Demo Abstract: A Testbed Infrastructure to Study the Impact of Temperature on WSN

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***Abstract*—Temperature strongly affects the operation of integrated circuits, and its impact has been largely investigated on a device level. However, the impact of temperature variations on *networks of multiple devices* is far less understood and requires investigation. We aim to close this gap and analyse the impact of temperature fluctuations on low-power wireless sensor networks, a key enabling technology of pervasive computing. As we are moving forward into an era of human-centric safety-critical applications (e.g., smart health and intelligent transportation systems), it is particularly important to make sure that a networked system offers a reliable and deterministic performance despite all possible temperature changes over its deployment lifetime.**

In this demo, we present a testbed infrastructure based on infra-red heating lamps that allows to vary the on-board temperature of sensor nodes on a large scale in a repeatable fashion. Using this experimental infrastructure, we show the effects of temperature variations on network performance in two different ways. First, in a small-scale local testbed at PerCom, we highlight the degradation of the wireless link quality at high temperatures, and show that the performance of radio transceivers is temperature-dependent. We quantify this degradation and parametrize the dependency between temperature and link quality using the signal strength information captured between four wireless sensor nodes. Second, we connect remotely to our large-scale experimental infrastructure at TU Graz, and assess the impact of temperature variations on the performance of state-of-the-art network protocols, showing that the typical outdoor temperature fluctuations occurring during 24-hours do affect key network metrics such as throughput, delay, and lifetime.

Keywords—Temperature, Testbed, Wireless Sensor Networks.

I. Introduction and Motivation

Wireless sensor networks (WSN) are often deployed in outdoor environments to monitor natural phenomena such as earthquakes, wildfire, and glaciers, civil infrastructures such as bridges, road tunnels, and heritage buildings, or industrial production processes such as oil rigs. Experiences from long-term outdoor deployments have highlighted that the on-board temperature of wireless sensor nodes packaged into airtight enclosures can vary by as much as 56°C between day and night, and up to 82°C across different seasons [1], [2].

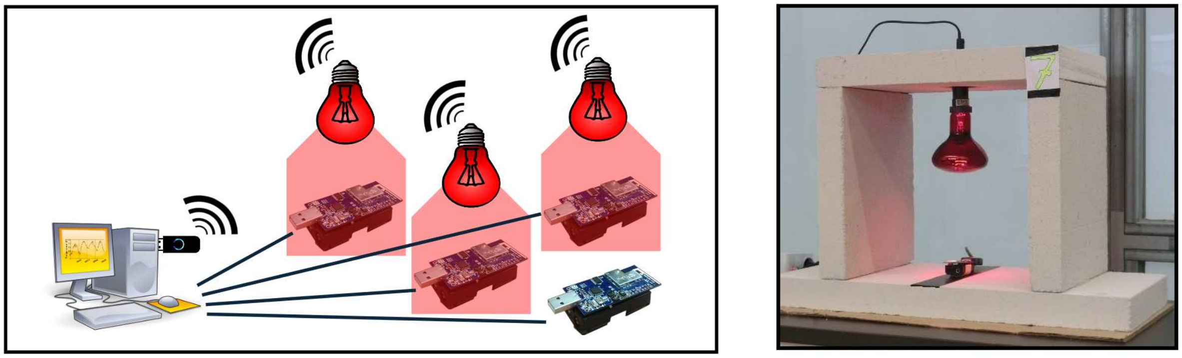
A large body of work has shown that these variations can have a strong impact on the efficiency of electronics and batteries. Temperature fluctuations much lower than the ones mentioned above can introduce a frequency offset on the crystal oscillator frequency sufficient to affect the rendezvous process of synchronous duty-cycled Medium Access Control (MAC) protocols [3]. Similarly, the battery capacity and discharge (and consequently the lifetime of a wireless sensor node) is also strongly dependent on those variations.

We focus on the impact of temperature on a network-level, a research area that has received only little attention. Following the observations by Bannister et al. [4], we have shown in previous work that temperature can drastically affect the wireless link quality [5]. A daily variation in temperature of 56°C can indeed reduce the received signal strength between two sensor nodes enough to vary the packet reception rate of a link from 100% to 0% [1]. As we will show, this reduction in signal strength drastically affects the operation of routing and networking protocols, leading to a lower throughput, higher delays, and a reduced energy-efficiency.

Obtaining a clear picture and a deep understanding of the impact of temperature on networking protocols using mere observations from real-world deployments or outdoor testbed facilities can be very hard. Meteorological conditions cannot be controlled, making it impossible to ensure repeatability across several experiments. Furthermore, the temperature profiles that can be tested are highly specific to the deployment location and to the time of the year in which the experiment is carried out. Therefore, there is a need for an experimental infrastructure that allows to evaluate the impact of temperature on wireless sensor networks in a precise and repeatable fashion.

In this demo, we present TempLab [6], an extension for WSN testbeds that allows to control the on-board temperature of sensor nodes and to study the effects of temperature variations on the network performance. We use infra-red heating lamps to accurately reproduce the on-board temperature recorded in outdoor environments with fine granularity and show that it can be used to analyse the detrimental effects of temperature variations on networking protocols.

In particular, we show *live* at PerCom the degradation of the wireless link quality at high temperatures between two links, characterizing the dependency between temperature and link quality in real-time using signal strength information. We further connect remotely to our large-scale experimental infrastructure at TU Graz, and replay pre-recorded outdoor temperature traces on several sensor nodes running a state-of-the-art routing protocol. We show that temperature variations have a strong impact on key network metrics such as throughput, delay, and lifetime, and illustrate how the dependency between temperature and link quality (that we compute live) can be used to drive the design of robust networking protocols.



(a) Sketch of the testbed's architecture

(b) Heating lamp on top of a wireless sensor node

Fig. 1. Sketch of the augmented testbed infrastructure with the ability of reproducing real-world temperature profiles [1] (a). We use infra-red (IR) heating lamps placed on top of each wireless sensor node to vary the on-board temperature (b).

II. A TESTBED EXTENSION TO REPRODUCE THE IMPACT OF TEMPERATURE ON WSN

In the context of the EU-funded RELYonIT project [7], we have designed TempLab, an extension for existing testbed infrastructures that allows to vary the on-board temperature of sensor nodes by reproducing real-world temperature profiles [6]. We use infra-red (IR) heating lamps to vary the on-board temperature of wireless sensor nodes between their maximum operating range (+85 °C) and ambient temperature, and we control the intensity of the IR lamps remotely using *wireless dimmers*.

To instantiate a temperature profile and control the intensity of the heating lamps, we use a controller running on a centralized gateway computer, as illustrated in Figure 1(a). The controller can generate different temperature profiles on wireless sensor nodes using three approaches. Firstly, it can re-play previously recorded temperature traces to accurately reflect the temperature variations measured outdoors. A second possibility is to use a model-based temperature profile to have an approximation about the temperature dynamics at a certain location without the need of pre-recorded traces. Thirdly, one can vary the temperature of each sensor node using specific test patterns (e.g., a series of cold and warm periods), a useful tool to quickly debug the behaviour of networking protocols.

In our university testbed at TU Graz equipped with 17 Maxfor MTM-CM5000MSP wireless sensor nodes, we employ Philips E27 infra-red 100W light bulbs dimmed using Vesternet Everspring wireless dimmers. To communicate with the dimmers, we use the Z-Wave wireless home automation standard that operates on the 868 MHz ISM band, and hence does not interfere with the communications between the wireless sensor nodes (that use the 2.4 GHz ISM band).

The heating capabilities of our experimental infrastructure strongly depend on the employed hardware. With our current configuration, we can heat a wireless sensor node from room temperature to 80 °C in less than 5 minutes (an average heating slope of 11.3 °C/minute). This is sufficient to accurately re-play temperature changes recorded in the real-world, since long-term outdoor traces [2] have shown that a sensor node that receives the first sun-rays at the beginning of the day increases his temperature by as much as 1.98 °C/minute.

A preliminary evaluation of the accuracy of the regenerated traces in our testbed has shown that one can instantiate a desired temperature profile on a sensor node with an average error of only 0.18 °C and a maximum error of 1.90 °C[1].

III. DEMO DESCRIPTION

Our demo consists of two parts. On the one hand, we will recreate during the demo session a small-scale setup of our testbed infrastructure with four infra-red heating lamps placed on top of four Maxfor MTM-CM5000MSP wireless sensor nodes. On the other hand, we will remotely connect to our large-scale experimental infrastructure at TU Graz, where we will replay pre-recorded outdoor temperature traces on 17 Maxfor MTM-CM5000MSP wireless sensor nodes.

Small-scale testbed at the demo. We reproduce a small-scale setup of our testbed infrastructure during the demo session with four infra-red heating lamps placed on top of four Maxfor MTM-CM5000MSP wireless sensor nodes. We will show the degradation of the wireless link quality at high temperatures between two links, and obtain the dependency between temperature and link quality in real-time using signal strength information. In particular, we divide sensor nodes in pairs and form bidirectional links operating on two different physical channels to avoid internal interference. All sensor nodes run the same Contiki software: each sensor node continuously measures the ambient temperature using the on-board SHT11 digital sensors, and periodically sends packets to its intended receiver at a speed of 128 packets per second using a predefined transmission power level. Statistics about the received packets[2] are logged using the serial port and collected by an application that computes the decrease in received signal strength as a function of temperature as we proposed in [1], and displays it as shown in Figure 2.

Remote large-scale testbed at TU Graz. We further connect remotely to our large-scale experimental infrastructure

[1]Evaluation carried out using a temperature trace captured outdoors in Sweden during summer [2], where temperature varied between 24 and 56 °C.

[2]We collect 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).

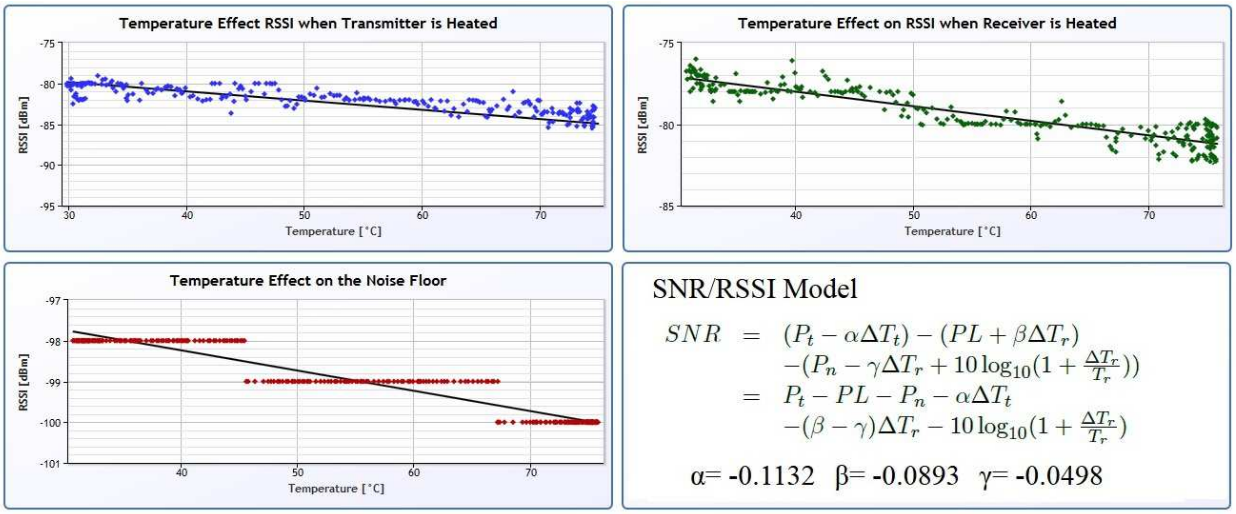


Fig. 2. Real-time capture of the degradation of the wireless link quality as a function of temperature, and parametrization of a first-order model.

Fig. 3. Snapshot of the testbed infrastructure available at TU Graz taken remotely using the steerable Web-cam.

at TU Graz, and replay pre-recorded outdoor temperature traces on 17 Maxfor MTM-CM5000MSP wireless sensor nodes. The testbed facility in Graz offers the possibility to monitor an experiment using a steerable Web-cam (Figure 3) as well as the ability to remotely control the lamps and program sensor nodes. We will connect remotely to the testbed and show how temperature fluctuations can affect the behaviour of Contiki's IPv6 Routing Protocol for Low-Power and Lossy Networks (ContikiRPL) [8] with potentially severe consequences for the connectivity of the nodes in the network [9]. We illustrate the impact that temperature variations have on key network metrics such as throughput, delay, and lifetime, and illustrate how the dependency between temperature and link quality can be used to drive the design of robust networking protocols.

IV. Conclusions

Temperature variations have a strong impact on the performance of wireless sensor networks and their effect must be analysed in a systematic way. To achieve this goal, we have designed TempLab, an extension for WSN testbeds that allows to vary the on-board temperature of sensor motes and study the effects of temperature variations on network performance. We use this infrastructure to demonstrate that temperature can significantly affect the operation of networking protocols and to precisely quantify the reduction in signal strength.

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