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Florian Schmidt, Matteo Ceriotti, Niklas Hauser, Klaus Wehrle

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HotBox: Testing Temperature Effects in Sensor Networks

Florian Schmidt[1], Matteo Ceriotti[2], Niklas Hauser[1], and Klaus Wehrle[1]

[1] Communication and Distributed Systems Group, RWTH Aachen University, Germany
{schmidt,wehrle}@comsys.rwth-aachen.de, niklas.hauser@rwth-aachen.de
[2] Networked Embedded Systems Group, University of Duisburg–Essen, Germany
matteo.ceriotti@uni-due.de

Abstract. Low-power wireless networks, especially in outside deployments, are exposed to a wide range of temperatures. The detrimental effect of high temperatures on communication quality is well known. To investigate these influences under controlled conditions, we present HotBox, a solution with the following properties: (1) It allows exposition of sensor motes to a wide range of temperatures with a high degree of accuracy. (2) It supports specifying exact spatial orientation of motes which, if not ensured, interferes with repeatable experiment setups. (3) It is reasonably easy to assemble by following the information (code, PCB schematics, hardware list and crafting instructions) available online, facilitating further use of the platforms by other researchers. After presenting HotBox, we will show its performance and prove its feasibility as evaluation platform by conducting several experiments. These experiments additionally provide further insight into the influence of temperature effects on communication performance in low-power wireless networks.

1 Introduction

Low-power wireless networked devices are seeing more and more uses, enabling monitoring of areas both remote and inaccessible, and within our own homes, from any point on Earth. Depending on the deployment scenario, those devices can be exposed to strongly varying environmental effects. In recent publications, it has been shown that temperature has a strong effect on communication quality [1–4, 15]: as temperature rises, communication becomes more challenging, up to an eventual complete breakdown. While initial results were extracted from real-world outside deployments, further investigation has largely moved to scenarios in which environmental factors are more controllable. This has led to solutions such as TempLab [4], which allows exposing a large number of sensor motes to strictly controlled temperatures. In this setup, motes are either inserted into a insulation enclosure that provides a heating and cooling element; however, the used hardware makes these boxes somewhat expensive. Alternatively, budget setups consist of only the mote and an infrared lamp; the lower cost is offset by lacking the capability to cool the device and, more significantly, the absence of any insulation, which allows a greater impact of environmental influences. Finally, no setup allows to anchor the devices under test in such a way that experiments are reproducible with a given accuracy.

In this technical report, we present HotBox, an alternative solution to exactly control temperature and spatial orientation of sensor nodes. Furthermore, we exploit this setup to perform an investigation of the impact of temperature on low-power wireless communication and describe the preliminary result of our measurement campaign. Most of the research on this topic focuses on the effects of temperature on packet error rate (PER) or packet loss rate (PLR), that is, the fraction of sent packets that are received with errors or not received at all. While we also present results on this level, we additionally take a more detailed look into the erroneously received packets, and investigate the influence of temperature on the distribution of bit errors within a packet. Overall, this technical report makes three contributions: (1) We present “HotBox”, our system to exactly control temperature and spatial orientation of sensor nodes. HotBox is a budget solution that nevertheless works very well and can easily be used by other researchers. (2) We use HotBox to investigate the influence of temperature on bit error distribution patterns within erroneous messages. (3) Using the same setup, we present results regarding various packet- and connection-based metrics.

2 Related Work

Following the list of contributions we target in this work, we turn our attention now to the current state of the art in testbeds for the study of the impact of temperature, and knowledge about error distributions in low-power wireless networks and the impact of temperature on them.

WSN Testbeds and Temperature Control The most commonly used testbeds of low-power devices, e.g., TWIST [6] or Indriya [5], provide indoor infrastructures to analyze protocol and application behavior in realistic settings with increased visibility through the use of wired back-channels. Being mostly indoor, they are not well suited to analyze the impact of temperature on system performance. Bannister et al. [1] were one of the first to provide a systematic analysis of the impact of temperature on the performance of the CC2420 radio, the one also employed in our study. Two radios were connected together via coaxial cable and exposed to temperatures ranging from 25 to 65 °C. While this shields the setup from the effect of radio irregularities and environment interference, it also raises the question of how this abstraction influences the results. Boano et al. [4] introduced TempLab, a testbed allowing fine-grained analysis of temperature impact on wireless sensor networks based on two different types of setups. A budget solution (€65) is composed exclusively of a remotely-controlled IR light bulb placed near the device under test. Alternatively, the additional use of polystyrene foam enclosures, and Peltier elements allows to build small, more accurate temperature chambers at a relatively low cost (€293 per chamber). In our work, we aim to explore the ground in between such alternatives, and to make available the solution for everybody to reproduce.

Bit Error Distributions The study of errors in low-power 802.15.4 wireless communication has mostly stopped at the packet level, with several experimental studies analyzing PLR. However, there typically is a large fraction of packets that are received with errors and discarded as corrupted. Only recently, the study of these erroneous receptions has drawn interest and in-depth experimental studies have been performed. Schmidt et al. [11] examined the bit error distributions within corrupted messages in an outdoor testbed comprising 20 TelosB devices. Most interestingly, the study observed that within 4-bit symbols, the Most Significant Bit (MSB) is significantly less likely to break and that symbols with MSB set to 1 are more likely to break. This finding was also corroborated by

Wennerström et al. [15]. The behavior was subsequently explained by Hermans et al. [7] with the CC2420's use of an MSK demodulator to receive the signal sent from an O-QPSK modulator. While the two modulation schemes are sufficiently similar to allow successful demodulation, the translation of code words introduces the observed skew. All these studies, however, explore the behavior in general, without focusing on quantitative differences among individual devices or analyzing the impact of temperature on the observed behavior.

Impact of Temperature on Packet Errors In the aforementioned study by Bannister et al. [1], the setting with a pair of nodes connected via coaxial cable was used to gather knowledge about the behavior of low-power devices under the impact of temperature. The results demonstrated a reduction of RSSI with an increase of temperature, more marked with a heated transmitter. In [2], this behavior was also identified, again with larger differences when the transmitter was heated than when the receiver was. In both studies, the correlation between signal power reduction and temperature increase is identified to be caused by the loss of gain in the CC2420 Low Noise Amplifier (LNA). These studies are further validated by the long-term measurements taken by Wennerström et al. [14] in an outdoor deployment. Boano et al. [3] conducted a comprehensive study on the effects of temperature on RSSI, Noise Floor, PLR and LQI, further confirming the asymmetry observed by Bannister et al. [1]. In our work, we further extend the available knowledge by demonstrating deviations from the previously reported behavior, in particular showing a greater impact of an heated receiver on the decrease in link quality.

3 HotBox: a Budget Solution for Exact Temperature Control

One goal of our work was to design a hardware solution to easily control temperature effects on sensor nodes which can be produced relatively quickly and cheaply. To facilitate this, all hardware elements are off-the-shelf items, while all manufacturing can be done with a soldering iron, a PCB mill, and a laser cutter, which are often available in university settings via the rapidly-spreading FabLab concept.

The core part of the box is the heating element, a 150 W ceramic heater which is driven by an ATmega328 controllerwhich in turn is controlled via USB by a central entity that also can be (and in our experiments was) used to monitor and record the experiment results. Up to five temperature sensors can be distributed within the box to verify and manage homogeneous temperature distribution. A standard ATX power supply is connected to the control board to provide power to the controller, the heating elements, and the fan. Since in our experiments, the motes were either powered by batteries or by the USB cables already needed for data exchange, there is currently no provision to power the motes from the control board; however, since the ATX power supply already provides a 5 V circuit, the control board could be easily extended to also power the mote. All elements are mounted to a wooden baseplate, which then is inserted into a polystyrene box of roughly cubic dimensions with a 30 cm edge length. We chose polystyrene for its high thermal insulation capabilities combined with low attenuation of wireless signals [10] and easy and cheap availability in box form. The setup as used in

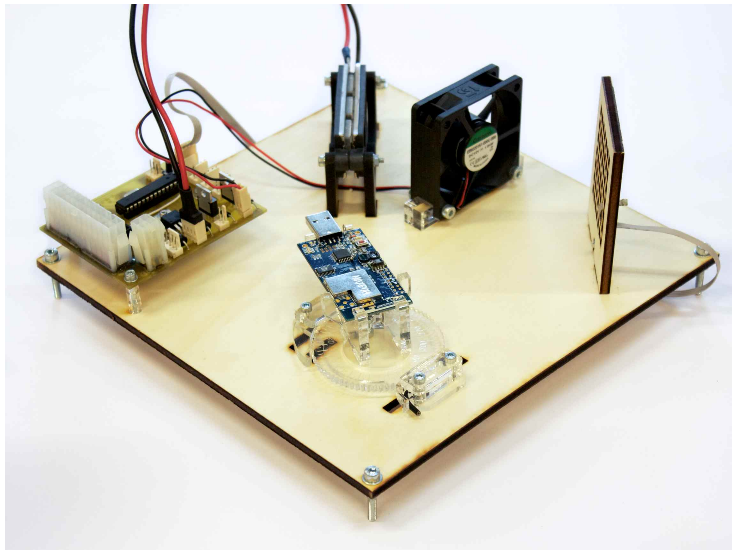


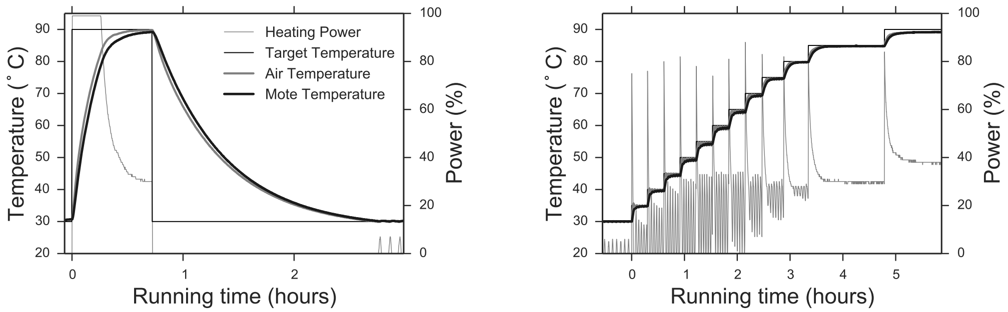
Fig. 1: HotBox hardware. The control board measures temperature and drives the heating element. The fan and diffusor facilitate even temperature distribution within the enclosure. The mote is fastened to a harness that ensures exact spatial orientation. All parts are mounted on a baseplate, which fits into a polystyrene box (not depicted).

our experiments is depicted in Figure 1. All in all, each box costs about €90 in hardware.

Figure 2 shows the performance of the box in terms of timeliness and accuracy. We pre-heated the box to 30 °C and then increased the target temperature to our allowed maximum of 90 °C.[1] As can be seen in Figure 2a, temperature increases almost linearly up to approximately 85 °C within 20 minutes, then spends another 20 minutes for the last 5 °C. After reaching 90 °C, we switched the target temperature back to 30 °C. Since HotBox does not provide any active cooling, the temperature follows a natural cooling pattern with decreasing gradient as the box temperature approaches the environment temperature. Overall, it takes approximately two hours to cool down from 90 °C to 30 °C. This time can be significantly shortened by removing the polystyrene lid, facilitating ventilation. Another solution would be to add active cooling to the box. While we decided against this to keep costs low, HotBox has support to complement the heating unit with a cooling system: the control board already provides additional outlets, while the software would need to be adapted to also drive the cooling element.

During our experiments, we used small temperature steps, so time spent for heating and cooling was secondary to the accuracy of the chosen temperature. Figure 2b shows the temperature over time when slowly stepping up the temperature in 5-degree steps, similarly to the setup used in the evaluation presented later. Since the box is only designed for heating and not active cooling, control was set up in a way to prevent overshooting of temperature. With the TelosB

[1] While we tested HotBox with temperatures up to 120 °C, the point at which the microcontroller stopped functioning, we deliberately limited the maximum temperature to 90 °C in our experiments to stay within the specifications of the microcontroller and reduce possible fire hazards.



(a) Heating from 30 °C to 90 °C, then letting it cool back to 30 °C

(b) Heating from 30 °C to 90 °C in steps of 5 °C

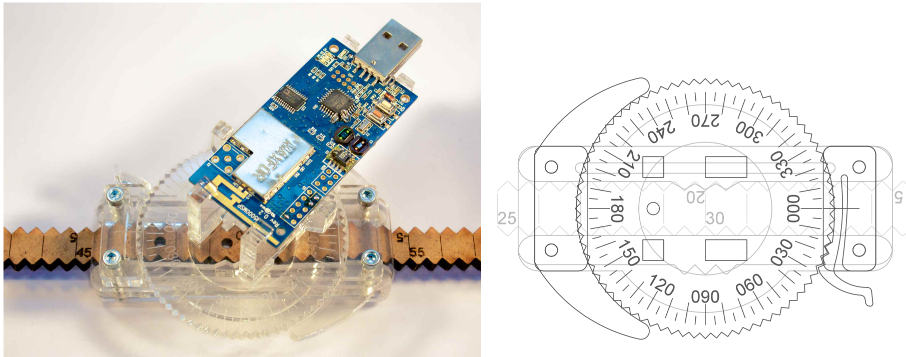
Fig. 2: HotBox facilitates accurate temperature control. Since the current setup does not include a cooling element, cooling relies on heat exchange with the environment and takes significantly longer than heating. Hence, the heater control loop was designed to not overshoot the target temperature, which is apparent from the asymptotical approach of actual temperature to the target temperature, a result of reduction in power to the heating element as the the two converge.

motes used in our experiments, it takes approximately 10–15 minutes to heat them to within 0.5 °C of the target temperature. The figure clearly shows that temperature can be controlled to a high degree of accuracy.

The figures also show that mote temperature closely follows air temperature. Our box setup could therefore also easily be used to accurately control temperature of similar motes which do not provide their own temperature sensor by providing a small "lag factor" to account for the slower temperature change within the sensor as opposed to the air.

In order to guarantee that both sender and receiver will not move during experiments, we developed a mote harness that was laser-cut out of acrylic. The mote snaps into the harness so that the axis of rotation goes through the middle of the PCB antenna which then allows rotation in 5° steps as shown in Figure 3. The reasoning for this is that, although the devices used in our experiments are equipped with a PCB-printed F-type antenna that nominally is omnidirectional, we witnessed strongly varying signal quality depending on the orientation of the nodes. By using the harness, spatial orientation could be reproduced exactly, supporting repeatability of experiments, especially when nodes are exchanged with each other between experiment runs to investigate potential influences of mote revisions and producers. We originally developed these harnesses independent of HotBox. By fastening them to distance bars, exact (to a resolution of 5 mm) and repeatable distance settings were also possible. While this is still possible, for use with HotBox, the harnesses are instead fastened to the baseplate. Thus, spatial orientation is still controllable, while distance has to be set by moving the polystyrene boxes.

In summary, HotBox facilitates temperature experiments on sensor motes by exposing them to a highly accurately controllable temperature. Furthermore, HotBoxes are cheap to produce. To allow other researchers to conduct temperature experiments using HotBoxes, we made the PCB schematics and control software available online [8].



(a) Harness with mote on a distance bar. (b) Vector drawing of the rotation disc.

Fig. 3: The mote harness allows precise positioning of motes. To set orientation, a disc rotates around the center of the PCB antenna at a 5° resolution. To set distance (if not fastened to HotBox's baseplate), the harness can slide along distance bars at a 5 mm resolution.

4 Experimental Results

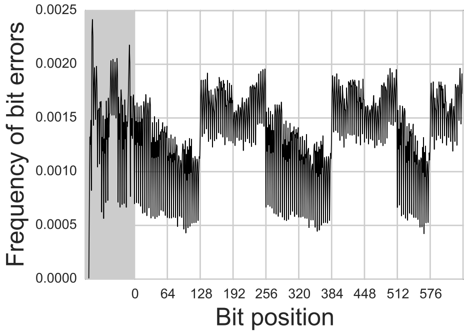
In the following, we will present results from our experimental setups on the influence of temperature on the error distribution of packet communications of sensor nodes. This presentation serves a dual purpose: first, it shows the practical applicability and usability of HotBox for conducting experiments; second, the results deepen the knowledge about factors such as bit error distributions within frames (see Section 4.2) and various other communication-related metrics (see Section 4.3) under the influence of temperature.

4.1 Experimental Setup

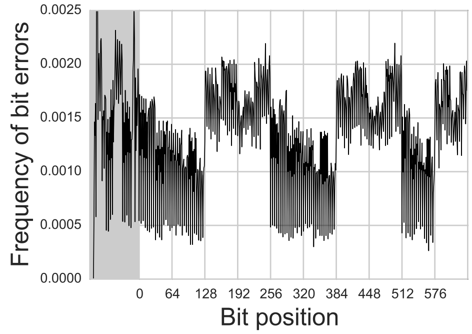
For our experiments, we used TelosB sensor nodes from two different manufacturers as well as production runs and ages. The TelosB is a widely-used platform that employs a Sensirion SHT11 [12] temperature sensor and a CC2420 [13] radio chip for communication which implements the IEEE 802.15.4 standard [9]. At the physical layer, the standard defines a DSSS (Direct Sequence Spread Spectrum) O-QPSK modulation in the 2.4 GHz ISM band, with a nominal data rate of 250 kbps.

All experiments were conducted in a university room that witnesses little interference from surrounding IEEE 802.11 (WiFi) networks operating in the same band; furthermore, we chose to use channel 26 of the 802.15.4 standard, which is outside the band allocated to 802.11 in Europe.

Experiments used direct (single-hop) connections between links. Each experiment comprised two boxes with one node each. Both nodes were connected to a PC via USB; the PC created the packets and sent them via USB to one node; the node would then send the packet via the CC2420 radio. If the other node received the packet, it forwarded the received version to the PC via USB, which then compared the original and the received version for bit errors. Otherwise, a timeout would be triggered at the PC to identify the missed reception. Each run



(a) Bit error distribution at 30 °C



(b) Bit error distribution at 70 °C

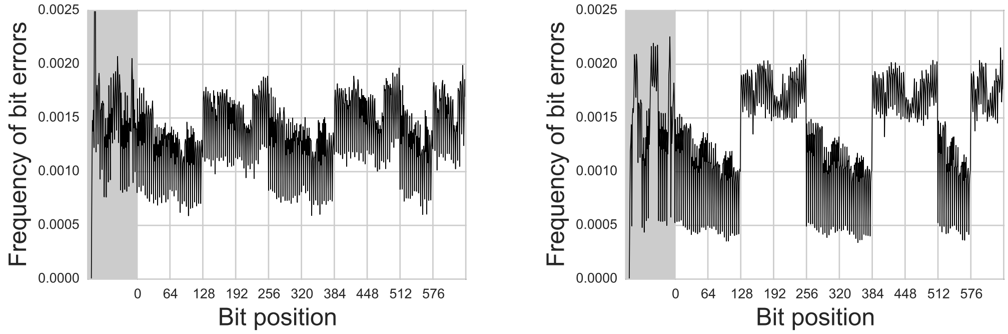
Fig. 4: When repeatedly sending fixed-content payloads, it is apparent that some bit pattern are more susceptible to errors than others. This behavior does not change significantly with temperature. While more bit errors occur at higher temperatures, the relative bit error frequencies when compared to each other stay very similar. (Gray area denotes the header portion of a frame.)

comprised 180 000 packets. We exchanged the nodes between experimental runs to account for potential performance differences between production runs and different models of the TelosB nodes. However, for most investigated metrics, we could not find any noticeable differences in the performance of those nodes. Unless specifically pointed out (cf. Section 4.2), the presented results are therefore representative of all investigated node types.

4.2 Bit Error Distributions

Previous work [11] had analyzed the distribution of bit errors within messages, and found out that some content is inherently more stable than other. Expanding on this point, we investigated whether changes in temperature change the bit error distribution in packets. To evaluate this fact, we sent messages with 80 bytes of payload containing a specific pattern between the sensor nodes. Each packet payload was created from a pattern of 0x0000, 0x1111, ..., 0xFFFF, repeating as necessary to fill the payload. The reason for this pattern is that the IEEE 802.15.4 standard employs a system in which the packet is split into 4-bit blocks (so-called nibbles) that are then replaced by a 32-bit chipping sequence and sent via DSSS. Hence, nibbles are the smallest "atomic" unit of 802.15.4, and the pattern mentioned above repeats each nibble 4 times before sending the next one.

Previous results [11] showed that low-value nibbles with a most-significant bit (MSB) of 0 were more robust to bit errors than those with an MSB of 1. Since first reporting on this behavior, a strong case has been made [7] that this is due to the hardware of the CC2420 radio, which during reception uses MSK to demodulate the signal instead of O-QPSK, which is compatible, but explains the uneven error distributions. In our experiments, we could witness the same error distributions at room temperature as reported on by previous work. When increasing the temperature, the relative distribution of the pattern stays the same, as can been seen in Figure 4, where we took an example result between two nodes. While the absolute number of errors within a message, and therefore



(a) Low susceptibility

(b) High susceptibility

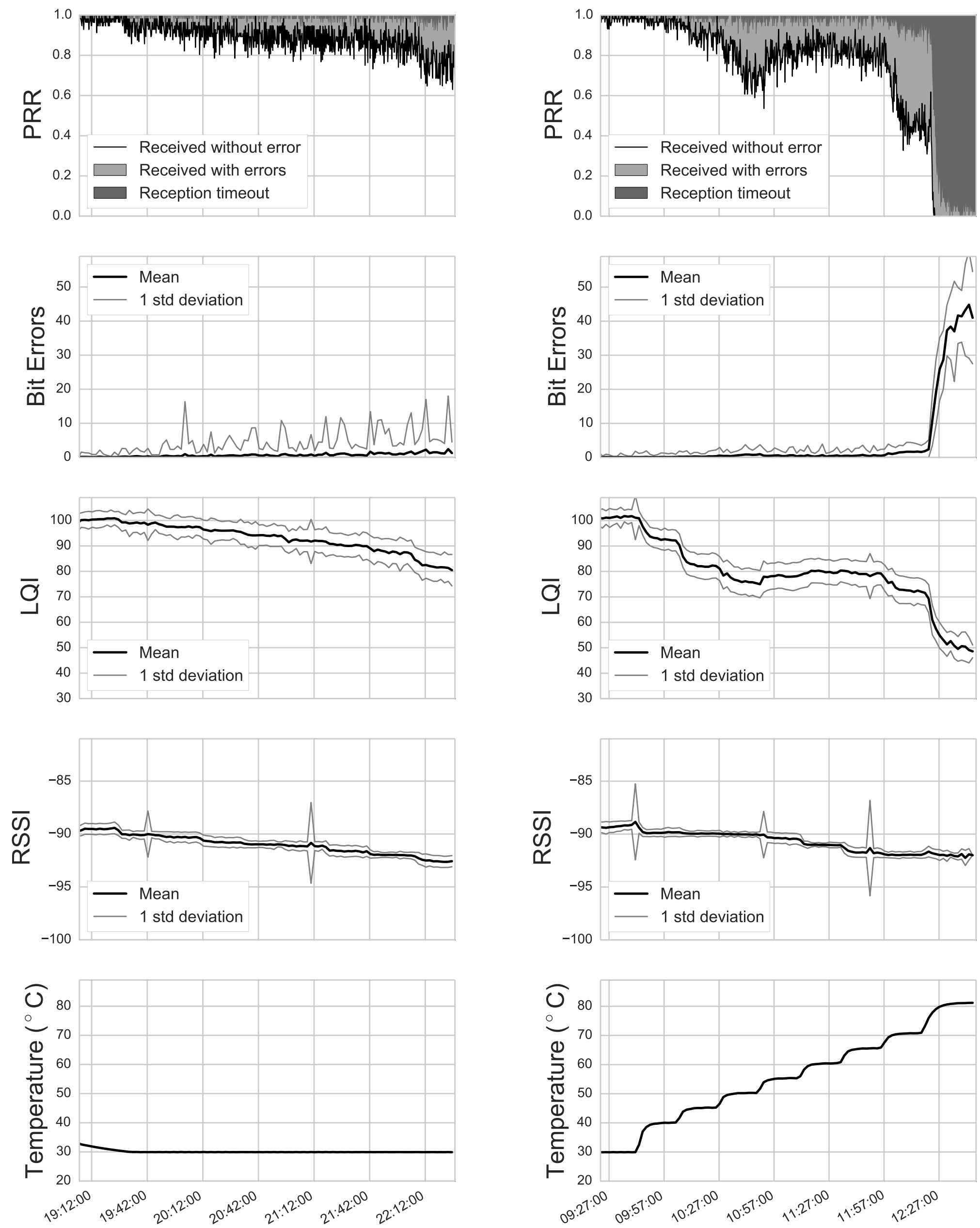
Fig. 5: Different hardware shows different susceptibility to uneven bit error distributions. While each magnitude of susceptibility is specific to a device and does not change noticeably with temperature or link quality, the differences cannot be traced back to specific production runs or producers; they are effectively random and cannot be predicted without testing. Shown are two examples of susceptibility from nodes at the extreme ends of the spectrum.

the Bit Error Rate (BER) increases, the *relative* distribution of errors between different bits stays roughly the same.

However, we did notice over the course of our experiments that motes could exhibit this behavior more or less strongly. While some motes would have 1-MSB nibbles break nearly twice as often as 0-MSB ones, the difference was much more subdued in other cases. Two examples of results from different motes are given in Figure 5. These characteristics were specific to a mote and would show up reliably in all tests. We could not trace back these differences to difference in manufacturer or production run; they seem to rely on effects that are within the production tolerances of the mote and its components. Without measuring the characteristics, it was effectively impossible to predict the susceptibility of a mote. Unless a way is found to reliably predict mote characteristics, this significantly complicates ideas of leveraging these imbalances in error distribution to create more robust coding schemes, as suggested in [11].

4.3 Packet Error Dependency on Temperature

Previous work [1–4,15] has shown a strong influence of temperature on communication quality. We therefore wanted to check whether we could reproduce these results with our HotBox hardware. For these experiments, we started with a temperature of 30 °C and then gradually increased the temperature in 5 or 10 °C increments, spending 20 minutes at each target temperature before switching to the next higher one. In these experiments, we distinguished between heating the transmitter and heating the receiver of a connection. Two nodes took turns sending messages to each other; one box was heated, while the other was kept at a constant temperature of 30 °C. Results for each node were saved separately, thereby creating two separate datasets from heating the transmitter and from heating the receiver during a single experiment. As metrics, we measured the RSSI, the Link Quality Indicator (LQI), and BER as well as packet reception rate (PRR). We split the latter into three cases: a packet could be received with-



(a) Transmitter heated

(b) Receiver heated

Fig. 6: Influence of temperature on several key communication metrics. Note that all results are collected at the receiver, hence temperature in 6a stays stable because only the transmitter is heated (in the same fashion as the receiver in 6b). While temperature has a negative effect on all metrics, the effect is much stronger if the receiver is heated, with the exception of RSSI, in which case there are no significant differences between heating the transmitter or the receiver.

out errors; it could be received, but with errors; or it could be not received at all (completely lost). The latter case is typically a result of strong corruption within the preamble of the packet, which prevents the receiver from detecting that a packet was sent over the wireless channel.

Figure 6 shows a typical result from one of our experiments. All presented results are values as witnessed by the receiving mote. As such, the temperature shown in Figure 6b shows the changing temperature settings throughout the experiments. Conversely, Figure 6a does not show any changes in the temperature, because it was the transmitter which was heated, while the receiver, whose values are shown, was kept at a constant temperature.

Overall, it can be seen that all metrics are negatively influenced by temperature. However, the amount as to which they are influenced differs, and heating the transmitter and the receiver has different magnitudes of effect for most metrics. The only metric that is largely independent of the fact which mote is heated is the RSSI. All other metrics show a much higher negative influence when the receiver is heated. Heating the transmitter to 80 °C still allows communication, albeit with a packet error rate of more than 20%. In contrast, communication completely breaks if that temperature is applied at the receiver's side, and even at 70 °C, PER is much higher at above 50%. This is reflected in the BER, which explodes at receiver temperature above 70 °C. At the same time, LQI significantly decreases.

Summarizing, our results reinforce the notion of temperature as a significant influence on the communication quality in low-power networks. However, we were not able to reproduce the results in [3], which showed transmitter heating as the larger influence on quality. In our experiments, heating the receiver produces a larger impact.

5 Conclusion

In this technical report, we first presented a new way to cheaply and accurately control temperature in wireless sensor testbeds. Our solution is cost-effective, can control temperature to an accuracy of 0.5 °C as well as orientation to an accuracy of 5°, and its schematics and software are available to the public [8]. We then used this temperature-controlled environment to investigate the effects of temperature on the communication quality of low-power wireless networks, both to validate the usability of HotBox as experimentation platform and to contribute to the current state of knowledge in the area of temperature-related effects on communications in such networks. We could confirm prior findings by Schmidt et al. [11], and that those effects are independent of temperature. However, we witnessed differences in the strength of these effects between different sensor nodes, without any apparent correlation with producers or production runs. At the packet level, we could confirm previous results in that an increase in temperature causes a decrease in communication quality. However, as opposed to other results, which showed a larger negative effect when the transmitter was heated [1, 2], we consistently measured a larger influence when the receiver was heated in our experiments. This difference warrants future, more thorough, investigations to scrutinize the effect of either communication partner on the overall performance.

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