Experimental Study of the Thermal Impacts on Wireless Sensor Batteries

Wenqi (Wendy) Guo, *Member, IEEE*, William M. Healy, and MengChu Zhou, *Fellow, IEEE*

***Abstract*—Wireless sensor networks are being considered for application within buildings to control various equipment in different working environments. As wireless sensors are powered by commercially available batteries, battery performance will directly affect the entire network performance. Battery performance is affected by ambient temperature as temperature can modify the microstructure of the batteries. Thus the lifetime of the battery can change depending upon ambient conditions. It is hard to find any published data that quantitatively analyze the battery lifetime for a sensor node operating under different ambient temperature settings. In this paper, we deploy wireless sensors subject to variations of ambient temperature, study the temperature effects on battery lifetime, and investigate how the variations of ambient temperature influence data delivery performance in a low power communication network. Our work consists of commercially available sensor nodes conforming to the IEEE 802.15.4 protocol, commercial alkaline batteries, and a suite of techniques for measuring battery lifetime under different working temperatures. In view of these experimental results, we quantitatively show that temperature not only affects battery lifetime, but directly affects the communication quality between sensor nodes. We expect our results to serve as a basis for future research in designing better wireless sensor networks for building applications.**

***Keywords*—Wireless sensor, battery, lifetime, ambient temperature, building automation and control systems.**

I. INTRODUCTION [1]

Wireless sensor networks (WSNs) are successfully used for applications such as precision agriculture, military surveillance, and environmental monitoring. Recently, wireless sensors, or "motes," have gained popularity for use within buildings to perform automation and control because of the reduced costs and increased flexibility that wireless deployment provides. To support building applications, WSNs must assure a certain level of reliability. As the wireless sensors are powered by commercially available batteries, battery performance (i.e., lifetime) will directly affect the entire network's performance. The batteries that are used today are simple variations of the early battery or voltaic cell, which consists of two electrodes, an anode (the negative end) and a cathode (the positive end). An electrical current runs between the two electrodes due primarily to a voltage differential between the anode and cathode. The voltage runs through a chemical called an electrolyte (which can be either liquid or solid). A battery is made up of plates of reactive chemicals separated by barriers. All the electrons gather on one side and become negatively charged after a battery is polarized. Meanwhile, the other side becomes positively charged. Connecting a device to the terminals of the battery creates a current in which the electrons flow through the device to the positive side. An electrochemical reaction takes place inside the batteries to replenish the electrons. The effect is a chemical process that creates electrical energy, but, as with many chemical reactions, the process is affected by temperature. When an increase in temperature occurs, the electrons become active. A decrease in temperature, on the other hand, can inhibit electron activities. If a device including the battery is exposed to extreme temperature for any length of time, then there will be a negative effect on batteries. Furthermore, a rapid temperature change can lead to condensation, creating a potential hazard for a battery and its related devices.

In this paper, we investigate how ambient temperature affects battery lifetime and the link quality of devices using those batteries in low power wireless communication applications. We focus our study on a sensor network deployment for building applications. We aim to characterize the effect of temperature on commercially available sensor nodes, and determine the degradation of the battery while being used under different temperature conditions. In this context, nodes are deployed indoors and are encased in a climatic chamber to achieve the specified temperatures. Furthermore, we characterize how the energy consumption of sensor nodes is affected by temperature. Our contributions are twofold. First, we show that temperature directly affects the

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Wenqi (Wendy) Guo was with the Department of Electrical and Computer Engineering, New Jersey Institute of Technology, Newark, NJ 07102, USA (E-mail:wg9@ njit.edu) and is with the National Institute of Standards and Technology, Gaithersburg, MD 20899 USA (E-mail: wenqi.guo@nist.gov)

William M. Healy is with the National Institute of Standards and Technology, Gaithersburg, MD 20899 USA (E-mail: william.healy@nist.gov).

MengChu Zhou is with The Key Laboratory of Embedded System and Service Computing, Ministry of Education, Tongji University, Shanghai 200092, China and also ECE Dept., New Jersey Institute of Technology, Newark, NJ 07102, USA (e-mail: mengchu@ieee.org).

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overall battery discharge lifetime. Then we provide experimental results that show how temperature fluctuations can create a significant variation of signal strength of up to 15 dBm.

This paper proceeds as follows. Section II provides a general review of related work. We give a brief introduction of the alkaline battery in Section III. Methodologies for experimental evaluation of lifetime boundaries of wireless sensor nodes are discussed in Section III. Thereafter, observations of temperature influences on wireless sensor communication and battery lifetime are presented in Section IV. In Section V, we conclude this paper.

II. RELATED WORK

There is little published research focusing on temperature effects on wireless sensor battery lifetime and link quality. In one WSN application that applies wireless sensors for thermal monitoring in data centers, nodes operated in temperature differences of more than 50 °C [1]. They verify that minimizing heat recirculation will result in the best cooling energy efficiency through both theoretical analysis and simulations. In the literature [2, 3], the discharge curve of different battery models are presented. In [2], they claim that a Ni-MH battery is able to charge and discharge at extremely high and low temperatures outside the normal operating temperature range. The battery's performance, however, is significantly degraded. Evidence that temperature decreases the efficiency of radio frequency (RF) circuitry is found in [4-7], but no data that completely quantify the losses on mote hardware are available. Bannister *et al.* [8] have shown that high temperatures negatively affect communication between sensor nodes. In their deployment in the Sonoran Desert of the southwestern United States, the reduction of the signal strength is largest during the hottest time of the day. Previous work on sensor network link quality is focused on spatial properties such as the effect of distance on reception rates [9, 10]. Most previous experiments have been run in indoor environments over short time periods [11]. Sun and Cardell [12] found that a link may perform better during the day or at night, and suggest that humidity or noise is the reason for the results. Thelen *et al.* [13] reveals an inverse relationship between the received signal strength indication (RSSI) and the ambient temperature, but focuses on humidity. Therefore, there is a need to better understand the temperature effect on a sensor's battery lifetime and quantitatively analyze corresponding communication performance change.

III. ALKALINE BATTERY

Alkaline batteries are most commonly used in WSNs owing to their high energy density and long shelf life. Compared with zinc-carbon batteries, their usage life is 5 to 6 times longer [14]. Cylindrical alkaline batteries are produced with a high surface area zinc anode, a high density manganese dioxide cathode, and a potassium hydroxide electrolyte. The nominal voltage of a fresh alkaline cell is 1.5 V, with the effective zero-load voltage of a non-discharged alkaline battery varying from 1.5 V to 1.65 V depending on the composition of manganese dioxide in the cathode and zinc oxide in the electrolyte. Higher voltages are achieved by arranging cells in series. An alkaline battery produces electricity when its manganese dioxide cathode is reduced and its zinc anode becomes oxidized. The equation for a simple alkaline cell reaction is as follows [15]:

$$Zn+2MnO_2+H_2O \rightarrow ZnO+2MnOOH$$

During this reaction, water (H_2O) is consumed and hydroxyl ions (OH) are produced by the MnO_2 cathode under the following reaction:

$$2MnO_2+2H_2O+2e \rightarrow 2MnOOH+2OH^-$$

At the same time, the anode is consuming hydroxyl ions and producing water:

$$Zn+2OH^- \rightarrow ZnO+H_2O+2e$$

The electrons (*e*) generated during the reaction are used to power devices. The rate of the reaction depends on the quality of the raw materials and availability of water and hydroxyl ions during the reaction. A battery is designed to keep the cathode and anode separated to prevent the reaction from occurring. The stored electrons will only flow when the circuit is closed. This closure occurs when the battery is placed in a device and the device is turned on. Because batteries are devices that convert chemical energy into electrical energy, operation in extreme conditions such as extreme temperature modifies the microstructure of the battery compound and can thereby seriously affect battery characteristics.

IV. EXPERIMENT OVERVIEW

In this section, we describe the experimental procedure used in these studies. We provide (i) a brief background on the sensor and power supply hardware, and (ii) details of the setup used for experiments that require measurements of packet error rate (PER), RSSI, and battery lifetime.

A. Sensor Hardware and Power Supply

To determine the operating time of a node, exact measurements on its voltage changes are needed. Commercially-available wireless sensor nodes [4] are used in these tests. A node primarily consists of a microcontroller for taking sensor data and controlling its operations including transmitting data via a transceiver (transmitter/receiver). All components can be switched on or off or can be placed in an energy saving mode. The node contains an IEEE 802.15.4-compliant RF transceiver. The usable capacity of a battery depends mainly on the minimum operational voltage needed by a device, the required current, and the temperature. The measurement can be stopped when the radio transmission is turned off as there is a sensing chip integrated onto the node.

B. *Experimental Setup*

Lab experiments are performed using two motes to characterize the effect of temperature on wireless communication as shown in Fig. 1. The measurements are specifically obtained from the micro-controller on the sensor node. The test is performed by placing the sender node in a thermal chamber, in which the temperature can be changed from 20 °C to 50 °C (due to the equipment limitation, temperatures below 20 °C are not investigated at this time). Since the original door of the chamber was metal, which would greatly alter the wireless transmissions, the experiments were conducted with the door removed and a layer of plastic separating the conditioned interior of the chamber with the outside conditions. Sensor nodes are instrumented with temperature sensors and are programmed to transmit the data as well as the time stamp, node ID, battery voltage, and RSSI readings to a central receiving station via ZigBee wireless connection. Sensor readings consume minimal energy compared to the transmission of the data, so the results are thought to be valid for any sensor that uses power of the same order of magnitude as temperature sensors. The central receiving station consists of a sensor node which is attached to a programming board. The board is also connected to a laptop through a serial/USB cable through which sensor data are streamed to a computer for analysis. The sender and the receiver are placed 1 m away from each other, and are kept at the same height during the communication. Data are recorded and transmitted at specified intervals until data from transmitters can no longer be successfully read by the receiver. Alkaline batteries with an initial nominal voltage of 3 V (two 1.5 V batteries in series) are used, and the nodes function until the voltage drops to 1.8 V. Actual measurements provide (i) an understanding of the battery discharge behavior under different temperature settings, and (ii) RSSI and PER profiles as the batteries lose capacity. The voltages of the batteries are determined by the software in the nodes and are transmitted along with each sensor measurement. The collected discharge profiles can also be used as a starting point for synthesizing discharge profiles under different ambient temperature settings. We perform a total of three trials to obtain an average reading of the collected data to better understand experimental variability.

V. EXPERIMENTAL OBSERVATIONS AND ANALYSIS

The recommended operating temperature range for alkaline batteries is -18 °C to 55 °C. However, it is important to keep in mind that battery performance is still impacted by temperature within the recommended range. Performance of the battery is primarily dependent on how fast critical fuels, water and hydroxyl ions can move and react in the battery.

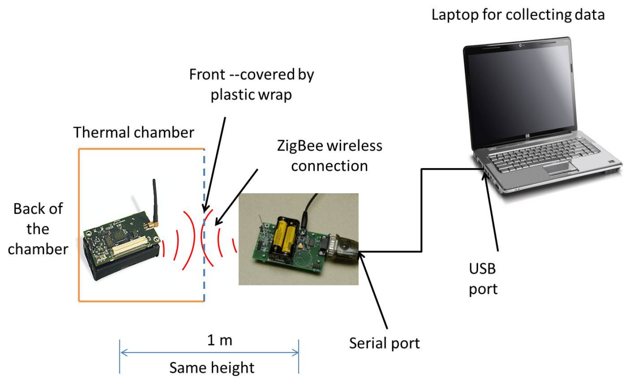

Fig. 1 Experimental setup for the battery testbed

A. *Thermal effects on battery lifetime*

A discharge curve is a convenient means to examine the energy capabilities of a battery. In order to precisely evaluate the battery lifetime, the duration of the battery under different voltage levels has been measured. During the discharge process, the output voltage level of the battery under test gradually decreases but not at a constant rate. Fig. 2 shows the length of time that a node spends at a particular voltage while the node sits in an ambient temperature ranging from 20°C to 50 °C. The figure presents a family of bell shape curves through the entire range of battery voltages. It also indicates that the batteries quickly fall from their initial voltages to settle at a voltage of approximately 2.5 V until they begin to fail. Both the beginning and ending voltages are observed for a short duration compared to the voltage levels approaching 2.5 V. These results suggest that batteries for a transmitter can last more than 1300 minutes at the mid-level voltage with the ambient temperature setting being approximately 20 °C. It can be calculated that the battery spends almost 50 times as much time at voltage level of 2.5 V than it does at the beginning and ending voltages at 20 °C.

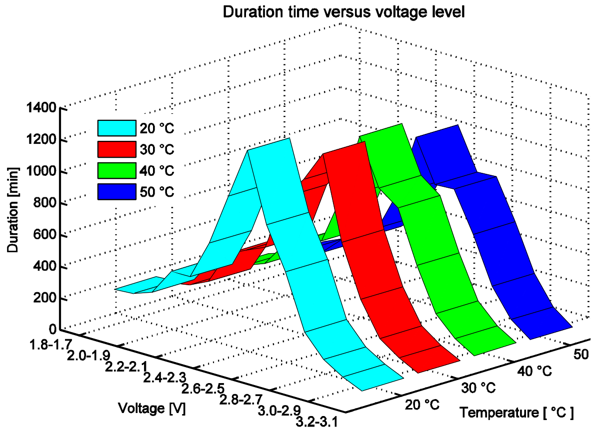

Fig. 2 Duration of wireless sensor battery at different voltage level. Temperature settings are 20°C, 30°C, 40°C and 50°C, respectively.

Lowering the temperature causes chemical reactions to proceed more slowly, and thus a battery produces less current at a lower temperature. As the batteries begin to lose capacity, they quickly reach the point where they cannot deliver enough current to keep up with the demand.

The overall battery lifetime discharge curves versus the voltage of the battery terminal at different temperatures are presented in Fig. 3. As shown in Fig. 3 (a), the voltage at the battery terminals decreases faster when the temperature is set to 20 °C than that at other temperature settings. Despite these initial effects, however, other factors may be at play later in the battery discharge cycle that affect battery lifetime. A zoom-in of the overall battery lifetime plot at the voltage level of 1.8 V is given in Fig. 3 (b), which is the level at which the nodes cease transmitting data. It suggests that the battery lifetimes are degraded by the high ambient temperature effect after certain voltage level. The battery usually fails gradually due to separator and electrolyte breakdown, as well as a deterioration of the vent seal that lets the electrolyte evaporate and allows the cell to dry out. All of these factors are made worse by higher temperature [16]. Accordingly, we notice that at 50 °C, 2 out of 3 experiments fail when the voltage level reaches either 2.0 V or 1.9 V, which occurs earlier than the desired 1.8 V. At this time, the receiver does not obtain any data package from the sender. The network performance and corresponding routing protocol can therefore change. In some cases, the death of a single sensor can even stop the communication of the entire network.

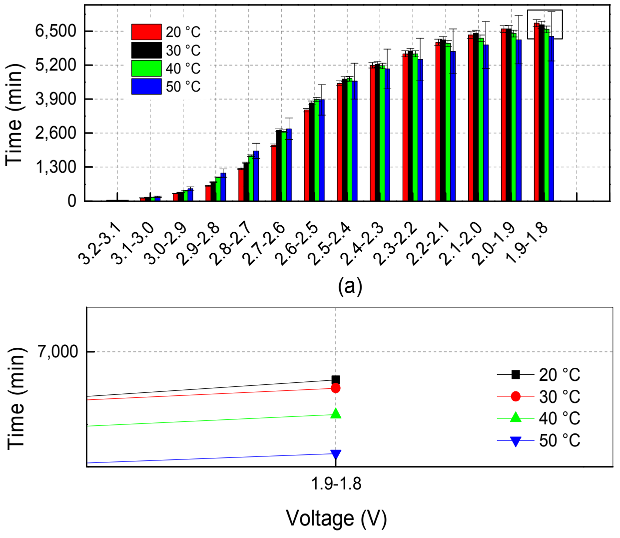

Fig. 3: (a) The cumulative lifetime of wireless sensor battery. The four temperature settings are 20°C, 30°C, 40°C and 50°C. (b) Detailed plot of battery lifetime distribution at 1.9 – 1.8 v.

B. *Thermal effects on battery voltage changing rate*

To further look into the voltage changing rate (VCR) as a function of different temperature settings, VCR versus voltage level at different temperatures are presented in Fig. 4. The VCR is calculated based on the following equation:

$$\varphi_{VCR} = \frac{t_c - t_p}{t_c}$$

where t_c stands for the duration under the current voltage level and t_p stands for the duration at the previous voltage level. For all temperatures, the area graph shows that initially the VCR decreases gradually with a positive number. After the peak duration level is reached, it immediately turns to a negative value with two troughs. The first trough appears at 2.5 V to 2.4 V and returns to a larger VCR compared to the second trough, which occurs when voltage level approaches 2.1 V.

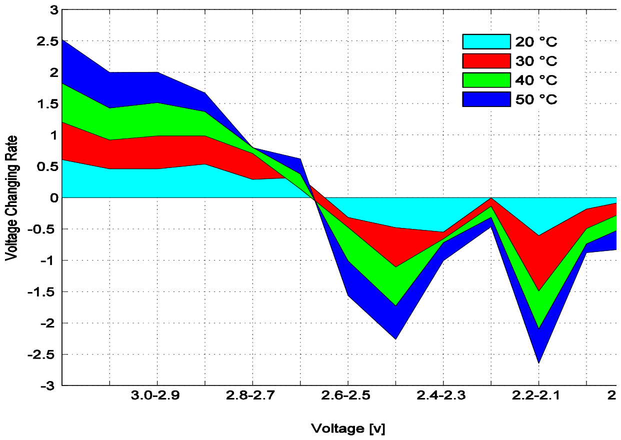

Fig. 4 Voltage level changing rate over battery voltage level

C. *Thermal effects on communication*

The influence of temperature variations on battery lifetime for wireless sensor communication must be taken into account when deploying a WSN in building applications, as the indoor temperature may vary with different applications. In addition to affecting the battery lifetime, temperature variations can also affect wireless communication quality between sensors. Evidence that temperature decreases the efficiency of the RF circuits is found in [6] as well, but no data that completely quantify the losses are available. In this test, we investigate how ambient temperature affects communication reliability. The working frequency band is set to 2.4 GHz, and data rate of 57600 bps. The measurements are specifically obtained for the transceiver that is used on some popular sensor nodes. The RSSI measurements are assessed throughout the entire experiment.

A reduction in the RSSI with temperature was detected and shown in Fig. 5. The plots demonstrate readings at 20 °C, 30 °C, 40 °C, and 50 °C levels as described in the previous setup section. To reduce the experimental variability, all tests were repeated 3 times to obtain an average result. In addition, the standard deviation of RSSI for different temperature settings has been calculated and shown as uncertainty bars in the plot. As one can see from the figure, the impact of temperature on the radio chip is considerable, with higher temperatures leading to a lower signal strength. The readings at 50 °C show a decrease of more than 15 dBm compared to readings taken at 20 °C. This reduction is substantial given that the typical range of RSSI is between -50 dBm and -75 dBm. Hence, a high temperature might lead to a loss of connectivity within the WSN. This conclusion is in line with [8], which finds that if the power amplifier of the radio chip is subject to a temperature increase, the signal strength of transmissions will decrease if the transmission power is constant.

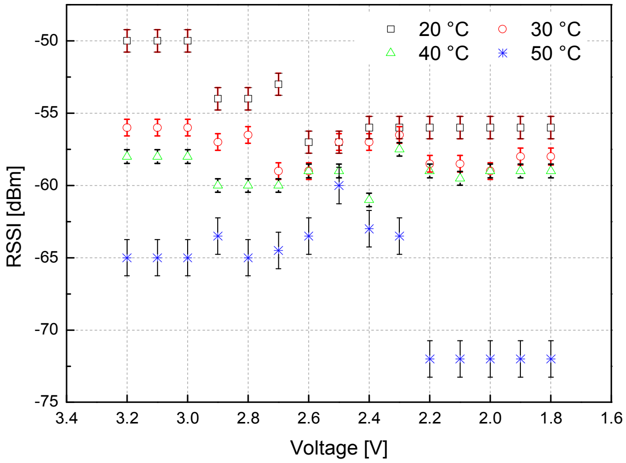

Fig. 5 RSSI plots over battery voltage at different temperature settings

High temperatures can lead to a loss of connectivity within the sensor network. We quantify that impact and show that RSSI at the receiver decreases when the sender is at an elevated temperature. At the same time, this finding means that a sensor node running at high temperature needs a higher transmission power to obtain the same signal strength as one at a lower temperature. This observation is important because the RSSI value can be used as an important indicator for the medium access control layer to determine if the channel is currently available or not, as well as for defining a more realistic and efficient routing protocol for the entire WSN.

Besides the analysis of temperature vs. RSSI, experiments are performed to evaluate PER changes during data communications at different temperature settings. PER readings collected at different temperatures for the transmitter and receiver are shown in Fig. 6. To evaluate experimental uncertainty, all tests are repeated 3 times. The variability of PER is represented in the plot via the standard deviation. We observe that PER readings increase with higher temperatures without other factor changes. The PER plot at 50 °C climbs faster than those observed at other temperatures. In addition, the plot demonstrates that the battery terminal stops producing energy at 2.0 V with a PER reading of approximately 60 %. By the end of 2.0 V, the PER readings at 50 °C are 3 times higher than those at 20 °C. Meanwhile, we notice that there is a significant PER increase when voltage level reaches 2.2 V at 50 °C, which corresponds to RSSI changes that occur at the same voltage level.

In summary, our experiments indicate that a temperature increase affects the amplifier of the radio chip negatively; the signal strength of transmissions will decrease with increasing temperature. In addition, the percentage of successfully received packages and overall network communication performance will decrease as well.

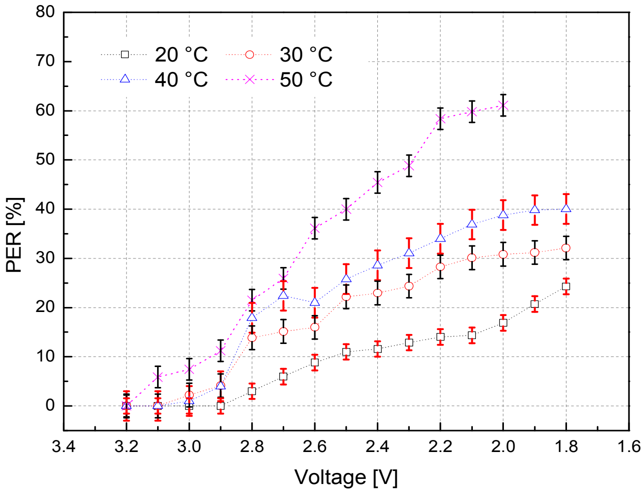

Fig. 6 PER vs. voltage at different temperature settings

VI. DISCUSSIONS AND CONCLUSIONS

In this paper, we have investigated the temperature influence on alkaline batteries for low-power wireless communications. For our case study, we use an indoor WSN in a thermal chamber to mimic different ambient temperatures. As batteries are chemical devices and temperature has an effect on chemical reactions, wireless sensor batteries can present different battery lifetimes under a variety of temperature settings. The outputs of the batteries are very dependent upon their ambient temperature. The ability of a battery to hold a charge is significantly degraded by exposure to high temperatures. Most batteries are not rated above 50 °C, and even below 50 °C their useful lifetime is degraded. Since the impact of temperature on a communication chip is not negligible and can further influence the design choice of the WSNs, we collect the RSSI data during the data communication to further analyze the temperature. Experimental results confirm that an increase in temperature leads to a reduction of the signal strength at the receiving side, due to the impact of temperature on the radio driver, and more precisely on the power amplifier of the transmitter. At high temperature, the communication signal becomes weaker. Thus, it can be expected that with an increase in temperature, a higher transmission power is required to maintain the same signal strength and thus to ensure successful data transmission. We have carried out several long-term indoor experiments to investigate this effect. Sensor placement, enclosure characteristics, and proper thermal insulation should be carefully evaluated to mitigate the effect of better exposure to the sun or other heating sources. We believe that the findings presented in this paper can help to improve the design of WSN deployments for industrial processes, building applications, and control system design. Furthermore, the presented results can be used to construct energy-efficient protocols that adapt the transmission power to the measured ambient temperature in order to save energy and increase the lifetime of the system at no sacrifices of network performance.

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