Pitfalls in Measuring Ultra Low Power Energy Harvesting Wireless Sensor Networks

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***Abstract*—Applications and evaluations in the area of ultra-low power energy harvesting Wireless Sensor Networks (WSNs) verge toward utilizing state-of-the-art hardware with extremely low power consumption. For the evaluation of these networks, real-world deployments are a common approach where special performance logging hardware is often used in conjunction with the sensor nodes. This hardware needs to be kept simple and cost-effective to allow for scalability. At the same time, it needs to be ensured that the measurement hardware does not interfere with the performance of the sensor node, thereby distorting the evaluation results. Herein lies an especially prominent challenge with ultra-low power sensor nodes. We outline some pitfalls that should be considered when designing or selecting this hardware.**

***Index Terms*—sensor network, real-world, evaluation**

I. INTRODUCTION

Advances in the field of Energy Harvesting (EH)-WSNs and the development of new approaches in this area enable a variety of novel applications. With increasing work in approaches to aspects like scheduling and communication in these networks, the need for real-world testing also increases. Testing, either by performing a deployment or by recording and reproducing real-world conditions in a lab [1], [4], [8], [9], requires accurate logging of the performance of a EH sensor node.

As software approaches in ultra-low power EH-WSNs advance, at the same time power consumption of sensor nodes reduce, both during active operation, as well as during sleep. For instance, the sleep current of low power Microcontroller Units (MCUs) can be as low as $20\,\mathrm{nA}$ [6], and Bluetooth Low Energy (BLE) Systems on a chip (SoCs) are capable of transmitting and receiving with supply current in the mA range [7].

Using such low-power systems in WSNs presents a logging device with high requirements in terms of accuracy. At the same time, the nature of these deployments results in challenging cost and environmental requirements, which often rule out professional lab equipment. Therefore, custom logging devices are often used in these deployments. The low power consumption of WSN devices and the small energy storage used in EH-WSNs make these systems susceptible to influences from the measurement device if not carefully designed.

We present commonly used approaches to measuring EH-WSNs and discuss the benefits and drawbacks. In addition, we outline the possible effects of custom low-cost measurement devices and analyze the contributing factors to aid development and troubleshooting in EH-WSN evaluations.

II. RELATED WORK

A portable testbed for recording and reproducing energy traces for use with EH-WSNs is presented in [1]. The authors present a data collection fronted for both, current and voltage using low noise op-amps, but the exact type is not given. However, the currents present in the emulation are in the μA to mA range, which is still an order higher than the sleep current required by extremely low power MCUs. Furthermore, the effect of the data logging setup on the voltage source is not explicitly considered. In [4] an EH emulation framework is presented. The authors collect real-world voltage and current traces using a custom analog fronted and reproduce them in a lab setting. The results are validated using a professional measurement device. However, the custom analog front-end is not described in great detail. Many challenges of designing a logging device for EH-WSNs is detailed in [9]. The authors outline the need for small form factor and inexpensive devices for measurements in WSNs. The presented logging device uses an op-amp based circuit with a very high input resistance that allows voltages measurements with a leakage current of approx. $5\,\mathrm{pA}$. The authors of [3] present a low-cost platform for the energy measurement in WSNs based on an op-amp, to allow high impedance measurements of voltage and current. While the feasibility of a scalable energy measurement in an outdoor WSN scenario is shown, the effects of different analog front ends is not discussed.

To the best of the authors knowledge the effects of different types of measurement equipment on EH-WSN evaluations have not been fully discussed in the literature.

III. MEASUREMENT SETUPS

For WSN deployments in a research context, using equipment alongside the sensor nodes to gain insights into the network's performance is a widely adopted approach. As with the nodes, a variety of different types of measurement equipment is available and a selection needs to be made according to the metrics required. Voltage measurements, either of an energy source or storage is a common task for this equipment, especially in energy harvesting sensor networks.

A. *High precision measurement equipment*

Precise voltage measurement with an extremely high input impedance can be achieved with high-performance measurement equipment. However, using such equipment might not always be feasible in real-world and long-term deployments for many reasons.

First, most of such measurement equipment is powered by mains voltage. This can be a significant obstacle for a sensor network, which might be deployed at remote locations. E.g., due to a lack of mains power supply, it might be necessary to power the sensor node as well as the logging equipment using energy harvesting. Second, laboratory-grade equipment often comes in comparatively large form factors without robust weather sealing. This can be a challenge for outdoor deployments since the measurement equipment faces the same harsh conditions as the sensor node. Lastly, evaluating scalability often requires the deployment of large nets, which also require a large number of measurement devices. Therefore, the comparatively high price tag often makes the use of laboratory equipment in these deployments infeasible.

B. *Handheld digital multimeter*

Commonly used, especially for manual measurements in lab setups, digital handheld multimeters are a cost-effective solution for accurate measurements in WSNs. Often equipped with a digital interface, these can also be used for autonomous and continuous measurements.

Handheld devices share some of the drawbacks of the laboratory equipment discussed in Section III-A. While smaller and less expensive than most laboratory equipment and often battery-powered, these devices are not always applicable for long-term outdoor deployments. Especially in outdoor deployments with small nodes, these devices are challenging to deploy. In addition, many low-cost handheld devices have an input impedance of some tenths of megaohms, resulting in a significant measurement current compared to the sleep current of most sensor nodes. Thus, care has to be taken when using these devices, especially in deployments requiring continuous measurements.

C. *Op-Amp buffer amplifier*

The voltage levels in a WSN deployment can be digitized by means of an Analog to Digital Converter (ADC), which is integrated into many MCUs. However, ADCs typically have a comparatively small input impedance, e.g., up to $50\,\mathrm{k\Omega}$ for the STM32F411 MCU [10]. Therefore, a relatively high current will flow into the measurement device and introduce an error in the voltage measurement. A high input impedance is desirable to limit the current flowing into the measurement device and, therefore, reduce the amount of energy lost to the measurement. A widely adopted approach is using an op-amp in a voltage follower configuration. With its exceptionally high input impedance, the current required for the measurement is reduced drastically [5]. However, an important characteristic to consider for measurements in low power WSNs is the input bias current, which can flow in, as well as out of the amplifier. Depending on the relation between the magnitude of this current and the current consumption of the sensor node, a significant error in the measurement results may arise [2].

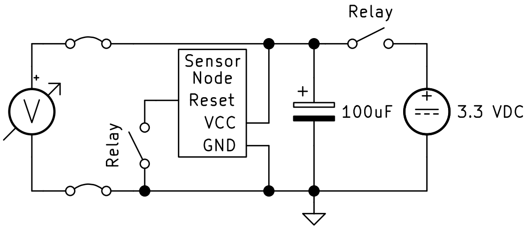

Fig. 1. Measurement setup of the sample application. Relays control the connection to the power supply and the start of the sample application.

IV. Typical application

To illustrate the impact of a voltage measurement on a WSN node we consider a sample application using an MCU (PIC24F04KA201) and a low-power real-time clock (RTC) (RV-3028-C7). Every 3 minutes, the MCU is woken by the RTC and performs some dummy operations for a few milliseconds before entering a sleep mode again. This low-power system, which could be used for applications such as EH-WSNs, has a measured sleep current consumption of approximately $80\,\mathrm{nA}$. The power source used here is a $100\,\mathrm{\mu F}$ electrolytic capacitor, which would be used to store electrical energy collected from the environment in a real-world deployment. As shown in Figure 1, in our lab setup, the energy harvesting circuitry is replaced with a power supply connected with a relay.

The capacitor is charged to the nominal operating voltage of $3.3\,\mathrm{V}$. After charging, it is disconnected from the power supply, and the sensor node is reset so that it performs its dummy task in intervals of 3 minutes. The sensor node then uses the energy stored in the capacitor, which is not recharged and, therefore, slowly depleted. As in many real-world deployments evaluating the performance of an EH sensor node, a measurement device constantly measures the supply voltage.

A. *Measurement Devices*

In our evaluation, four different measurement devices are compared. Two off-the-shelf laboratory devices, a UNI-T UT61D handheld multimeter, a Keithley DMM6500 and two custom-designed measurement boards using an op-amp buffer amplifier connected to an ADC. The custom boards

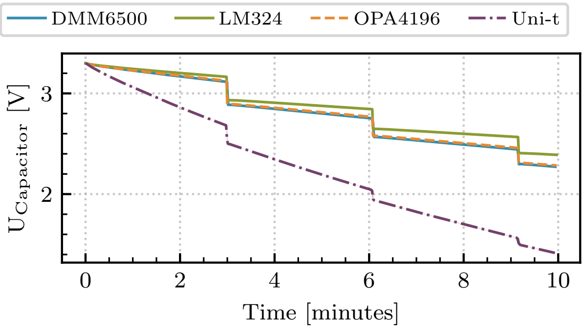

Fig. 2. Comparison of the measured supply voltage of a low-power MCU with a 100 µF capacitor used as a power supply. Voltage given are the average of 10 runs. Error bars are not visible as they are extremely small.

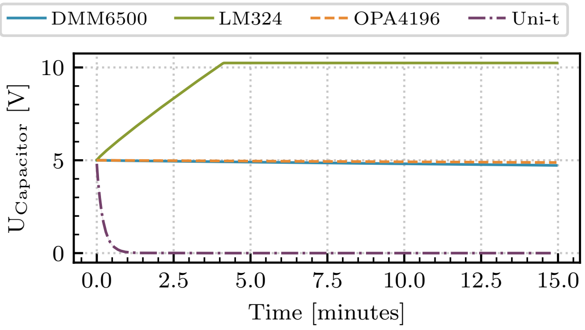

Fig. 3. Average voltage at the capacitor over time. Error bars are are extremely small.

are identical except for the op-amp in use, an LM324 and an OPA4196.

B. Measurement Results

Each measurement device is tested in sequential runs, which last for 10 minutes. The capacitor is charged, and the sensor node is reset before every run to present equal starting conditions. This process is repeated ten times for every measurement device. The capacitor and the sensor node are the same for each run. The supply voltage measured during the runs is given in Figure 2.

During the test interval, the voltage drops slowly whenever the node is in sleep mode and fast whenever the node executes a task, as expected. The drop in the voltage level is not constant for each task since the voltage of a capacitor falls not linear but exponentially as it is discharged. Qualitatively, the result from each of the devices on its own matches what is to be expected from the application: A small amount of energy is consumed during sleep, and each task consumes a specific amount of energy in a very short period. Any one of the logged voltages could be considered a valid result in a WSN evaluation.

However, comparing the different measurement approaches in Figure 2, it is evident that the measurement equipment has a rather significant influence on the capacitor voltage in this sample application. The start voltage is 3.3 V for every run, but the voltage after 10 minutes differs significantly depending on the measurement device in use. The handheld multimeter's voltage is at 1.41 V. With the DMM6500 the voltage after 10 minutes is 2.27 V. The custom measurement board with the OPA4196 op-amp results in 2.28 V after the measurement, and the LM324-based board is at 2.39 V.

Quantitatively, the difference of 0.98 V for a time span of just 10 minutes is quite considerable. In a long-term real-world EH-WSN evaluation, this difference will integrate over time and significantly impact the result. In an energy harvesting setup, where a volatile energy source is present, judging the contribution of the measurement equipment to the discharge of a given energy storage might be even harder.

Since the input impedance of the measurement device will result in a small measurement current flowing from the capacitor into the measurement device, a high impedance is desirable. With its exceptionally high input impedance, the buffer amplifier circuit based on the LM324 satisfies this requirement. Looking at the voltage levels after the measurement runs, this setup seems to have the lowest measurement current. However, this evaluation approach misses the critical point of the op-amp input bias current discussed in Section III-C. To further evaluate these effects, additional experiments are performed.

V. MEASUREMENT ERROR ANALYSIS

To highlight the influence of a voltage measurement device on the energy storage in a WSN deployment, the voltage at a capacitor, which is not connected to any source or load, is measured. As the charge of a capacitor will decrease over time due to the leakage current, a drop in the voltage is expected.

For this, the sensor node is removed from the experiment setup and the capacitor is replaced with a smaller 1 µF capacitor, to outline the influence of the measurement device more clearly. Ten additional runs, each lasting 15 min, are performed with each measurement device. This time the capacitor is recharged to 5 V before each run.

Looking at the results of the voltage measurement in Figure 3, the measurement devices show drastically different behaviors.

During the 15 min of measurement with the DMM6500, the voltage drops exponentially to 4.73 V. The voltage measured using the custom board with an OPA4196 shows a very similar result, the drop is also exponential, but the voltage drops less, to 4.88 V. These results are close to what can be expected from the typical leakage current of a capacitor.

Looking at the results from the UNI-T UT61D, the voltage drops with a steep exponential curve and is very close to 0 V after just one minute. Here, the effect of the lower input impedance can be seen, as it leads to a rapid discharge of the capacitor. Of course, in case of an EH-WSN, this is undesirable, since the capacitor is used as an energy storage.

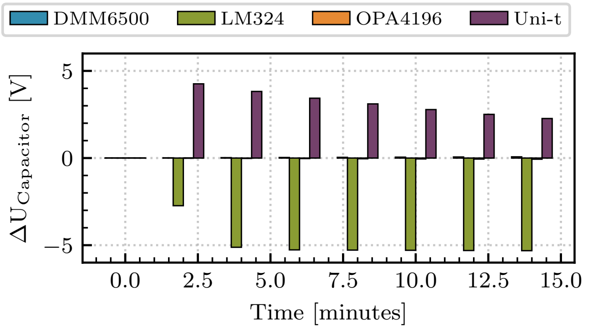

Fig. 4. Difference in measured voltage with device intermittently and constantly connected at discrete time intervals.

The custom board using an LM324 produces a voltage curve that shows the capacitor is charged to the supply voltage rail of the op-amp of $10.24\,\mathrm{V}$. The bias current of the LM324 is negative and larger in magnitude than the leakage current and therefore charges the capacitor. Of course, for an energy harvesting application, this would influence the performance evaluation, as the WSN will have slightly more energy available than it would have without the voltage measurement.

Depending on the device in use, the energy supply of a WSN node can either be discharged or charged, which is unwanted in an evaluation. Additional measurements are performed to evaluate the qualitative and quantitative influence of the different devices on the voltage at the capacitor.

Instead of a continuous measurement, the measurement is performed for $200\,\mathrm{ms}$ at intervals of $2\,\mathrm{min}$. In between the measurements, a relay is used to disconnect the measurement device. In doing so, the influence of the measurement device on the capacitor charge is significantly reduced, albeit not completely eliminated. Therefore, the difference of the continuous and the interval measurement can serve as an indicator for the type and magnitude of influence on the discharge.

Figure 4 shows the difference between the interval and continuous measurements for every device. A positive difference between the interval and the continuous measurement means, the capacitor voltage was larger in the interval measurement. Therefore the capacitor is discharged by the measurement device. The higher difference between the continuous and the interval measurement, the higher the influence of the measurement device.

For the initial measurement, right after the capacitor is charged, the difference between the continuous and the interval measurement is close to zero for all devices. Looking at the handheld multimeter UNI-T 61D, after $2\,\mathrm{min}$ the voltage delta is close to $5\,\mathrm{V}$, as the capacitor is discharged almost entirely at this point in the continuous measurement. For the later measurements, the voltage in the continuous measurement is zero, while the slowly decreasing ΔU shows that the capacitor is discharged more slowly in the interval measurement.

The custom board with the LM324 op-amp shows a negative ΔU in Figure 4, i.e. the voltage is lower when the measurement device is connected only briefly during the measurement instead of continuously. This verifies the observation made in the continuous measurement: The capacitor is charged by the measurement board. This is likely an effect of the op-amp's input bias current, which is typically up to $-20\,\mathrm{nA}$ according to the datasheet.

With the OPA41196, the lower input bias current of typically $\pm 5\,\mathrm{pA}$ results in a much lower ΔU in Figure 4. While lower, the difference is slightly negative, so the capacitor is charged with this custom board as well. However, the measurement has a significantly lower impact on the capacitor.

Looking at the result of the measurement performed with the DMM6500, it can be seen that the measurement influence is also very small. However, the influence is opposite to that of the OPA41196-based custom board, indicating a slightly faster discharge of the capacitor while the DMM6500 is connected.

VI. CONCLUSION

Our discussion of available measurement approaches and devices outlines the challenges of measuring low power EH-WSNs. Given the particular requirements of real-world deployments, the need for custom low-cost measurement hardware is obvious. Our experiments show the drastic influence a measurement device can have on the results obtained in a WSN evaluation. In a further investigation, the critical factors to consider when designing or selecting a measurement device are outlined.

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