Impact of Temperature Variations on the Reliability of LoRa
An Experimental Evaluation

Carlo Alberto Boano, Marco Cattani, and Kay Römer
Institute of Technical Informatics, Graz University of Technology, Austria
{*cboano, m.cattani, roemer*}*@tugraz.at*

Keywords: Long-range technology, Networks, PHY settings, Temperature, Reliability, RSSI, Wireless.

Abstract: Temperature variations are known to affect the performance of wireless sensor networks deployed outdoors. Whilst the impact of temperature on IEEE 802.15.4 transceivers has long been investigated by the research community, still little is known about how temperature affects the performance of increasingly popular long-range wireless technologies such as LoRa. To fill this gap, this paper presents an experimental evaluation of the reliability of LoRa in the presence of temperature variations. First, we highlight that temperature can have a significant impact on LoRa's communication performance and show that an increase in temperature can be sufficient to transform a perfect LoRa link into an almost useless one. We then carry out a detailed investigation on the performance of different LoRa physical settings with fluctuating temperatures and show that an optimal selection can help in increasing the probability of packet reception and is hence key to mitigate temperature-induced effects. We believe that our results will serve as a reference to orient researchers and system designers employing LoRa to build large-scale low-power wide area networks.

1 INTRODUCTION

Outdoor environmental conditions are known to drastically affect the performance of wireless sensor networks (WSN). Networks deployed outdoors, indeed, often experience a reduction of the delivery rate and the connectivity between nodes in the presence of fog (Anastasi et al., 2004), rain (Boano et al., 2009), snow cover (Stoianov et al., 2007), thick vegetation (Marfievici et al., 2013), and temperature variations (Bannister et al., 2008). Especially the latter can have a severe impact on the performance of outdoor WSN systems (Wennerström et al., 2013), as they can affect clock drift, battery capacity and discharge, as well as radio efficiency, hence directly affecting fundamental aspects such as time synchronization, network lifetime, and reliability of transmissions.

Most of the existing work investigating the impact of temperature on low-power wireless networks has focused on IEEE 802.15.4 transceivers. The impact of temperature was shown to be platform-specific (Boano et al., 2010) and to lead to severe consequences on the functionality of duty-cycled medium access control (Boano et al., 2014a) and routing (Keppitiyagama et al., 2013) protocols.

Despite the comprehensive studies carried out on IEEE 802.15.4 transceivers, however, still little is known about the impact of temperature on other low-power wireless technologies, especially on the increasingly popular low-rate and long-range transmission technologies used to realize low-power wide area networks (Centenaro et al., 2016).

Long-range wireless technologies such as Sigfox (Sigfox, 2017), Weightless (Weightless SIG, 2017), and LoRa (LoRa Alliance, 2017) are very promising for the realization of large-scale Internet of Things (IoT) applications, as they allow city-wide deployments and large outdoor installations in remote areas. Among others, LoRa has been proposed to realize a number of smart city applications (Kartakis et al., 2016), outdoor parking guidance systems (KSK Developments, 2017), as well as smart water management infrastructures (Cattani et al., 2017b).

As a few preliminary works have shown a possible temperature-dependent performance of LoRa networks deployed outdoors (Iova et al., 2017), (Cattani et al., 2017a), it is important to investigate in detail the impact of temperature on LoRa communications and understand how it can be possibly mitigated.

Contributions. In this paper we experimentally study the impact of temperature on the performance of LoRa using a temperature-controlled testbed. We first show that temperature has a strong impact on the performance of LoRa, and that an increase in temperature similar to the daily and seasonal fluctuations of temperature outdoors may transform a good link (i.e., a link with high packet reception rate) into an almost useless one (i.e., a link sustaining a packet reception rate close or equal to 0). In particular, we show that a gradual increase in temperature leads to a higher number of corrupted and lost packets, as well as to a progressive reduction of the received signal strength (RSS). We show that such RSS attenuation is platform-dependent and that it varies depending on the distance between nodes.

We then thoroughly analyze the performance of different LoRa's physical layer (PHY) settings in the presence of varying temperatures and show that an optimal selection is key to minimize temperature-induced effects. In particular, we show that selecting a lower bandwidth and a higher spreading factor, as well as a more robust coding rate can significantly help in maintaining a reliable communication despite an increase of the on-board temperature.

This paper proceeds as follows. In the next section, we introduce the reader to the increasingly popular LoRa long-range technology and to the physical layer settings that can be configured to fine-tune the transceiver's operations. After describing related work in Sect. 3, we show the results of a series of experiments conducted in a temperature-controlled testbed in Sect. 4, highlighting how an increase in temperature can transform a perfect link into an almost useless one. We then thoroughly analyze the performance of each PHY setting in LoRa at varying temperature in Sect. 5 and show how an optimal selection can help minimizing temperature-induced effects. After elaborating on our findings in Sect. 6, we conclude the paper and outline possible future work in Sect. 7.

2 LORA TECHNOLOGY

LoRa is a proprietary radio modulation technology developed by Cycleo and acquired by Semtech in 2012 that is very promising for building wide access networks with star topology (often referred to as low-power wide area networks). The latter provide long-range communication to thousands of devices at minimal cost and limited energy expenditure, therefore allowing to realize large-scale urban IoT networks.

LoRa has the ability to improve the signal-to-noise ratio (SNR) at the receiver by spreading the energy of the signal over a wider frequency band, effectively reducing the spectral power density of the signal (Kartakis et al., 2016). The core of LoRa technology is its chirp spread spectrum (CSS) modulation: the carrier signal of LoRa consists of *chirps*, signals whose frequency increases or decreases over time (Cattani et al., 2017a). LoRa's chirps allow the signal to travel distances up to several kilometers (Centenaro et al., 2016) and to be demodulated even when its power is up to 20 dB lower than the noise floor.

One of the key advantages of LoRa is the reduced complexity of networking protocols, as the long communication range allows to form star topologies where the low-power end devices directly communicate with a more powerful orchestrator. This allows to design asymmetric communication schemes and to shift the load to a powerful central device, keeping the design of end devices simple and cheap.

LoRa transceivers communicate using the sub-GHz unlicensed industrial, scientific, and medical (ISM) bands. Among others, LoRa exploits for its communications the 433 MHz and 868 MHz ISM bands in Europe, and the 915 MHz ISM band in North America. LoRa radios also allow to adjust the transmission power and hence to control the energy necessary to transmit a packet: common transceivers support transmission powers between -4 and +20 dBm.

Besides the selection of carrier frequency and transmission power (supported by most low-power transceivers used to build IoT applications), the communication performance of LoRa can be fine-tuned by varying a number of PHY settings, such as *bandwidth*, *spreading factor*, *coding rate*, and *carrier frequency*. Among others, these specific PHY settings allow to trade receiver sensitivity (and hence a longer communication range and a more robust communication) for a higher data-rate, as we describe next.

Bandwidth (BW). By varying the range of frequencies over which LoRa's chirps spread (i.e., by varying the bandwidth), one can trade radio air-time against radio sensitivity, thus choosing between a higher energy-efficiency (lower air-time) and a higher communication range and robustness. The use of a narrow bandwidth maximizes sensitivity, but increases air-time. Increasing the bandwidth, instead, allows for faster transmissions (and hence a lower air-time), but reduces sensitivity (Semtech Corporation, 2013).

Spreading Factor (SF). LoRa "spreads" each symbol (information bits) over several chips to increase the receiver's sensitivity. LoRa's spreading factor can be selected between 6 and 12, resulting in a spreading rate ranging from 2^6 to 2^{12} chips/symbol. Please note that LoRa modulation employs orthogonal spreading factors. This enables multiple spread signals to be transmitted at the same time and on the same channel with minimal degradation of the receiver sensitivity (Semtech Corporation, 2015), i.e., packets transmitted with different spreading factors appear as noise to the target receiver.

Setting	Typical values	Impact on communication performance
Bandwidth [kHz]	125 … 500	A higher bandwidth allows to transmit packets at a higher data rate. However, a higher bandwidth also reduces the receiver sensitivity and hence the communication range.
Spreading Factor	6 … 12	A high spreading factor increases the signal-to-noise ratio and hence the radio sensitivity / communication range. However, a higher spreading factor increases the length of packets, hence causing a higher energy expenditure.
Coding Rate	4/5 … 4/8	A larger coding rate increases the resilience to interference bursts and decoding errors. However, a large coding rate implies the transmission of longer packets and hence increases the energy expenditure.

Table 1: Summary of the main configurable physical settings in LoRa and their impact on communication performance.

Coding Rate (CR). LoRa makes use of forward error correction to increase the resilience to packet corruption. In particular, one can specify the number of redundant bits, ranging from 1 to 4, where a higher number should be used when transmitting in congested radio environments (i.e., one should select a higher coding rate to maximize the probability of successful packet reception). Transceivers operating with different coding rates can still communicate to each other, since the packet header (transmitted using the maximum coding rate of 4/8) includes the code rate used for the payload.

Table 1 summarizes the typical values and the impact of each PHY setting on data rate, receiver sensitivity, communication range, and energy-efficiency (Semtech Corporation, 2015).

3 RELATED WORK

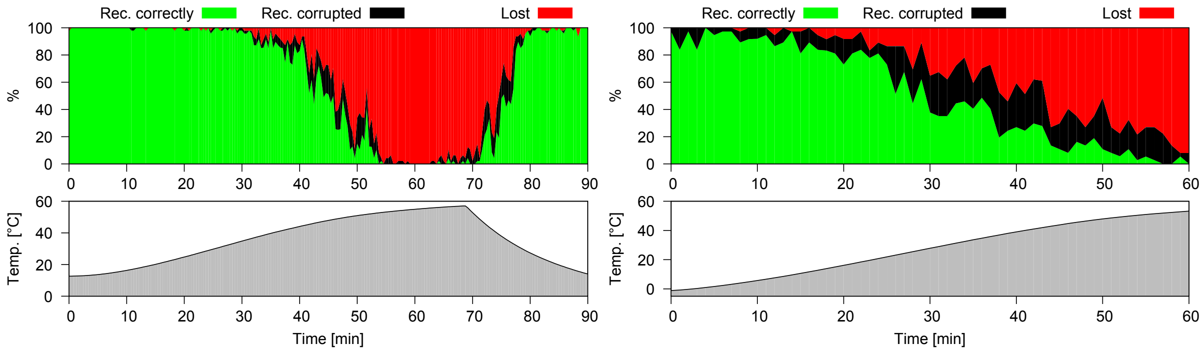
The impact of temperature on the performance of wireless sensor networks has been largely analyzed by the research community, especially in the context of IEEE 802.15.4 radios. After showing the correlation between temperature and received signal strength (RSS) in a deployment in the Sonoran desert, Bannister et al. have confirmed in a temperature-controlled chamber that the RSS of the TI CC2420 radio attenuates at high temperatures. The authors have further identified that such RSS attenuation is due to the impact of temperature on the CC2420 transceiver's low-noise and power amplifiers (Bannister et al., 2008).

Based upon this work, a number of researchers have confirmed that these findings also apply in a similar way to other IEEE 802.15.4 platforms such as the TI CC1020 and CC2520 (Boano et al., 2010), and have highlighted how diurnal and seasonal temperature variations can cause a complete disruption of an IEEE 802.15.4 link (Boano et al., 2013). Wennerström et al. have also presented results from a long-term outdoor deployment of TelosB nodes and have shown that packet reception ratio and RSS are highly correlated with temperature, whereas their correlation with other factors such as absolute humidity and precipitation is less pronounced (Wennerström et al., 2013). Other authors have also shown how the impact of temperature variations on low-power radio transceivers may strongly affect the operations of duty-cycled medium access control (Boano et al., 2014a), (Oppermann et al., 2015), as well as routing protocols (Keppitiyagama et al., 2013).

The impact of environmental conditions on long-range radios, instead, has not yet been investigated in detail. In previous work (Cattani et al., 2017a) we have reported that one can observe a certain correlation between temperature fluctuations and variations in packet reception rate and received signal strength in outdoor and underground LoRa deployments. However, we did not study the problem in depth and we did not investigate the impact of temperature on communication when using different LoRa PHY settings.

Iova et al. (Iova et al., 2017) have deployed a number of LoRa networks in urban and mountain environments, and reported that environmental factors such as the presence of vegetation and temperature variations can negatively affect communication performance. The authors, however, did not quantify the impact of these environmental factors (especially the one of temperature) in detail.

The remaining body of work on LoRa has focused primarily on the characterization of packet loss (Marcelis et al., 2017), signal attenuation (Petäjäjärvi et al., 2015), sensitivity (Augustin et al., 2016), channel utilization (Georgiou and Raza, 2017), (Voigt et al., 2017), and energy consumption (Bor and Roedig, 2017). Other works have also studied the ability of LoRa to penetrate buildings (Bor et al., 2016a) and to receive packets from concurrent transmissions (Bor et al., 2016b).



(a) Link 0–1 (SF = 7) (b) Link 0–2 (SF = 12)

Figure 1: Disruption of two LoRa links caused by an increase of the on-board temperature. A very good link (i.e., sustaining almost 100% successful receptions) at low temperature experiences an increasing corruption and loss as soon as temperature increases, up to a point in which the link becomes unusable. The two links make use of spreading factor 7 and 12, respectively.

In this paper, we specifically study the impact of temperature on LoRa's communication performance and answer two key questions: (i) how severe is such an impact, and (ii) whether it can be minimized with a proper selection of PHY settings. Towards this goal, we carry out several experiments in a temperature-controlled testbed and analyze the communication performance of LoRa links using different PHY settings, as we describe in the next sections.

4 IMPACT OF TEMPERATURE ON LORA COMMUNICATIONS

We first study whether variations in temperature can lead to a significant packet loss or a visible RSS attenuation, similar to the one shown in the literature for IEEE 802.15.4 radios. Towards this goal, we make use of an experimental setup where the temperature of several nodes can be controlled in a fine-grained fashion (Sect. 4.1), and analyze the evolution of packet reception rate (Sect. 4.2) and RSS (Sect. 4.3).

4.1 Experimental Setup

We make use of TempLab (Boano et al., 2014b), a temperature-controlled testbed, to expose a number of LoRa nodes to repeatable temperature variations[1]. TempLab has the capability to heat the nodes up to 80°C thanks to dimmable infra-red 100W light bulbs, as well as to cool down a node's temperature below 0°C thanks to thick Polystyrene foam enclosures and an ATA-050-24 Peltier air-to-air assembly module by Custom Thermoelectric. Infra-red heating lamps and enclosures are distributed across a $50m^2$ area and can be controlled wirelessly.

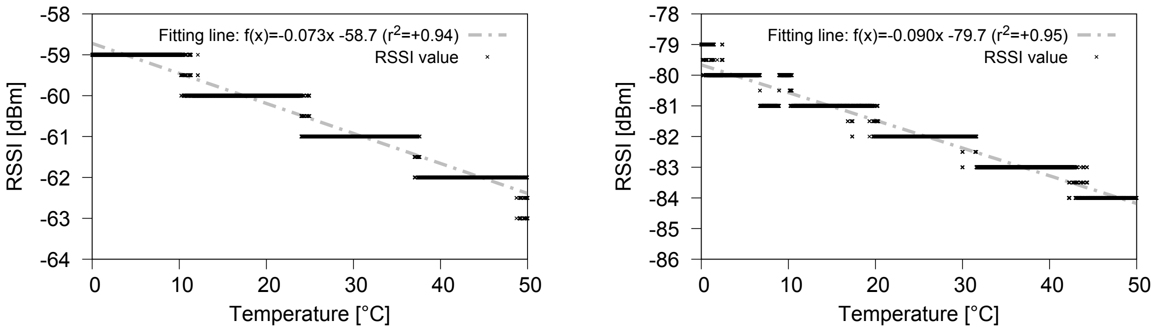
We build a star network of LoRa nodes composed of a sink (node 0) periodically broadcasting messages with 5 bytes payload to four nodes (1 to 4). Two of the nodes (1 and 2) are at the edge of their communication range (signal strength of received packets close to -100 dBm), whereas the remaining nodes (3 and 4) are located closer to the sink and hence receive packets with a higher signal strength. All nodes are based on the Moteino MEGA platform (LowPowerLab, 2016) that embeds a HopeRF RFM95 LoRa transceiver (Hope RF Microelectronics, 2017). We employ the highest transmission power available (+5 dBm), a coding rate of $4/5$, a bandwidth of 125 kHz and a spreading factor of 7 or 12.

All nodes measure temperature using a Bosch BME280 sensor and log this information via USB on a central testbed PC, along with the content of the received messages, the results of the cyclic redundancy check, the received signal strength, and the SNR. Depending on the employed spreading factor, the sink transmits messages at 0.5 or 2 Hz (SF=12 or SF=7, respectively). We do not make use of any radio duty cycling and initially do not connect an SMA antenna to the nodes in order to limit their range. We have later repeated some of the experiments with an SMA antenna or cable and obtained similar results.

4.2 Impact on Packet Reception

In a first experiment, we focus on the two receivers that are located at a distance from the sink that is close to the edge of their communication range, but that still guarantees a high packet reception rate (i.e., nodes 1

[1]Please note that the temperature variations to which LoRa transceivers are exposed when using TempLab are within the supported temperature range of LoRa transceivers, i.e., between -55 and +115°C for the HopeRFM95 and the Semtech SX1272 transceivers.



(a) Node 3 (SF = 7)   (b) Node 4 (SF = 7)

Figure 2: RSSI attenuation as a function of temperature on the Moteino MEGA employing a HopeRF RFM95 transceiver.

and 2). We then instruct the temperature-controlled testbed to slowly increase the temperature of the sink node and to then quickly cool down its temperature to the initial value. We repeat the test multiple times and make use of different temperature profiles.

Link disruption. Fig. 1 shows the distribution of lost, corrupted, and successfully received packets over time for the two different links. In both cases, we can observe that what was a perfect link at low temperatures, i.e., a link sustaining a 100% packet reception rate (PRR), slowly becomes unusable at higher temperatures. An increase in temperature at the transmitter, indeed, causes node 1 to experience a significant corruption and loss (Fig. 1(a)), up to a point at which the link becomes unusable when the transmitter's on-board temperature is higher than 55°C. Similarly, also node 2 does not receive any packet at high temperatures (Fig. 1(b)): what was an almost perfect link at 0°C becomes unusable when the transmitter's on-board temperature is higher than 55°C.

It is worth highlighting that the two links shown in Fig. 1 exhibit a visibly different amount of corruption and react to temperature variations differently. Indeed, link 0–2 experiences more corruption than its counterpart, and its transitional region (i.e., the region in which the nodes do not communicate reliably (Zúñiga and Krishnamachari, 2004)) covers approximately a temperature variation of 60°C, whereas the latter is 30°C for link 0–1. As the two links make use of largely different spreading factors (SF=7 for link 0–1, whilst SF=12 for link 0–2), our results seem to hint that the behavior of LoRa links exposed to temperature variations depends on the PHY settings used.

4.3 Impact on Received Signal Strength

In a second experiment, we focus on the two Moteino MEGA that are located in closer proximity to the sink (i.e., nodes 3 and 4), configure them with identical settings (i.e., CR=4/5, BW=125 kHz, and SF=7),

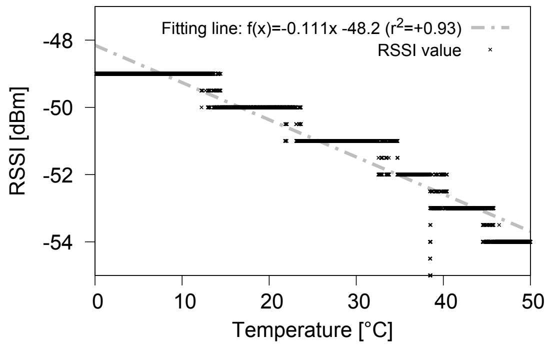


Figure 3: RSSI attenuation as a function of temperature recorded on ST Microelectronics Nucleo L073RZ platform employing a Semtech SX1272 transceiver.

and study the evolution of received signal strength while temperature increases. We instruct the testbed to slowly increase the on-board temperature of all nodes in the range between 0 and 50°C during five hours. We then plot the relationship between the RSS of received packets and the average temperature of the communicating nodes. Fig. 2 shows the results.

RSS attenuation at high temperatures. A first observation is that the received signal strength on a Moteino MEGA board (HopeRF RFM95 radio) exhibits an attenuation at high temperatures similar to the linear trend observed on IEEE 802.15.4 transceivers (Boano et al., 2013). Both nodes 3 and 4 exhibit indeed a linear decrease of the RSS in discrete steps for a total of about 3-4 dB in the temperature range of $[0-50]$°C. Bannister et al. argue that the reason for this attenuation in the TI CC2420 radio is due to the fact that, for a given voltage, a higher temperature increases the resistance of conductors, while reducing the pass-through current. For radio transceivers, this implies that higher temperatures reduce the received signal strength and SNR (Bannister et al., 2008). We conjecture that LoRa transceivers are affected in a similar way.

Setting ID	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
SF	7	7	7	7	7	7	9	9	9	9	9	9	12	12	12	12	12	12
CR	4/5	4/5	4/5	4/8	4/8	4/8	4/5	4/5	4/5	4/8	4/8	4/8	4/5	4/5	4/5	4/8	4/8	4/8
BW (kHz)	125	250	500	125	250	500	125	250	500	125	250	500	125	250	500	125	250	500

Table 2: PHY settings used in our experiments ordered by decreasing bit-rate.

RSS attenuation varies at different distances. Another observation from our results is that the fitting line shown in Fig. 2(a), interpolating the received RSS values of node 3 (whose RSS is about -60 dBm), has a smaller slope than the one shown in Fig. 2(b) for node 4 (whose RSS is in the area of -80 dBm). This hints that the impact of temperature is specific to each node and may depend on the distance to the transmitter.

Platform-specific attenuation. We further investigate the RSS attenuation using a different LoRa platform. We employ the same experimental setup described in Sect. 4.1 and expose ST Nucleo L073RZ boards (ST Microelectronics, 2016) equipped with a Semtech SX1272 radio (Semtech Corporation, 2017) to the same change in temperature. We employ the same settings described previously, i.e., CR=4/5, SF=7, BW=125 kHz. Fig. 3 shows the relationship between RSS and temperature: also in this case we can observe a linear decrease of RSS in discrete steps by a total of about 5-6 dB in the temperature range of $[0-50]$°C. The absolute decrease is higher than that observed on the Moteino MEGA nodes, which hints that the RSS attenuation – as for IEEE 802.15.4 transceivers – may be platform-specific.

5 THE ROLE OF PHY SETTINGS

Next, we explore whether changing LoRa's PHY settings helps in minimizing the impact of temperature on the reliability of communications. In our current investigation, we specifically focus on the role of bandwidth, spreading factor, and coding rate.

5.1 Explored Settings

We create an application that periodically reboots all nodes and switches to a different combination of PHY settings over time. Using the time-stamp provided by a Maxim DS3231 real-time clock, we reboot transmitter and receivers every 6 minutes and iterate over a list of 18 hard-coded combinations of bandwidth, spreading factor, and coding rate, as summarized in Table 2. Please note that the settings are ordered by decreasing bit-rate (i.e., setting ID 21 is the slowest one) and that they have been selected to enable an easy comparison with earlier works studying LoRa's performance as a function of its PHY settings (Cattani et al., 2017a).

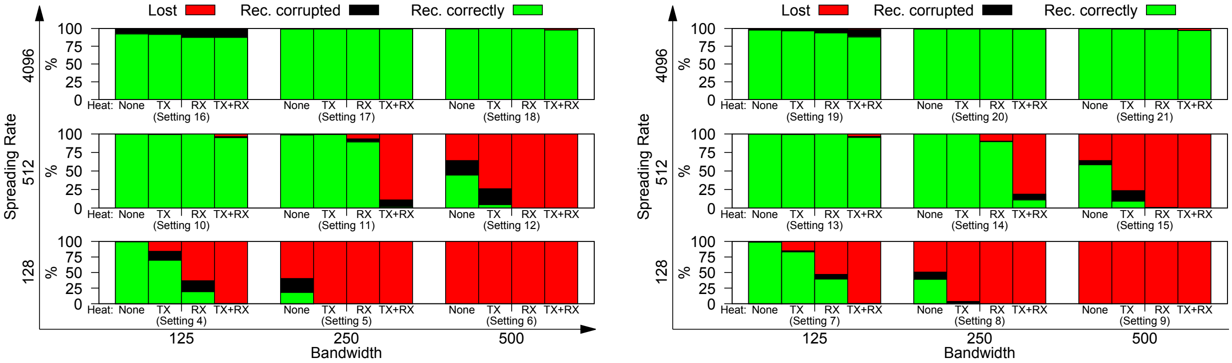
We first let the temperature-controlled testbed heat transmitter and receiver nodes to 30°C – a temperature that we use as a baseline. After running each combination of PHY settings at least three times, hence allowing the transmitter to broadcast about 5000 packets, we let the testbed vary the temperature of the transmitter and the receiver to 70°C and re-iterate over the 18 combinations of settings. In order to study whether an increase in temperature at the transmitter or at the receiver affects performance differently, we let the testbed heat to 70°C first only the transmitting node, then only the receivers (while keeping the transmitter at the 30°C baseline), and then both transmitter and receivers.

The rest of the experimental setup is the same as described in Sect. 4.1, with each Moteino MEGA logging via USB all statistics about packet reception, RSS, and SNR to the main testbed PC. We analyze the impact of temperature on PRR and RSS/SNR as a function of the employed PHY settings, describing our findings in Sect. 5.2 and 5.3, respectively.

5.2 Packet Reception

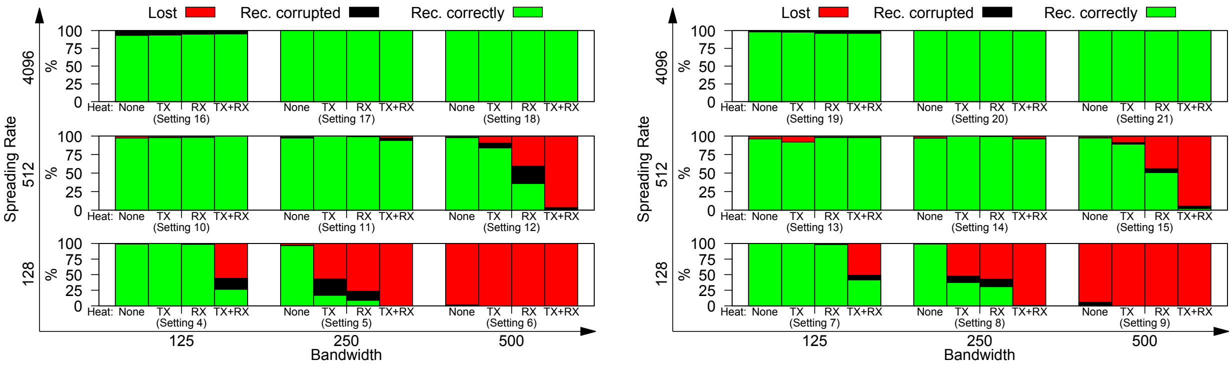
Figs. 4 and 5 summarize the impact of bandwidth, spreading factor and coding rate on the packet reception of nodes 2 and 1, respectively. For each combination of PHY settings, four bars depict the packet reception when none of the nodes was heated (*None*), when only the transmitter (*TX*), only the receiver (*RX*), or when both transmitter and receiver (*TX+RX*) were heated. The green portion of each bar shows the ratio (in percent) of packets that have been received correctly; the black and red portions of each bar, instead, indicate the percentage of corrupted and lost packets, respectively. Independent from the quality of the two links, we note four consistent effects that LoRa's PHY settings have on packet reception.

1. Impact of heated device(s). When both transmitter and receivers are at our baseline temperature (*None*-labeled bars), the amount of packets received correctly is the highest. As soon as we increase the temperature of the transmitter (*TX* bars), the percentages of corrupted and lost packets increase (black and red areas). The effect worsens if the receiver is heated instead of the transmitter (*RX* bars) and



(a) Coding Rate = 4/5 (b) Coding Rate = 4/8

Figure 4: Number of packets that are lost, corrupted, and received correctly by node 2 when employing different PHY settings. For each combination of PHY settings, four bars depict the packet reception when none of the nodes was heated (*None*), when only the transmitter (*TX*), only the receiver (*RX*), or when both transmitter and receiver (*TX+RX*) were heated.



(a) Coding Rate = 4/5 (b) Coding Rate = 4/8

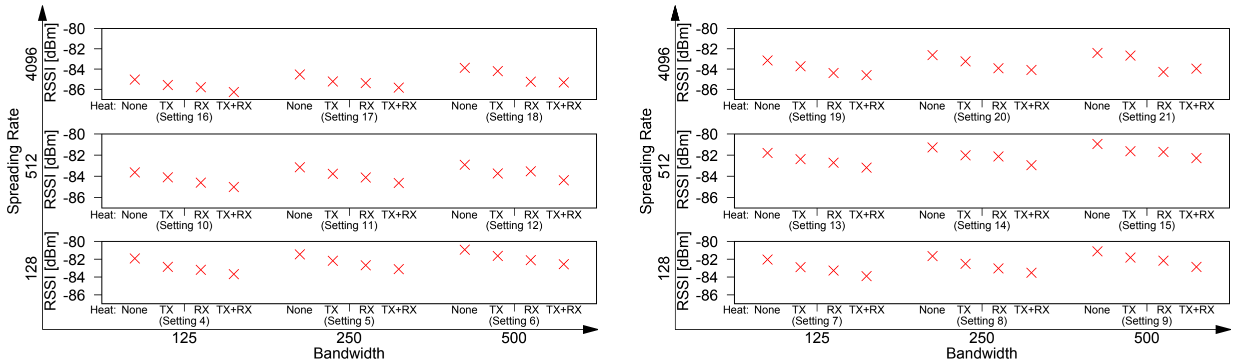
Figure 5: Number of packets that are lost, corrupted, and received correctly by node 1 when employing different PHY settings. For each combination of PHY settings, four bars depict the packet reception when none of the nodes was heated (*None*), when only the transmitter (*TX*), only the receiver (*RX*), or when both transmitter and receiver (*TX+RX*) were heated.

when both receiver and transmitter are heated simultaneously (*TX+RX* bars). While this effect is coherent with the observations made in previous work on IEEE 802.15.4 transceivers (Boano et al., 2013), we cannot explain the reason why heating the receiver has a higher impact compared to the case in which only the transmitter is heated. We plan to further analyze this aspect in future work. Nevertheless, independent from the selected PHY setting, we note a consistent degradation of the link quality whenever one or more devices are heated.

2. Bandwidth. In the presence of message loss due to heat, it is possible to improve the reliability of LoRa links by lowering the bandwidth (left region of the x-axis in Figs. 4 and 5). Whilst it is expected that a lower bandwidth results in a more robust communication, we are – to the best of our knowledge – the first to show that such robustness extends also to the effects of temperature.

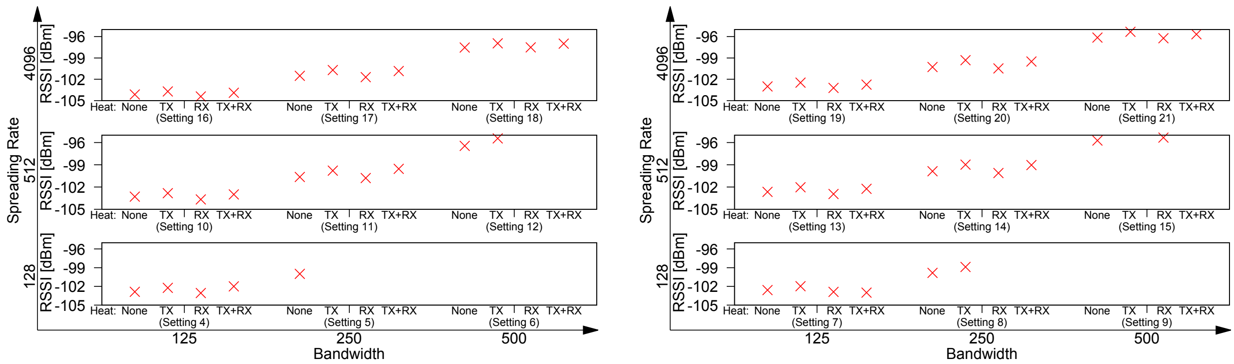
3. Coding rate. Using an higher coding rate allows to recover corrupted packets and to increase the success ratio. We can see this phenomenon by comparing Figs. 4(a) and 5(a) against Figs. 4(b) and 5(b). The former make use of less redundant bits and thus experience a higher corruption (areas in black). In spite of that, we notice that only in a few cases, when nodes experience heterogeneous temperatures, the number of corrupted packets is high enough to justify the use of an higher coding rate.

4. Spreading factor. Using a lower spreading factor drastically reduces the reliability of LoRa links at high temperatures. A higher spreading factor, indeed, increases the receiver sensitivity (i.e., the radio's ability to receive weaker signals) at the cost of longer transmission times. Figs. 4 and 5 show that a LoRa link that cannot sustain a reliable packet delivery rate when using a spreading factor of 7 (i.e., a spreading rate of 2^7=128).



(a) Coding Rate = 4/5 (b) Coding Rate = 4/8

Figure 6: RSS measured on node 3 when using different PHY settings. For each combination of PHY settings, four bars depict the packet reception when none of the nodes was heated (*None*), when only the transmitter (*TX*), only the receiver (*RX*), or when both transmitter and receiver (*TX+RX*) were heated.



(a) Coding Rate = 4/5 (b) Coding Rate = 4/8

Figure 7: RSS measured on node 2 when using different PHY settings. For each combination of PHY settings, four bars depict the packet reception when none of the nodes was heated (*None*), when only the transmitter (*TX*), only the receiver (*RX*), or when both transmitter and receiver (*TX+RX*) were heated.

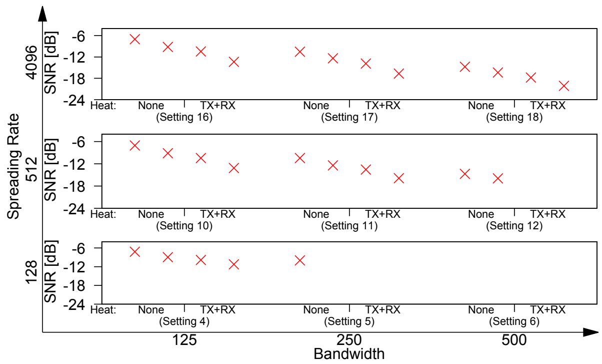
5.3 RSS and SNR

Figs. 6, 7, and 8 show the impact of temperature on the received signal strength and signal-to-noise ratio measured at receiving nodes 2 and 3. As for the previous experiment, for each combination of PHY settings, four bars depict the packet reception when none of the nodes was heated (*None*), when only the transmitter (*TX*), only the receiver (*RX*), or when both transmitter and receiver (*TX+RX*) were heated. Independent from the receiving node and the quality of its connection with the transmitter, we note four consistent effects that LoRa's PHY settings have on the received signal strength and the SNR.

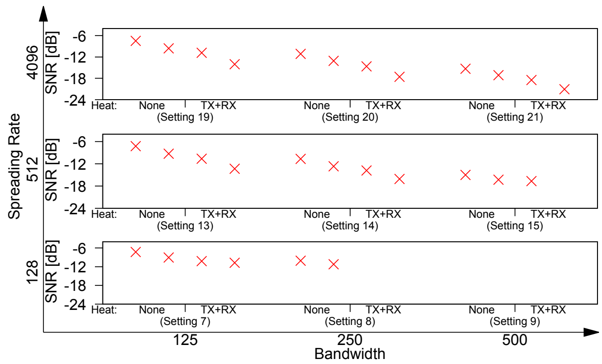
1. Impact of heated device(s). Consistent to what we observed for the PRR, the RSS decreases with the number of heated devices, with the worst effect being recorded when both transmitter and receiver nodes are heated (see Fig. 6). This is however not the case when nodes receive packets with a signal strength that is very close to the sensitivity threshold (≈ -100 dBm). This is indeed the case for node 2, which is at the edge of its communication range (see Fig. 7). Also the measured signal-to-noise ratio exhibits a trend that is temperature-dependent, with the lowest SNR being recorded when both transmitter and receiver nodes are heated (see Fig. 8).

2. Temperature-independent variations. Whilst we can clearly notice that the measured RSS and SNR values vary depending on the temperatures of the transmitter and receiver, we can observe that changes in RSS and SNR occur also when varying bandwidth, spreading factor, and coding rate, independently of the nodes' temperature.

Bandwidth. We note that the absolute RSS value, measured in dBm at the transceiver after the reception of a packet, changes depending on the employed LoRa setting. In particular, increasing the bandwidth results in higher measured RSS. In the case of node 2, this is because at higher bandwidths LoRa sensitivity worsens, allowing only the packets with high signal



(a) Coding Rate = 4/5



(b) Coding Rate = 4/8

Figure 8: SNR measured on node 2 when using different PHY settings. For each combination of PHY settings, four bars depict the packet reception when none of the nodes was heated (*None*), when only the transmitter (*TX*), only the receiver (*RX*), or when both transmitter and receiver (*TX+RX*) were heated.

strength to be received (see Fig. 4 and 7). On the contrary, at higher bandwidths we observe the SNR decreasing (see Fig. 8), indicating that LoRa is more sensitive to noise when higher bandwidths are used.

Spreading factor. A higher spreading factor increases the receiver sensitivity and hence the reliability of LoRa communications at high temperatures. The increased sensitivity when using a higher spreading factor can be confirmed by comparing Figs. 6 and 7 against Fig. 8. We can observe that, whilst there is no significant difference in SNR when using different spreading factors, the RSS decreases significantly when using a SF of 9 or 12, hinting that the sensitivity of the radio increases proportionally.

Coding rate. By comparing Figs. 6(a) and 7(a) against Figs. 6(b) and 7(b), we can observe that a higher coding rate results in higher measured RSS. A higher coding rate also results in a slightly lower SNR (approximately 0.7 dB lower), regardless of temperature variations. A more thorough analysis of these phenomena is out of the scope of this paper and will be carried out in future work.

6 DISCUSSION

The experimental results described in Sects. 4 and 5 show that the effects of temperature on LoRa's packet delivery can be quite severe, in line with earlier studies carried out on IEEE 802.15.4 transceivers (Bannister et al., 2008), (Boano et al., 2013), (Wennerström et al., 2013). We derive next a number of insights and recommendations for developers and network engineers that may be useful to minimize the impact of temperature on LoRa communication performance.

Monitor temperature variations. Having knowledge about the evolution of the on-board temperature at run-time is important to be able to understand whether a decrease in RSS is due to heat or to other environmental effects such as multi-path fading or interference. Furthermore, as our experiments show that the impact of temperature is platform and node-specific, each node needs to derive its own strategy to mitigate the effects of temperature.

Adapt PHY settings accordingly. A thorough understanding of the evolution of the on-board temperature also allows to predict trends and, if necessary, proactively switch PHY settings to increase the chances of packet reception. In case temperature increases to a point at which it starts affecting communication performance, one should, if possible, switch to a lower bandwidth, a higher spreading factor, as well as a higher coding rate.

Do not always prefer faster PHY settings. Earlier studies have shown that selecting the fastest PHY settings and the highest transmission power – where possible – is more efficient than selecting slower settings that maximize the link quality (Cattani et al., 2017a). Our results in Sect. 5, however, highlight that selecting a higher bandwidth and lower spreading factor makes the LoRa nodes less robust to temperature variations. When selecting PHY settings that minimize the air time and the radio's energy expenditure, one should hence carefully monitor fluctuations of the on-board temperature and make sure that these do not affect communication performance. If, despite the selection of a lower bandwidth and a higher spreading factor (and coding rate), communication performance is still insufficient, one can only resort to a higher transmission power, where applicable.

Careful deployment of nodes. An important take-away message from our experimental study is that LoRa nodes employing the radio transceivers used in our experiments (i.e., the Semtech SX1272 and the HopeRF RFM95 transceivers) should be deployed during the warmest time of the day or year, to ensure that network performance is sufficient throughout the system lifetime despite temperature variations. Deployments of wireless sensor networks have indeed observed that on-board temperature fluctuations across different times of the year can be as high as 85 °C (Wennerström et al., 2013), (Beutel et al., 2009), (Boano, 2014).

Avoid sun exposure. When deploying a network, one should also pay attention to shield nodes from sunlight as much as possible. Especially the orchestrator should be shielded from sunlight as, in a star network, an increase of its temperature would affect all other nodes (see Fig. 1). Sunshine may indeed easily heat a packaged sensor node up to 70 °C – especially if the enclosure absorbs infra-red radiation (Polastre et al., 2004), (Szewczyk et al., 2004). Furthermore, airtight and waterproof enclosures may protect the node from corrosion, humidity and atmospheric contaminants (Barrenetxea et al., 2008), (Beutel et al., 2009), but may also increase the temperature of the inner casing (Boano et al., 2009), (Polastre et al., 2004).

7 CONCLUSIONS

Large temperature fluctuations are typical of outdoor scenarios where most low-power wide-area networks are deployed. Hence, it is important to understand the impact of temperature on the performance of long-range wireless technologies.

This paper presents an experimental evaluation of the reliability of LoRa in the presence of temperature variations. First, using a temperature-controlled testbed we have shown that an increase in temperature can be sufficient to transform a perfect LoRa link into an almost useless one. Second, we carried out a detailed investigation on the performance of different LoRa's PHY settings with fluctuating temperatures and shown that an accurate selection helps in increasing the probability of packet reception and is hence key to mitigate temperature-induced effects. Finally, we distilled a list of recommendations to help the successful deployment of low-power wide-area networks in outdoor scenarios.

Future work includes a more detailed investigation of the problem on a hardware-level, in order to suggest an improved transceiver layout.

ACKNOWLEDGEMENTS

The authors would like to thank the anonymous reviewers for their thorough and valuable feedback. This work has been supported by the Sino-Austrian Electronic Technology Innovation Center and was partially performed within the LEAD-Project "Dependable Internet of Things in Adverse Environments", funded by Graz University of Technology (Graz, Austria).

REFERENCES

Anastasi, G., Falchi, A., Passarella, A., Conti, M., and Gregori, E. (2004). Performance Measurements of Motes Sensor Networks. In *Proceedings of the* 7^{th} *ACM International Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM)*, pages 174–181.

Augustin, A., Yi, J., Clausen, T., and Townsley, W. M. (2016). A Study of LoRa: Long Range & Low Power Networks for the Internet of Things. *Sensors*, 16(9).

Bannister, K., Giorgetti, G., and Gupta, S. K. (2008). Wireless Sensor Networking for Hot Applications: Effects of Temperature on Signal Strength, Data Collection and Localization. In *Proceedings of the* 5^{th} *International Workshop on Embedded Networked Sensors (HotEmNets)*.

Barrenetxea, G., Ingelrest, F., Schaefer, G., and Vetterli, M. (2008). The hitchhiker's guide to successful wireless sensor network deployments. In *Proceedings of the* 6^{th} *ACM International Conference on Embedded Networked Sensor Systems (ACM SenSys)*, pages 43–56.

Beutel, J., Römer, K., Ringwald, M., and Woehrle, M. (2009). Deployment techniques for sensor networks. In *Sensor Networks*, Signals and Communication Technology, pages 219–248. Springer Berlin Heidelberg.

Boano, C. A. (2014). *Dependable Wireless Sensor Networks*. PhD thesis, Graz University of Technology, Graz, Austria.

Boano, C. A., Brown, J., He, Z., Roedig, U., and Voigt, T. (2009). Low-power radio communication in industrial outdoor deployments: The impact of weather conditions and ATEX-compliance. In *Proceedings of the* 1^{st} *International Conference on Sensor Networks Applications, Experimentation and Logistics (SENSAPPEAL)*, pages 159–176.

Boano, C. A., Brown, J., Tsiftes, N., Roedig, U., and Voigt, T. (2010). The Impact of Temperature on Outdoor Industrial Sensornet Applications. *IEEE Transactions on Industrial Informatics*, 6(3):451–459.

Boano, C. A., Römer, K., and Tsiftes, N. (2014a). Mitigating the Adverse Effects of Temperature on Low-Power Wireless Protocols. In *Proceedings of the* 11^{th} *IEEE International Conference on Mobile Ad hoc and Sensor Systems (MASS)*, pages 336–344.

Boano, C. A., Wennerström, H., Zúñiga, M. A., Brown, J., Keppitiyagama, C., Oppermann, F. J., Roedig, U., Nordén, L.-Å., Voigt, T., and Römer, K. (2013). Hot Packets: A Systematic Evaluation of the Effect of Temperature on Low Power Wireless Transceivers. In *Proceedings of the* 5*th* *Extreme Conference on Communication (ExtremeCom)*, pages 7–12.

Boano, C. A., Zúñiga, M. A., Brown, J., Roedig, U., Keppitiyagama, C., and Römer, K. (2014b). TempLab: A Testbed Infrastructure to Study the Impact of Temperature on Wireless Sensor Networks. In *Proceedings of the* 13*th* *ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN)*, pages 95–106.

Bor, M. and Roedig, U. (2017). LoRa Transmission Parameter Selection. In *Proceedings of the* 13*th* *IEEE International Conference on Distributed Computing in Sensor Systems (DCOSS)*.

Bor, M., Roedig, U., Voigt, T., and Alonso, J. M. (2016a). Do LoRa Low-Power Wide-Area Networks Scale? In *Proceedings of the* 19*th* *ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM)*, pages 59–67.

Bor, M., Vidler, J., and Roedig, U. (2016b). LoRa for the Internet of Things. In *Proceedings of the* 1*st* *International Workshop on New Wireless Communication Paradigms for the Internet of Things (MadCom)*, pages 361–366.

Cattani, M., Boano, C. A., and Römer, K. (2017a). An experimental evaluation of the reliability of LoRa long-range low-power wireless communication. *Journal of Sensor and Actuator Networks (JSAN)*, 6(2).

Cattani, M., Boano, C. A., Steffelbauer, D., Kaltenbacher, S., Günther, M., Römer, K., Fuchs-Hanusch, D., and Horn, M. (2017b). Adige: An Efficient Smart Water Network based on Long-Range Wireless Technology. In *Proceedings of the* 3*rd* *International Workshop on Cyber-Physical Systems for Smart Water Networks (CySWATER)*.

Centenaro, M., Vangelista, L., Zanella, A., and Zorzi, M. (2016). Long-Range Communications in Unlicensed Bands: the Rising Stars in the IoT and Smart City Scenarios. *IEEE Wireless Communications*, 23(5):60–67.

Georgiou, O. and Raza, U. (2017). Low Power Wide Area Network Analysis: Can LoRa Scale? *IEEE Wireless Communications Letters*, 6(2):162–165.

Hope RF Microelectronics (2017). RFM95/96/97/98(W) – Low Power Long Range Transceiver Module, v1.0.

Iova, O., Murphy, A. L., Ghiro, L., Molteni, D., Ossi, F., and Cagnacci, F. (2017). LoRa from the City to the Mountains: Exploration of Hardware and Environmental Factors. In *Proceedings of the* 2*th* *International Workshop on New Wireless Communication Paradigms for the Internet of Things (MadCom)*.

Kartakis, S., Choudhary, B. D., Gluhak, A. D., Lambrinos, L., and McCann, J. A. (2016). Demystifying Low-Power Wide-Area Communications for City IoT Applications. In *Proceedings of the* 10*th* *ACM Workshop on Wireless Network Testbeds, Experimental Evaluation, and Characterization (WiNTECH)*, pages 2–8.

Keppitiyagama, C., Tsiftes, N., Boano, C. A., and Voigt, T. (2013). Poster abstract: Temperature hints for sensornet routing. In *Proceedings of the* 11*th* *ACM Conference on Embedded Networked Sensor Systems (ACM SenSys), poster session*.

KSK Developments (2017). KSK Outdoor Parking Guidance System. `http://www.ksk-dev.com/wp-content/uploads/2017/06/KSK-Magnetic-ENG.pdf`.

LoRa Alliance (2017). LoRa: Wide Area Networks for IoT. `http://www.lora-alliance.org/What-Is-LoRa/Technology`.

LowPowerLab (2016). Moteino MEGA LoRa. `http://lowpowerlab.com/shop/product/119`.

Marcelis, P., Rao, V., and Prasad, R. V. (2017). DaRe: Data Recovery through Application Layer Coding for LoRaWAN. In *Proceedings of the* 2*nd* *International Conference on Internet-of-Things Design and Implementation (IoTDI)*, pages 97–108.

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

Oppermann, F. J., Boano, C. A., Zúñiga, M. A., and Römer, K. (2015). Automatic protocol configuration for dependable internet of things applications. In *Proceedings of the* 10*th* *International Workshop on Practical Issues in Building Sensor Network Applications (SenseApp)*, pages 742–750.

Petäjäjärvi, J., Mikhaylov, K., Roivainen, A., Hänninen, T., and Pettissalo, M. (2015). On the Coverage of LPWANs: Range Evaluation and Channel Attenuation Model for LoRa Technology. In *Proceedings of the* 14*th* *IEEE International Conference on ITS Telecommunications (ITST)*, pages 55–59.

Polastre, J., Szewczyk, R., Mainwaring, A., Culler, D., and Anderson, J. (2004). Analysis of wireless sensor networks for habitat monitoring. In *Wireless Sensor Networks*, pages 399–423. Kluwer Academic Publishers.

Semtech Corporation (2013). SX1272/3/6/7/8: LoRa Modem, Designer's Guide – Application Note 1200.13, Revision 1.

Semtech Corporation (2015). LoRa Modulation Basics – Application Note 1200.22, Revision 2.

Semtech Corporation (2017). SX1272/73 – 860 MHz to 1020 MHz Low-Power Long-Range Transceiver, Revision 3.1.

Sigfox (2017). Sigfox Technology. `http://www.sigfox.com`.

ST Microelectronics (2016). STM32 Nucleo Pack for LoRa Technology (P-NUCLEO-LRWAN1), DocID029505 Rev. 2.

Stoianov, I., Nachman, L., Madden, S., and Tokmouline, T. (2007). PIPENET: a wireless sensor network for pipeline monitoring. In *Proceedings of the* 6*th* *International Conference on Information Processing in Sensor Networks (IPSN)*, pages 264–273.

Szewczyk, R., Polastre, J., Mainwaring, A., and Culler, D. (2004). Lessons from a sensor network expedition wireless sensor networks. *Wireless Sensor Networks*, 2920:307–322.

Voigt, T., Bor, M., Roedig, U., and Alonso, J. (2017). Mitigating Inter-network Interference in LoRa Networks. In *Proceedings of the* 2^{th} *International Workshop on New Wireless Communication Paradigms for the Internet of Things (MadCom)*.

Weightless SIG (2017). Weightless open standard. `http://www.weightless.org/`.

Wennerström, H., Hermans, F., Rensfelt, O., Rohner, C., and Nordén, L.-A. (2013). A Long-Term Study of Correlations between Meteorological Conditions and 802.15.4 Link Performance. In *Proceedings of the* 10^{th} *International Conference on Sensing, Communication, and Networking (SECON)*, pages 221–229.

Zúñiga, M. A. and Krishnamachari, B. (2004). Analyzing the transitional region in low-power wireless links. In *Proceedings of the* 1^{st} *IEEE International Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON)*, pages 517–526.