial. The communication range drops from 450-550m (in a LOS environment) to 50-90m in a NLOS vegetation environment, which is *an order of magnitude* difference in range. It is worth mentioning however, that these tests where a) on a slope b) through thick vegetation / trees, i.e., the worst conditions in our case.

Another observation is that for LoRa, the radio transmission power does not seem to be a dominant parameter affecting the connectivity range or the PDR. Instead, other parameters such as BW, SF, and CR play more relevant roles. This is interesting because the transmission power was *the* parameter used for increasing the communication range in *classical* Wireless Sensor Network (WSN) radio technologies (e.g., CC2420 used in TMote devices).

4.2 What Influences the Communication?

After observing that transmission power does not have a large impact on the communication range for LoRa, we address the question of which of the other parameters does have the most influence. Therefore, we ran experiments over a series of different parameter configurations, to study the variation of the connectivity range.

Table 2. LoRa parameter exploration. Experimental results at the AIRPORT.

BW (kHz)	SF	CR	Distance (m)	PDR	Time on air (ms)
500	6	4/5	270	93%	4.51
125	6	4/5	500	94%	18.05
125	7	4/5	500	94%	41.22
125	8	4/5	700	96%	72.19
125	8	4/8	900	96%	90.62
125	6	4/8	500	96%	22.66

Experimental setup. The experiments took place at the AIRPORT, using the same methodology as before. We tried however, a larger combination of values for all the parameters: bandwidth (125 kHz and 500 kHz), spreading factor (from 6 to 8) and coding rate (4/5 and 4/8), while keeping the radio transmission power at 7 dBm. This time, however, the weather was warmer, with a temperature of 36° C, humidity 30% rh, and no wind (short bursts of 1.6 km/h).

Results. As we can see in Table 2, we found that bandwidth is one of the parameters that has the most impact on the communication range. Indeed, by only changing the bandwidth from 500 kHz to 125 kHz (the first two lines in the table), the communication range almost doubles, reaching 500 m. Another important change is noted when the spreading factor is increased from 6 to 8 (the last two lines in the table): again, the communication range almost doubles from 500 to 900 m. However, this increase severely impacts the duration of the transmission: the time on air of a packet reaching 90 ms, which as a consequence means more energy consumption and lower data rate.

Considering the environmental factors, we note the severe impact that high temperature has on the communication range. For the same settings as in our first test ($< 500\text{kHz}, 6, 4/5 >$), the distance drops almost by half at a temperature of 36° C, barely reaching 270m. This phenomena was already observed on other technologies (e.g., IEEE 802.15.4) [4], but never before on LoRa radios.

4.3 How Consistent Is the Communication?

After evaluating LoRa's connectivity range through an exploration of its parameters, we now select one configuration and explore it in depth, analyzing how consistent the quality of the signal is in different environments. We immersed the two LoRa devices in our representative sites: MOUNTAIN (a hilly mountain with sparse vegetation) and FOREST (a mountain with a dense forest) and tested their connectivity around the whole area.

Experimental setup. With respect to the previous tests, we reversed our approach, since we were not interested in detecting the maximum range of connectivity for any particular setting. Rather, we aimed at evaluating whether the connectivity was good all around the area, at a given distance from a point of interest that we consider to be more or less in the middle (denoted with red lines in Figure 1). We set this distance at 100 m and we assessed the connectivity every 30° (0 - 30 - 60 - . . . - 330) clockwise from the North, measuring the distance of 100 m from the site by means of a compass and a rangefinder and/or a metric rope. At each of the 12 dis-

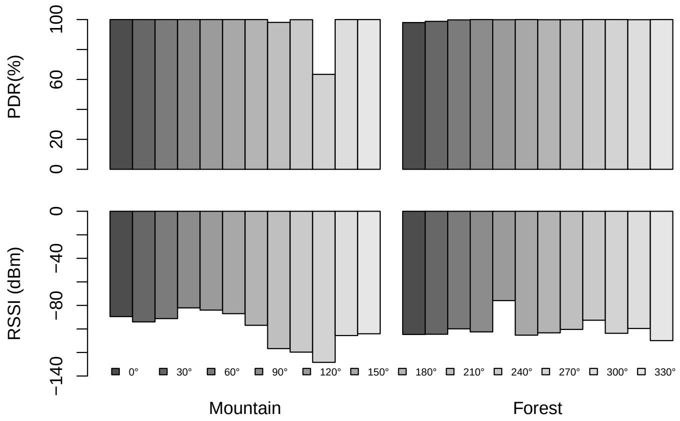

Figure 2. Average PER and RSSI for the three experiments done at the MOUNTAIN (Malga Covelo) and FOREST (Maso Ariol) environments.

tances we measured the PDR and the RSSI over 100 packets. We replicated the experiments 10 times towards each direction, to increase the statistical robustness of our data.

To reach our desired distance of 100 m, we use the < 125 kHz$, 9, 4/6 >$ settings, at a transmission power of 7 dBm, taking into account what we learned from the previous experiments. We had to change the packet delay to 200 ms, as 100 ms was too short for the time on air spent by a packet in these new settings (156.67 ms). We ran the experiments in sunny and cloudy conditions, with temperatures between 20° C and 30° C and weak winds.

Results. Overall, we found good results at both sites tested. In MOUNTAIN, the connectivity is generally very good in every direction except at 210°, and especially at 270°, where the PDR drops to 63.4% and the RSSI to -128 dBm, close to LoRa's minimum receiver sensitivity (Figure 2). When we tested in these directions we found that the 100 m point fell on the opposite side of a small hill (height ca. 20 m) with respect to the receiver. As such, the presence of this obstacle hampered the connectivity in these directions. It is worth noting that in all other directions the connectivity was good, despite the presence of other obstacles (e.g., *Pinus mugus* shrubs), or a remarkable elevation gap between transmitter and receiver (up to 25 - 30 m).

In FOREST, we found consistent patterns, although the area presents different environmental characteristics. The connectivity is generally very good in any direction, despite the high vegetation (Figure 2). The PDR drops to 98% only at 0° (as the measured point was on the other side of the road), and the RSSI has quite constant values, around -100 dBm. Indeed, the presence of dense wood in all directions (except at 120°) and of relevant altitudinal gap between the transmitter and the receiver (from + 30 m to - 25 m) does not seem to affect the connectivity of LoRa.

4.4 Lessons Learned

We derive three main conclusions from the extensive evaluation of LoRa in a mountainous environment:

Vegetation matters. The connectivity range drops by an order of magnitude when devices are moved from open space to a dense forest environment. However, once in the forest, the PDR stays mostly constant, except for the presence of hills between the receiver and transmitter.

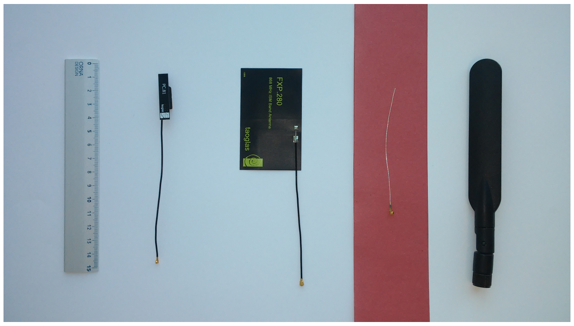

Figure 3. Different antennas. From left to right: PC81, FXP280, Laird and the dipole.

Temperature matters. High temperature degrades the quality of the link, similar to common narrowband technologies.

Transmission power is not key to range. Unlike classical WSN technologies, with LoRa transmission power is not the dominant parameter affecting the connectivity range and the PDR. Instead, other parameters such as the bandwidth, the spreading factor and the coding rate play more relevant roles.

5 Impact of Using Different Antennas

To the best our our knowledge, the experiments performed with LoRa devices to date have all used a dipole antenna, in part because it comes with the evaluation kit, but also because it is a very common antenna. However, when the application requires small, embedded devices, a dipole antenna is bulky, and in many cases bigger than the device itself. Motivated by this, we took it upon ourselves to identify an antenna that could meet these physical requirements while maintaining the propagation characteristics of the dipole. We follow again the first breadth, then depth approach: first exploring a set of antennas, then selecting the most suitable one for small embedded devices and testing it further in the different mountainous environments.

5.1 Overview of Antennas

In this section we evaluate the differences in connectivity range arising from using different antennas, and their suitability to be used in small embedded devices. Therefore, we tested several antennas with different characteristics and sizes (Figure 3), connecting them to the evaluation kit:

- PC81 [9]: consists of a PCB antenna, a 1.13 mm mini coaxial cable, and a foam attachment with adhesive on the underside which assists in placing the antenna with sufficient clearance for optimal performance. It has a size of only $34 \times 7 \times 0.8$ mm for the PCB and $16 \times 6 \times 7$ mm for the foam;
- FXP280 [8] has been designed in a flexible material with a square form-factor and cable connection for an easy installation. It has a size of $75 \times 45 \times 0.1$ mm;
- Laird [1] is an omnidirectional flexible antenna that measures only 84 mm.

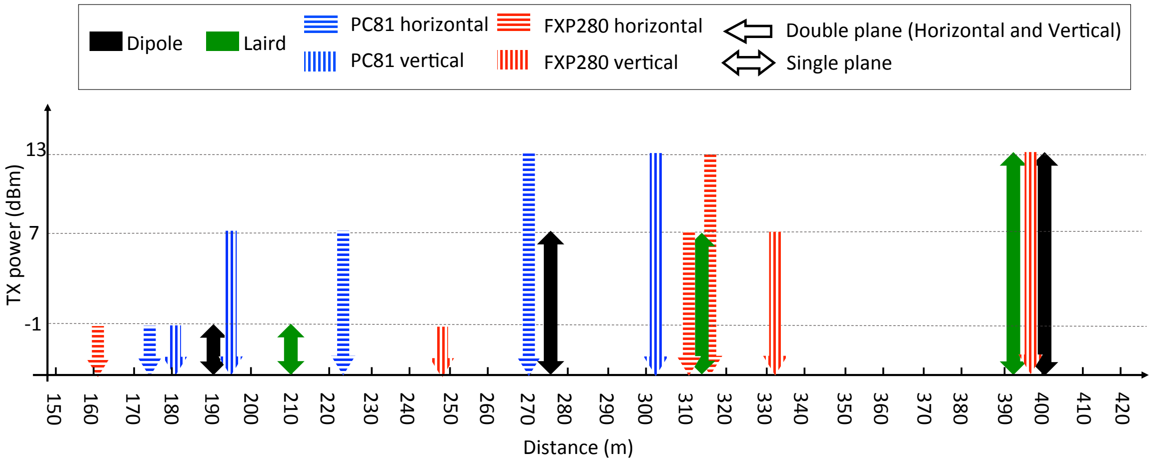

Figure 4. Communication range for the different antennas and transmission power.

Experimental setup. We compared the performance of these three antennas against the dipole. We used the settings for the minimum range $< 500 \text{ kHz}, 6, 4/5 >$ and tested different radio transmission powers (-1, 7 and 13 dBm). In the case of PC81 and FXP280 we also tested both the horizontal and vertical radiation planes. The experiments were done at the AIRPORT, when the temperature was between 35-36°C, humidity 30% rh, and there was no wind.

Results. As we can see in Figure 4, the PC81 antenna had the most consistent results on both radiation planes of interest, even though it exhibited a decrease in communication range with respect to the dipole. This decrease is most likely impacted by a 5 dBm antenna loss (as indicated in the datasheet [9]), and hence, it might be compensated by increasing the transmission power. The FXP 280 showed an uneven behavior across both planes, and its size might be too big for the packaging of some small embedded devices, even though it is very thin. The Laird antenna has slightly better performance than the dipole antenna, but since it has only one radiation plane, it might not be suitable for use in some cases (e.g., if the device is attached on an object/animal/person that changes its position), as it needs to stay on a vertical position.

5.2 Connectivity Assessment

Based on the previous assessment of the antennas, we chose the PC81 antenna (due to the combination of its size and constant performance) to conduct a more in-depth analysis of its performance, both in terms of its two radiation planes, and on its communication range.

Experimental setup. We changed the LOS test site from the AIRPORT to the BIKE, to avoid interference problems due to the helicopters. We connect the PC81 antenna to one device (e.g., an embedded device on an animal), and the dipole to the second device (e.g., a fixed node). The receiver was placed on the Eastern corner of the bike road while the transmitter was moved in a westward direction with steps of 50 m until the radio contact between devices was almost lost. The two antennas were then switched between the transmitter and the receiver, in order to study the symmetry of the communication. We used the same settings as in the mountain experiments $< 125 \text{ kHz}, 9, 4/6 >$. The transmission power for the dipole antenna was set to 7 dBm, while for the PC81 antenna it was set to 12dBm, to account for the 5 dBm antenna loss. The temperature was 32-35°C, humidity 25-30% rh, and weak winds.

Results. The PDR shows a sudden drop at a distance of 500-550 m for all tests (Figure 5). This is due to a factory building present in the vicinity of where these measurements were taken, and which apparently impacted the communication, as it is also shown by a drop in the SNR at this point. The two radiation planes of the PC81 antenna show similar PDR results when the antenna is used in the same direction, which confirms our previous findings. However, the surprising results come when we look at the symmetry of the communication: it seems that when the PC81 antenna is used as a receiver, the communication is more susceptible to noise, the SNR reaching values two times smaller than the when it is used as a transmitter. The reason is the attenuation of the signal of the PC81 antenna due to its 5dBm loss. While we can compensate this attenuation on the transmitter by increasing the transmission power with 5 dBm, there is nothing that we can do on the receiver. As a consequence, the PDR in the area of the factory drops down to 40% and the range for good communications (PDR close to 100%) is shortened from 750-850m to 600m.

5.3 Consistency of the Signal

To have a more complete evaluation of the PC81 antenna, we tested how consistent the quality of a signal is in the different mountainous environments. Moreover, since we wanted to simulate a scenario closer to reality, we did not pay particular attention to the position of the antenna plane.

Methodology. The experiments were performed both in the MOUNTAIN and FOREST sites, in a clockwise direction every 30° starting from the North, at a fix distance of 100m. We kept the PC81 antenna on the transmitter, and the dipole on the receiver (i.e., playing the role of a base station). We used the same $< 125 \text{ kHz}, 9, 4/6 >$ settings. The transmission power for the dipole antenna was set to 7 dBm, while for the PC81 antenna it was set both to 7 and 12dBm, to ascertain whether the gain in power compensated for the 5dBm loss. We ran the experiments in sunny and cloudy

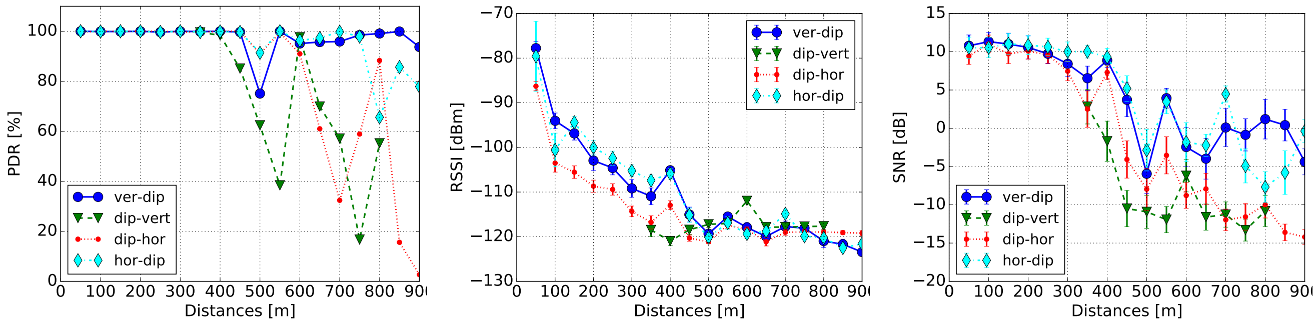

Figure 5. PDR, RSSI, and SNR of the communication between the PC81 (with both radiation planes: vertical and horizontal) and the dipole antennas in open field. In the legend, the communication is specified as TX antenna - RX antenna. The PC81 is named only corresponding to the used radiation plane.

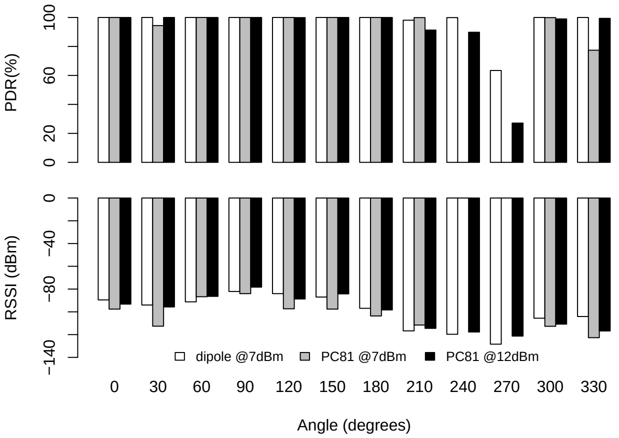

Figure 6. Results from the MOUNTAIN site comparing the dipole and PC81 antennas. The antenna used for transmission is depicted in the legend.

conditions, with temperatures between 20° C and 30° C and weak winds in most of the cases.

Results. Due to limitation in space, we show here only the results from the MOUNTAIN, as they are more representative (Figure 6). At a transmission power of 7dBm for the PC81 antenna, the transmitter shows an overall decrease of the quality of the signal with respect to when the dipole is used, with complete lack of connectivity at 240° and 270°, where there is a hill between the transmitter and receiver. This is in line with our previous findings, showing that the attenuation of the PC81 antenna is having a big impact on the communication quality.

On the other hand, the increment of 5 dBm to the transmission power on the PC81 antenna produces results similar to the dipole, with PDR 100% in most of the cases. PDR drops to 20% only when the transmitter is behind the hill, as the RSSI gets close to LoRa's minimum receiver sensitivity.

5.4 Lessons Learned

There is one main takeaway from the study of different antennas on the communication of LoRa:

Antenna matters. Especially when having several radiation planes, as they might have different communication ranges. The choice of an antenna must be made extremely carefully as any attenuation might induce asymmetry in the communication.

6 Conclusions

We have shown through in-field evaluations that LoRa connectivity changes significantly when devices are moved away from a smart city scenario into mountainous environments: the communication range drops by an order of magnitude, and high temperatures deteriorate the signal. Also, choosing the right antenna for use in an embedded device will make the difference for a successful deployment.

This work represents a steppingstone towards a full characterization of LoRa communication. In the future we plan to quantify how environmental factors (e.g., temperature, wind) impact LoRa communication over both short and long periods of time.

7 References

[1] Anaren Integrated Radio (AIR). 66089 U.FL antenna series. `https://www.anaren.com/sites/default/files/Part-Datasheets/66089-xxxx-Antenna.pdf`. Accessed: 2016-10-27.

[2] M. Aref and A. Sikora. Free space range measurements with Semtech Lora^{TM}technology. In *2014 2nd International Symposium on Wireless Systems within the Conferences on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications (IDAACS-SWS)*, pages 19–23, Sept 2014.

[3] A. Augustin, J. Yi, T. Clausen, and W. M. Townsley. A study of LoRa: Long range & low power networks for the internet of things. *Sensors*, 16(9), Sept. 2016.

[4] C. A. Boano, N. Tsiftes, T. Voigt, J. Brown, and U. Roedig. The impact of temperature on outdoor industrial sensornet applications. *IEEE Transactions on Industrial Informatics*, 6(3):451–459, Aug 2010.

[5] M. Bor, J. Vidler, and U. Roedig. LoRa for the internet of things. In *Proc. of the 2016 International Conference on Embedded Wireless Systems and Networks (EWSN)*, pages 361–366, Feb. 2016.

[6] LoRa Alliance^{TM}. Wide area networks for IoT. `https://www.lora-alliance.org/`. Accessed: 2016-10-27.

[7] J. Petajajarvi, K. Mikhaylov, A. Roivainen, T. Hanninen, and M. Pettissalo. On the coverage of LPWANs: range evaluation and channel attenuation model for LoRa technology. In *2015 14th International Conference on ITS Telecommunications (ITST)*, pages 55–59, Dec. 2015.

[8] Taoglas Antenna Solutions. FXP280.07.0100A, 868MHz ISM band flex circuit antenna. `https://www.taoglas.com/wp-content/uploads/2015/05/FXP280.07.0100A.pdf`. Accessed: 2016-10-27.

[9] Taoglas Antenna Solutions. PC81.07.0100A.db, TheStripeTM 868Mhz PCB antenna. `http://www.taoglas.com/wp-content/uploads/2015/06/PC81.07.0100A.dB_.pdff`. Accessed: 2016-10-27.