Hot Packets: A Systematic Evaluation of the Effect of Temperature on Low Power Wireless Transceivers

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ABSTRACT

Temperature is known to have a significant effect on the performance of radio transceivers: the higher the temperature, the lower the quality of links. Analysing this effect is particularly important in sensor networks because several applications are exposed to harsh environmental conditions. Daily or hourly changes in temperature can dramatically reduce the throughput, increase the delay, or even lead to network partitions. A few studies have quantified the impact of temperature on low-power wireless links, but only for a limited temperature range and on a single radio transceiver. Building on top of these preliminary observations, we design a low-cost experimental infrastructure to vary the on-board temperature of sensor nodes in a repeatable fashion, and we study systematically the impact of temperature on various sensornet platforms. We show that temperature affects transmitting and receiving nodes differently, and that all platforms follow a similar trend that can be captured in a simple first-order model. This work represents an initial stepping stone aimed at predicting the performance of a network considering the particular temperature profile of a given environment.

Categories and Subject Descriptors

Computer Systems Organization [**Embedded and cyber-physical systems**]: Sensor networks.

Keywords

Signal strength, Temperature, Wireless Sensor Networks.

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1. INTRODUCTION

Wireless sensor networks (WSNs) have proven to be an excellent monitoring tool and nowadays many installations exist. They are, for example, used to monitor natural phenomena such as glaciers, infrastructures such as bridges, or production processes on oil platforms. Many of these deployments are heavily exposed to the environment and experience extreme temperature changes within a day and over seasons. Temperature has a significant impact on wireless communication and a system has to be designed to handle all possible temperature changes over the deployment lifetime. This is of particular importance if we rely on the system and expect a deterministic performance at any given point in time. For example, we expect that a WSN-based process automation on an oil rig operates reliably while the installation is cycling through the extreme temperature changes that are typically found in such deployments. A system failure caused by a wrong prediction of the impact of temperature changes on wireless communication is not acceptable.

Many studies describing experiences from WSN outdoor deployments have reported that diurnal (day/night) and seasonal (summer/winter) fluctuations of ambient temperature have a strong impact on communication quality. Lin et al. [1] have found a daily variation in the received signal strength (RSS) of up to 6 dBm, with the highest RSS values being recorded during night-time. Similarly, in their deployment in an Australian outdoor park, Sun and Cardell-Oliver [2] have measured on-board temperature daily variations between 10 and 50 °C, and noticed that links perform very differently between day and night. Also Thelen et al. [3] have noticed a drastic decrease of RSS at high temperatures in their potato-field deployment.

While the *macro-view* of the problem is clear (temperature has an effect on signal strength and link quality), this knowledge does not help us to fully understand the dependency between link quality and temperature. Furthermore, existing work does not allow us to predict the performance of a network with respect to communication-related temperature dependencies. The aim of this work is hence to develop a *micro-view* of the problem by analysing systematically the impact of temperature on different radio transceivers. We design a low-cost experimental infrastructure to vary the on-board temperature of nodes in a repeatable fashion and study the effects on transmitting and receiving nodes, isolating hardware-specific effects. Our results show that all platforms follow a similar trend that can be captured in a relatively simple first-order generic model for low-power wireless transceivers. Such a model can be used for planning and constructing wireless sensor networks providing dependable service despite temperature changes.

In the next section, we describe existing work in the outlined research area. In Sect. 3 we present results from a 1-year long outdoor deployment in Sweden that we used as a starting point for this work. We then describe and analyse the results of extensive lab experiments to systematically study the effects of temperature in a controlled setting. We develop a first-order model of temperature and link quality dependency in Sect. 4 and conclude our paper in Sect. 5.

2. RELATED WORK

Results by Bannister et al. [4] from an outdoor deployment and from experiments in controlled scenarios have revealed that an increase in temperature causes a reduction in RSS. In their experiments in a climate chamber, the authors observe a linear decrease in RSS of about 8 dB over the temperature range 25-65 °C and show that this reduction may have severe consequences on the connectivity of a network. These results were confirmed by experiments by Boano et al. [5], [6], showing that one can safely decrease the transmission power of communications at low temperatures without deteriorating the performance of the network.

A recent long-term outdoor deployment by Wennerström et al. [7] has further shown that the average packet reception rate (PRR) in a WSN of 16 Tmote Sky nodes dropped by more than 30% when changing temperature from -5 to 25 °C, and that a clear degradation in PRR and average link quality occurred during summer, confirming that daily and seasonal fluctuations of ambient temperature have a strong impact on the quality of sensornet communications.

These existing works simply report the degradation of signal strength and link quality as a consequence of an increase in ambient temperature and do not provide a deeper analysis of the problem. In addition, every reported analysis is unique in terms of experimental setup and hardware. The used radio chips range from Nordic NRF903 [2] and CC1000 [3] to the popular CC1020 [6] and CC2420 transceivers [1], [7], making it difficult to separate general from hardware-specific effects.

Bannister et al. [4] have attempted to quantify the loss of RSS due to temperature changes, but only for a limited temperature range and for a single radio chip. Furthermore, when simulating the reduction of communication range and connectivity degradation due to an increase in ambient temperature, the authors assume that communicating nodes have similar temperatures.

This work goes beyond existing work and studies the impact of sender and receiver temperature on link quality systematically using different hardware platforms. After isolating hardware-specific effects, we show that temperature affects all platforms in a similar way and derive a model that captures its impact on low-power wireless transceivers.

3. EXPERIMENTAL RESULTS

In order to get a deeper understanding of the impact of temperature on WSNs, we study the evolution of link quality over one year in an outdoor deployment in Sweden. Our analysis shows that temperature has a strong impact on communication, with visible daily and seasonal differences.

Building on top of these results, we carry out a large set of experiments in controlled settings, where we can repeat and alter the conditions at different nodes separately. In all our experiments, we analyse the impact of temperature by measuring the hardware-based link quality metrics in IEEE 802.15.4 compliant radio transceivers [8], namely the received signal strength indicator upon packet reception (RSSI) and in absence of packet transmissions (noise floor), and the link quality indicator (LQI)[1].

3.1 Long-Term Outdoor Deployment

We now describe the impact of temperature on communication that we have observed in our outdoor deployment at a Swedish meteorological station spanning over a whole year.

Experimental Setup. We have deployed a sensor network comprising 16 TelosB sensor nodes outside Uppsala, Sweden, in an open field isolated from human activity and absence of electromagnetic interference. Sensor nodes are mounted on poles along a 80 meter straight line at intervals of 0, 20, 40, and 80 meters: on each pole, two nodes are mounted at 0.5 and 1.5 meters height, respectively. The nodes are powered via USB and attached to a Sensei-UU testbed [9], ensuring reliable and continuous data logging.

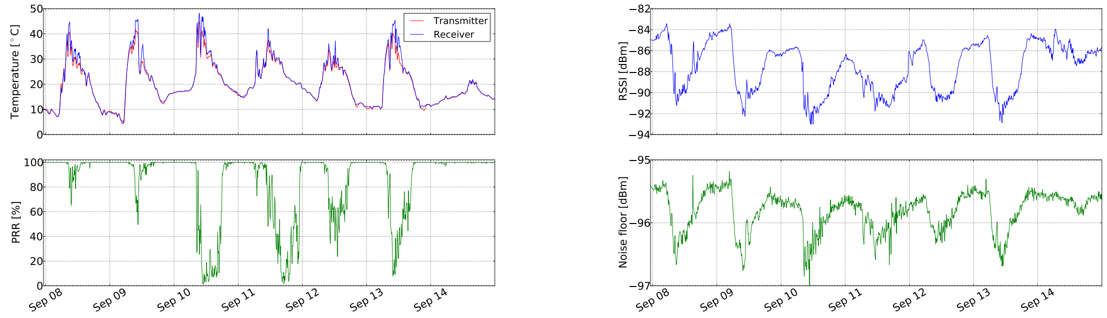
The software running on the sensor nodes periodically sends packets between every possible pair of nodes and works as follows. Each node is assigned the sender-role in a round-robin fashion every 30 seconds. During this phase, the designated sender transmits one packet per second addressed to each of the other nodes, again in a round-robin manner. When a packet is received by the intended recipient, a response packet addressed to the sender is sent. Each time a sensor node receives a packet – including when it is not the intended recipient – it logs several statistics about the received packet, namely RSSI, LQI, and noise floor. Onboard ambient temperature is measured on each node every two seconds using the on-board SHT11 temperature sensor. More details on the experimental setup can be found in [7].

Impact of temperature on PRR. To highlight the impact that ambient temperature has on the links deployed in our outdoor WSN, we focus on a specific link, close to the edge of the communication range. Fig. 1(a) (top) shows the temperature of two nodes (transmitter and receiver) forming a unidirectional link during a week in September. Temperature varies as much as 40 °C between day and night since sensor nodes are enclosed into air-tight enclosures and exposed to direct sunlight. Therefore daily temperature fluctuations may cause a combined overall variation between the two nodes of up to 80 °C. Although the highest variations occur over the 24-hours, temperature can fluctuate by as much as 34.9 °C within one hour, as we show in Table 1, in which we summarize the largest temperature ranges observed in our 12-months deployment for different time intervals.

Fig. 1(a) (bottom) further shows that each substantial increase in temperature (typically occurring during daytime) results in a decrease in PRR, leading to an almost complete disruption of the connectivity between the two nodes.

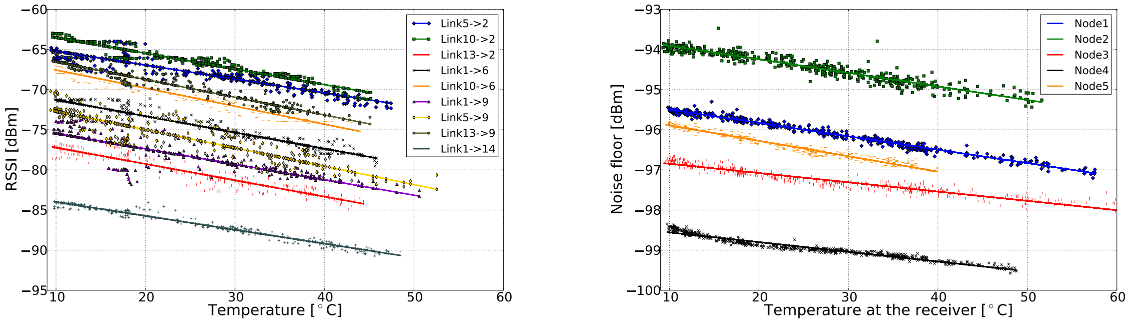
Impact of temperature on RSSI and noise floor. The decrease in PRR is strongly correlated with a decrease

[1]Please notice that the RSSI readings from all sensor nodes employed in our experiments are uncalibrated.



(a) Temperature and PRR (b) RSSI and Noise floor

Figure 1: Temperature has a strong impact on the quality of links in our outdoor WSN. During daytime, when temperature is high, there is a significant reduction in PRR (a). Also the trend of RSSI and noise floor resembles the one of temperature, with a sharp decrease when temperature increases (b).



(a) RSSI (b) Noise floor

Figure 2: The relationship between RSSI and temperature (a) and between noise floor and temperature (b) can be approximated as a linear function, and the trend is similar for different nodes.

	1 year	1 month	1 day	1 hour
Lowest temp. (°C)	-22.2	-3.0	7.2	21.2
Highest temp. (°C)	61.3	63.7	63.8	55.9
Temp. difference	82.5	66.7	56.6	34.9

Table 1: Largest temperature variations on a single node as seen in our outdoor deployment.

in the RSSI computed over the received packets, as shown in Fig. 1(b) (top), hinting that the change in temperature – and not external interference – was the cause of the packet loss. In particular, the RSSI fluctuates between -84 and -92 dBm, the latter being the threshold below which no packets are received. Interestingly, also the noise floor follows a trend similar to the RSSI and decreases as temperature increases, but to a much lower extent, as shown in Fig. 1(b) (bottom).

The strong correlation between temperature, RSSI, and noise floor is highlighted in Fig. 2(a) and 2(b), respectively. Fig. 2(a) shows the RSSI and the combined temperature of sender and receiver for nine links with different link quality over a timespan of three days. The relationship between temperature and RSSI can be approximated as a linear function and is clearly visible despite the intrinsic noise produced by long-term measurements. Using linear regression we have observed that different links have a similar trend, with an average slope of -0.205 and a standard deviation of 0.026.

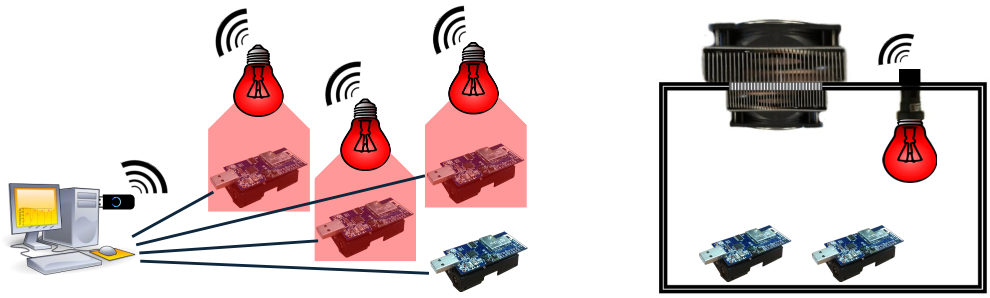
Fig. 2(b) shows the noise floor of five nodes over the same 3 days. Also in this case, the relationship with temperature is approximately linear, with a similar slope among different nodes, but with a less pronounced decrease compared to RSSI (average slope of -0.034 $\pm$ 0.006).

3.2 Controlled Testbed Experiments

To get a deeper understanding of the effects observed in Sect. 3.1, we have augmented an existing sensornet testbed with the ability of varying the on-board temperature of sensor motes and *reproduce the impact of temperature on link quality in a repeatable fashion.* We use this low-cost testbed infrastructure to systematically study the impact of temperature on different hardware platforms and to isolate the effects of temperature on transmitting and receiving nodes.

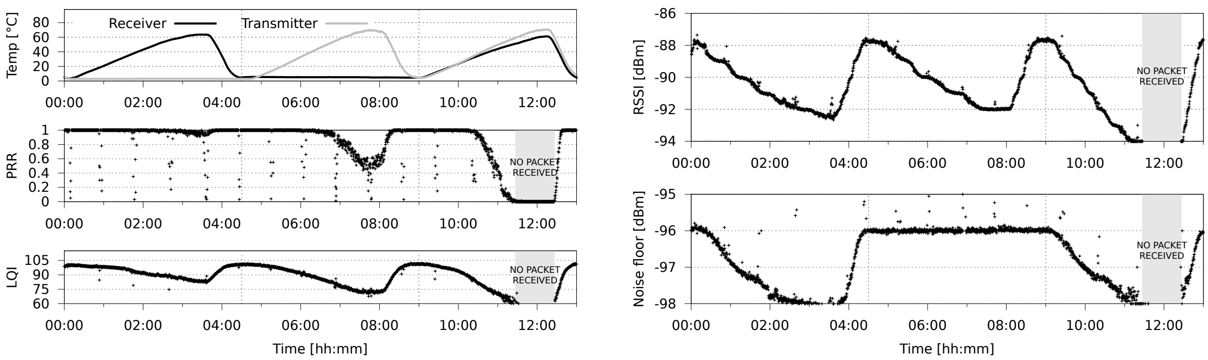
Experimental Setup. Fig. 3(a) shows an overview of our controlled experimental setup. We have extended an existing WSN testbed with the ability of varying the on-board temperature of sensor motes in the range -5 to +80 °C using infrared light bulbs placed on top of each sensor node. The light bulbs can be remotely dimmed using the 868 MHz frequency, and hence their operations do not interfere with the communications between the wireless sensor nodes, as the latter use the 2.4 GHz ISM band. In order to cool down the motes below room temperature, we have built custom Polystyrene enclosures as shown in Fig. 3(b), in which, in addition to the light bulb, a Peltier air-to-air assembly module by Custom Thermoelectric cools the temperature down to -5 °C when the enclosure is kept at room temperature and the light bulb is off. As we only have a limited number of Peltier enclosures, some of the nodes in the testbed are only warmed by the infrared light bulbs between room temperature and their maximum operating temperature range.

Our testbed is composed of Maxfor MTM-CM5000MSP and Zolertia Z1 nodes employing the CC2420 radio [10], as



(a) Setup overview (b) Sketch of a Peltier enclosure

Figure 3: Experimental setup in controlled testbed experiments.



(a) PRR and LQI (b) RSSI and Noise floor

Figure 4: Impact of temperature on the quality of links in our controlled testbed. We heat transmitter and receiver nodes separately first, and then both of them at the same time. When temperature increases, PRR, LQI, and RSSI decrease significantly, with the highest impact occurring when both nodes are heated at the same time. The periodic noise is due to a Wi-Fi access point beaconing in proximity of the testbed.

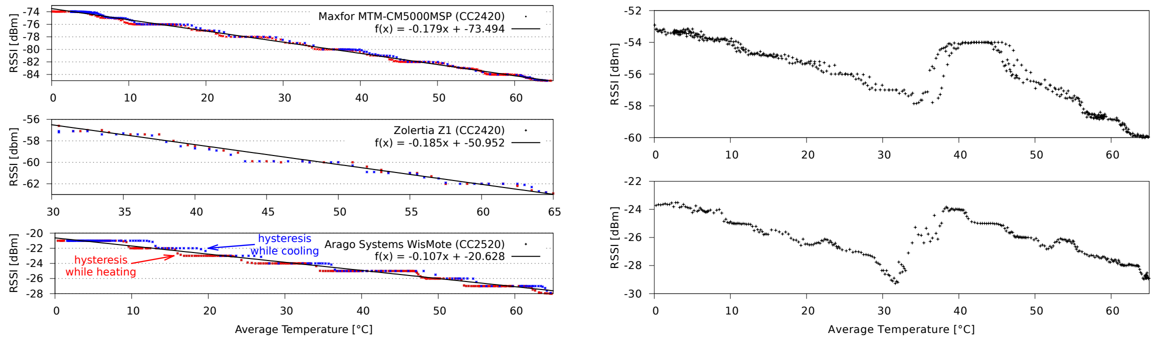
well as of Arago Systems WisMotes employing the CC2520 transceiver [11]. Sensor nodes are divided in pairs and form bidirectional links operating on different physical channels to avoid internal interference. All sensor nodes run the same Contiki software: each sensor node continuously measures the ambient temperature and relative humidity using the on-board SHT11 or SHT71 digital sensors, and periodically sends packets to its intended receiver at a speed of 128 packets per second using different transmission power levels. Statistics about the received packets are logged using the USB backchannel and are available remotely.

Validation of our controlled setup. Using our controlled testbed setup, we are able to reproduce the impact of temperature on link quality in a very fine-grained way. In a first experiment using Maxfor nodes, every link in the testbed is exposed to three heat cycles. First, each individual node, i.e., first the transmitter and then the receiver, is heated from 0 up to 65 °C. Afterwards, both nodes are heated in the same temperature range at the same time. Fig. 4(a) illustrates the impact of temperature on PRR and LQI on a particular link. The evolution of temperature at the transmitter and at the receiver over the 13-hours experiment is shown in the top figure. In correspondence to each increase of temperature, PRR and LQI decrease significantly, with the highest impact occurring when both nodes are heated. With both nodes heated, indeed, no packet was received and the connectivity between the two nodes was interrupted until the temperature started to decrease. Fig. 4(a) also shows that the packet loss rate is more pronounced when the transmitter is heated compared to the case in which only the receiver is heated, something that we have observed in the majority of links in our testbed.

Fig. 4(b) illustrates the impact of temperature on RSSI (top figure) and noise floor (bottom figure). The RSSI decreases in a similar way when transmitter and receiver are heated separately, whereas the decrease is more pronounced if both transmitter and receiver are heated at the same time. This proves that temperature decreases both the transmitted and received power [4], whereas the noise floor only decreases when the receiver node is heated, with an absolute variation smaller than the one of RSSI.

These results hence prove the validity of our setup and confirm the measurements obtained in our outdoor deployment, quantifying precisely the impact on temperature on each individual node. We now derive a set of observations obtained running experiments using the same experimental setup, i.e., three heat cycles in which each node is heated individually first and then both nodes are heated at the same time, on different hardware platforms.

The decrease in RSSI is consistent among different platforms. The trend observed in our outdoor deployment showing that RSSI decreases in an approximately linear fashion with temperature holds for different platforms and different radio chips, but with a different slope. Fig. 5(a) shows the relationship between RSSI and temperature obtained on different platforms when heating both nodes at the same time. The hardware platforms employing the same CC2420 radio exhibit approximately the same slope.



(a) Loss in RSSI when temperature changes (b) Non-linearities in the CC2420 radio

Figure 5: Figure (a) shows that the relationship between RSSI and temperature is similar when using different hardware platform and can be approximated as a linear function, but with different parameters. Figure (b) shows the non-linearities in the response of the CC2420 radio measured using Maxfor nodes. Temperature on the x-axis is computed as the average temperature of the transmitter and receiver temperature.

The decrease in RSSI does not depend on how quickly temperature changes. In our setup, the heat cycles are characterized by a slow increase in temperature followed by a quicker cooling phase, as can be seen in Fig. 4(a). This allows us to observe that both RSSI and noise floor are not affected by how quickly temperature varies. Hence, the impact of temperature can be modelled using the absolute temperature value at the transmitter and receiver nodes.

Discrete steps. On close inspection in Fig. 5(a), one can observe discrete steps in the relationship between RSSI and temperature. For the CC2420 platforms, the size of the prominent steps is 2 dBm, whereas for platforms employing the CC2520 radio the step is 1 dBm large. Bannister [12] has attributed the loss of RSSI to the loss of gain in the CC2420 Low Noise Amplifier (LNA). Our experiments bring further evidence to strengthen this claim, as there are references to 2 dBm steps in the CC2420 datasheet [10] with regard to the operation of the Automatic Gain Controller (AGC).

Hysteresis. Fig. 5(a) also shows an hysteresis in the relationship between RSSI and temperature that can be seen comparing the RSSI curve obtained when heating and when cooling down the motes. As for the discrete steps, the hysteresis also can be attributed to the operation of the AGC in the CC2420 radio. According to the CC2420 datasheet, hysteresis on the switching between different RF front-end gain modes is set to 2 dBm [10].

Non-linearity in the CC2420 curve. In our experiments, we have also noticed visible non-linearities when the RSSI is ≈ -28 and -58 dBm in the CC2420 platform, as shown in Fig. 5(b). These non-linearities were also measured by Chen and Terzis [13], and may lead to a false approximation in case the RSSI of the considered link falls *exactly* in this region (as in the experiments of [4]). When deriving our linear approximation for the CC2420 transceiver, we hence do not consider links falling in this range.

RSSI loss on transmitter and receiver. Fig. 6(a) shows the relationship between RSSI and temperature obtained on Maxfor nodes when transmitter and receiver nodes are heated individually and when both nodes are heated at the same time. Top and bottom figures refer to the same link, but are obtained using a different transmission power. Despite the link is the same, the relationship between RSSI and temperature is slightly different, with a steeper decrease when the receiver is heated in the top figure. Although a comparison between curves is difficult due to the AGC operations (depending on whether we capture the transition between two discrete steps, we may obtain slightly different slopes), by averaging the data from all our experiments we have obtained a relationship between receiver and transmitter of 0.5348 ± 0.061. The RSSI seems hence to have a slightly steeper slope when the receiver node is heated.

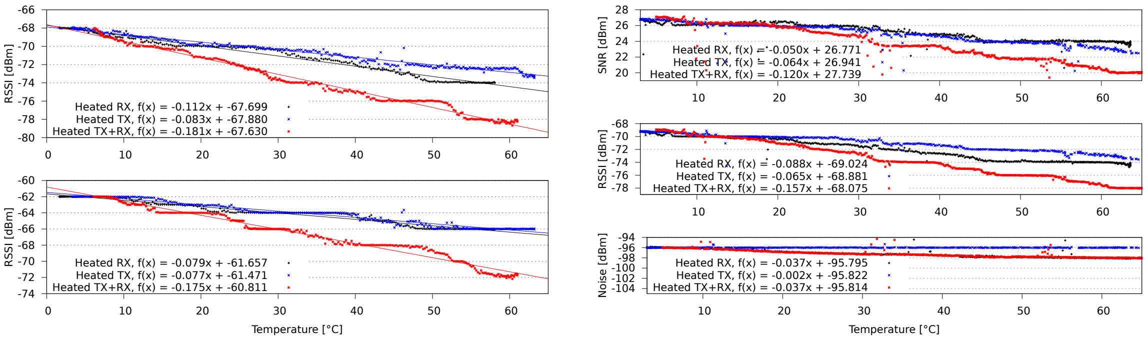
Impact on noise floor and SNR. Fig. 6(b) illustrates how noise floor, RSSI, and signal to noise ratio (SNR) vary on a given link when transmitter and receiver nodes are heated individually and at the same time. Since the noise floor decreases only when the receiver is heated, an increase in temperature on the transmitter has an higher impact on the SNR compared to an increase in temperature at the receiver. This also explains the different impact in PRR when heating the nodes individually that we observed in Fig. 4(a).

4. PLATFORM MODELS

The effect of temperature on electric conductors and semiconductors is well known. Various models have been created for a large range of devices to capture the relation between ambient temperature and electric conductance (and current leakage). Our goal is to build on top of this knowledge to create a generic model for low-power radio transceivers. It is important to remark that the goal of our model is not to benchmark a specific radio chip against others, as this is already done by manufacturers. Our goal is to develop a simple model to predict the performance of a network under extreme environmental settings. We now describe the overarching effect of temperature on radio transceivers and derive a generic model for low-power wireless transceivers.

4.1 The effect of temperature on RSS

In electric conductors, a higher temperature increases the resistance of the medium, whereas in semiconductors it leads to current leakages. In practice this means that, for a given voltage, a higher temperature reduces the current and hence the power of a device. In radio transceivers, these phenomena imply that a raise in temperature will reduce the SNR. A decrease in SNR leads to a lower link quality and a shorter radio link, which in turn may lead to lower throughput, higher delay or even network partitioning. Hence, our goal is to model the effect of temperature on SNR. Denoting PL as the path loss between a transmitter-receiver pair, P_t as the transmission power, P_r as the received power, and P_n



(a) Loss in RSSI when using different TX powers (b) Loss in noise floor, RSSI, and SNR for a given link

Figure 6: Relationship between RSSI, noise floor, SNR and temperature when transmitter (blue) and receiver (black) nodes are heated individually, and when both nodes (red) are heated at the same time.

as the noise floor at the receiver, the SNR is known to be:

$$\begin{aligned} SNR(dB) &= P_t - PL - P_n \\ &= (P_t - P_n) - (P_t - P_r) \end{aligned} \tag{1}$$

As we have shown in our empirical measurements, an increasing temperature has 3 main effects on the signal strength of radio transmissions; it (i) decreases the transmitted power, (ii) decreases the received power, and (iii) decreases the noise floor. We now model these three effects in Eq. 1.

4.2 A first-order model

Denoting α, β, γ as constants with units dB/K, and T_t, T_r as the temperature in Kelvin of transmitter and receiver, the effect of temperature on SNR can be defined as:

$$\begin{aligned} SNR &= (P_t - \alpha\Delta T_t) - (PL + \beta\Delta T_r) \\ &\quad -(P_n - \gamma\Delta T_r + 10\log_{10}(1 + \tfrac{\Delta T_r}{T_r})) \\ &= P_t - PL - P_n - \alpha\Delta T_t \\ &\quad -(\beta - \gamma)\Delta T_r - 10\log_{10}(1 + \tfrac{\Delta T_r}{T_r}) \end{aligned} \tag{2}$$

The proportional relation between ΔT and the constants α (effect on transmitted power), β (effect on received power) and γ (effect on noise floor) is based on the empirical observations made in the previous sections. The term $10\log_{10}(1+\frac{\Delta T_r}{T_r})$ is derived analytically from the well-known thermal equation. There are two important trends to highlight in this model. First, changes in temperature have a higher impact on the transmitted and received powers (linear relation of α and β), than on the thermal noise (logarithmic relation). Second, to some extent it is counter-intuitive that a higher temperature decreases the noise floor (negative sign of γ). This effect was also observed by Bannister, and he hypothesizes that it is due to the losses in the signal amplifier [12]. That is, a higher temperature not only reduces the gain of the signal but also the gain of the noise, and hence, the received signal strength (RSSI) is lower for both.

The accuracy of our model depends on identifying the right values for α, β and γ. In our case, these parameters are given by the slopes of the linear trends observed in our empirical results. These parameters are platform dependant, and hence require a systematic and fine-grained evaluation. Our testbed was designed to accomplish exactly that. For example, a network manager willing to deploy a network using the Maxfor platform, can use the slopes obtained in Fig. 6(b): $\alpha = 0.065$, $\beta = 0.088$ and $\gamma = 0.037$. Assuming that the network will be deployed in an environment where the maximum and minimum day temperature are 50 and 5°C respectively, the network manager can predict that the links can suffer an attenuation of $(\alpha + \beta - \gamma)\Delta T = 5.22$ dB (5 dB according to the SNR measurements in Figure 6(b) top). This level of attenuation can easily push a good link (with 100% PRR) to have a PRR of 0%.

5. SUMMARY AND OUTLOOK

The central tenet of our study is that the important role played by ambient temperature in the performance of sensor networks can (and must) be analysed in a systematic way. Motivated by initial studies focusing on single platforms, we use a low-cost yet precise testbed to show that most platforms have similar intrinsic characteristics that can be easily modelled. Our results capture with good accuracy how temperature affects the signal strength in transmitters and receivers. A thorough understanding of the effect of temperature on low-power wireless links is a first necessary step of a much broader goal: the ability to predict the performance of sensor networks in various environmental settings.

6. REFERENCES

[1] S. Lin, J. Zhang, G. Zhou, L. Gu, T. He, and J. A. Stankovic. ATPC: Adaptive transmission power control for wireless sensor networks. In *Proc. of the 4th SenSys*, 2006.

[2] J. Sun and R. Cardell-Oliver. An experimental evaluation of temporal characteristics of communication links in outdoor sensor networks. In *Proc. of the 2th RealWSN*, 2006.

[3] J. Thelen et al. Radio wave propagation in potato fields. In *Proc. of the 1st WiNMee*, 2005.

[4] K. Bannister, G. Giorgetti, and S. K. S. Gupta. Wireless sensor networking for hot applications: Effects of temperature on signal strength, data collection and localization. In *Proc. of the 5th HotEmNets*, 2008.

[5] C.A. Boano, J. Brown, N. Tsiftes, U. Roedig, and T. Voigt. The impact of temperature on outdoor industrial sensornet applications. *IEEE TII*, 6(3), 2010.

[6] C.A. Boano, J. Brown, Z. He, U. Roedig, and T. Voigt. Low-power radio communication in industrial outdoor deployments: The impact of weather conditions and ATEX-compliance. In *Proc. of the* 1^{st} *Sensappeal*, 2009.

[7] H. Wennerström et al. A long-term study of correlations between meteorological conditions and 802.15.4 link performance. In *Proc. of the 10th SECON*, 2013.

[8] N. Baccour et al. Radio link quality estimation in wireless sensor networks: a survey. *TOSN*, 8(4), 2012.

[9] O. Rensfelt et al. Sensei-UU: a relocatable sensor network testbed. In *Proc. of the 5th WiNTECH*, 2010.

[10] Texas Instr. *CC2420 datasheet, revision SWRS041c*, 2013.

[11] Texas Instr. *CC2520 datasheet, revision SWRS068*, 2007.

[12] K. Bannister. Impacts of thermal reduction in transceiver performance on outdoor sensing networks. Master's thesis, Arizona State University, Phoenix, AZ, USA, 2009.

[13] Y. Chen and A. Terzis. On the mechanisms and effects of calibrating RSSI measurements for 802.15.4 radios. In *Proc. of the 7th EWSN*, 2010.