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EG0N: Portable In-Situ Energy Measurement for Low-Power Sensor Devices

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***Abstract*—For assessing the energy consumption of an embedded system, typically measurements on a shunting resistor are conducted in a laboratory environment. While such measurements can be easily performed with high precision for stationary setups, obtaining data on the energy-consumption of mobile devices, such as body-worn electronics (wearables) is a significantly more challenging task, since the power consumption depends on the behavior of the user. For example, consider an activity sensor which transmits the detected activity type (e.g., walking, running, resting) wirelessly to a smartphone whenever the activity changes. Clearly, more current is drawn for the transmission whenever the activity needs to be updated. Connecting the device with long wires to a stationary measurement platform distorts the results and restricts the motion of the user. Therefore, the measurement platform needs to be mobile itself to measure in-situ. This imposes multiple challenges on such a system, e.g., the limited power budget for obtaining samples of the current consumption and the need for miniaturized electronics. In this paper, we propose EG0N, a mobile current measurement platform for wearables. While addressing the mentioned challenges, it supports useful advanced features, such as collaborative, context-aware measurements on the device-under-test (DUT).**

I. INTRODUCTION

With the recent developments in the area of body worn embedded systems, a lot of research is done on improving small sensor devices. These devices are usually characterized by having little computing power, a wireless interface and small physical dimensions. But most important, almost all of those devices have a limited energy source. In many cases this is a primary battery cell, which limits the lifetime of the sensor. Therefore, it is important to reduce the energy consumption to its minimum. While a large volume of research has proposed techniques for reducing the power-consumption, the optimization and also the evaluation is often based on simple energy models such as energy state machines, since mobile in-situ measurement is challenging. As a result, the evaluation often is less accurate and the optimization risks being error-prone. In particular, the current drawn by wearables depends on the behavior of their users in most cases. For example, power-optimized fall detection algorithms have been proposed [1] which are organized in multiple subsequent stages. Each stage performs a certain check for a fall and, in case of a positive result, launches the next one. In each stage, the energy consumption increases. Clearly, a device running such an algorithm consumes significantly more energy when worn on a body than in a laboratory environment, since the motion of the user might trigger multiple stages even when no fall occurs. Another example are opportunistic packet schedulers for body sensor networks (BSN), which transmit wireless packets whenever there is a low attenuation between sender and receiver [2] [3]. If no good opportunity occurs, the transmit power needs to be increased and the energy consumption grows. Even in much simpler devices, such as activity trackers which detect the type of motion the user is performing (e.g., walking, climbing stairs, running), a dependency between current consumption and user behavior exists. Therefore, measurements in a laboratory environment are not feasible. In-situ methods are inevitable for a realistic characterization of their energy demands. The data obtained thereby forms a valuable base for energy optimizations. Systems for in-situ energy characterizations need to be miniaturized and highly energy-efficient to be practicable. To the best of our

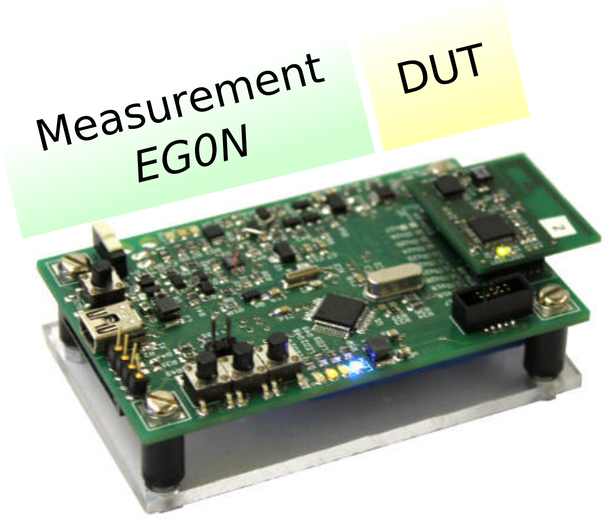

Fig. 1. Picture of first EG0N prototype, with connected target as device under test (DUT). Underneath is the internal battery.

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knowledge, there is currently no solution for in-situ energy measurement of wearables available.

For the design and verification of body-worn electronics, it is often required to record the energy consumption over a long period of time and additionally annotate it with data occurring in the device under test, such as sensor readouts and interrupts. This is a requirement for an extensive analysis on the empirical data obtained, which can be used for comparisons of the energy efficiency of different implementations and for developing more precise energy models.

To address this, we propose EG0N: a highly portable energy measurement device for low-power wireless sensors. As we will describe in the related work section, there are systems specifically designed for this purpose, but fail to be portable. EG0N is portable, self-powered and versatile to aid in experiments where this is required, like many body area sensor network applications.

The rest of this paper is organized as follows: Next we will present some use cases for our proposed system. Then, in Section II, we present existing research for measuring low-power sensor applications and describe the major differences compared to our approach. After that, Section III covers the technical details and will also cover the design goals. The results of the proposed system are evaluated in Section IV. Finally, in Section V we give an outlook on future works and in Section VI we present concluding remarks on our system.

Use cases: To further illustrate the purpose of in-situ measurements, we will in the following briefly describe a few additional use cases, in which our proposed system is helpful. In some low power wireless sensing applications it is quite easy to get accurate results of the consumed energy by simply measuring it. For example a temperature and humidity sensor will in most cases wake up after a certain time, take a data sample, transmit the data over the wireless link and go back to sleep. By identifying and measuring the sleep current and the energy consumption of the active phase, one can pretty accurately predict the overall energy consumption. This analysis can easily be done with a stationary measuring instrument.

If more advanced techniques are used, the power savings become more situation dependent. One example is the widespread use of transmit power control (TPC), which decreases the energy consumption by reducing the transmit power to a lower level, depending on the link quality. In [4], transmit power control was explored with respect to body area sensor networks. It was shown, that the link quality varies widely due to the human body moving. This can not only be used to reduce the power if the link quality is good, but also to increase the TX power if the link is bad, to improve the reliability. Furthermore, schemes which achieve power savings by carefully predicting the movements of the human body were also proposed [2]. Here the packets are scheduled for transmission, so that the path loss of the signal is kept to a minimum. This is done by exploiting periodic movement of the human body during certain activities, like walking or running. But how much energy the algorithm actually saves in a field test, can not be verified with a stationary measurement instrument. For such works, EG0N would be an appropriate solution because it allows for mobile measurements of the body-worn sensors involved.

As mentioned earlier, another use-case for EG0N are fall detection systems, which detect if a subject has fallen to the ground. The idea is to correctly detect a fall and then alert medical assistance. This detection can get quite complex to avoid false-negatives, which can be catastrophic. False positives also need to be avoided, because they reduce the acceptance of such a system by the users. Several solutions were presented in the past. Some are based on gyroscopic data [5] others rely on several gyroscopes and accelerometers [6] and achieve quite accurate results. To improve the energy consumption of such systems, interrupt-driven approaches have been proposed [1]. Such algorithms have several stages, which consume different amounts of energy. Here classification of the power consumption is more complicated and highly dependent on the current situation and past states. Therefore, an in-situ measurement, as proposed in this paper, is needed.

II. RELATED WORK

There are a number of measurement setups described in the literature, specifically designed to work with wireless sensor applications. Although most of them also have the functionality of measuring the energy, the overall goal is often different.

TWIST [7] was introduced as a testbed for indoor wireless sensor networks. It provides out-of-band communication with the sensors, like gathering debug data and reprogramming. Also it is possible to turn the energy supply for the target devices on and off. Those features allow quick reconfiguration of sensor networks, even with a large number of nodes. TWIST does not measure the power consumption. It relies on off the shelf consumer hardware, which keeps the cost low especially in larger setups. But since it is relying on USB and Ethernet, it is not mobile and cannot be used in our application.

A similar approach was presented with MoteLab [8]. Here the convenience of the user was emphasized. Over an easy to use web interface, the researchers are able to reprogram and monitor their network of a large number of permanently deployed devices. The devices are plugged into "interface boards", which directly control the target devices and measure their energy consumption. The backend is realized by an Ethernet network, over which the data is logged and stored into a database. Since MoteLab is cable-bound, it is not suitable for mobile BASN measurements.

A more sophisticated approach in terms of hardware logging was shown with FlockLab [9]. It provides a testbed for wireless sensor devices, which is able to not only measure power consumption and logging of serial communication of the target devices, but also getting accurate information on GPIO activities. Similar to our approach, it is possible to directly plug target devices onto the measurement platform. A FlockLab "observer" is able to multiplex up to four target devices. The back channel is provided either via ethernet or

Wi-Fi. This enables the system to synchronize data over a widely spread out network. While FlockLab can be battery powered, the units are relatively large and draw to much power, to be useful for our purposes.

Compared to the related work, to the best of our knowledge, our setup is the only one which is tailored towards body-worn sensors and wearables. For example, all known solutions are significantly larger than our approach.

A comprehensive overview on wireless sensor network (WSN) testbeds is given in [10].

III. TECHNICAL DETAILS

Our goal is to provide an easy to use and highly mobile energy measurement platform, to support our work with low power body area sensor applications. In particular, the focus is on detecting and quantifying the active phases of the target sensor. A typical wireless sensor will have a wide dynamic range in its power demand. Typically from less than $1\,\mu A$ during sleep mode, to about $10\,mA$ during active mode [11], which means having a range spanning over five decimal orders of magnitude. The active current can be even higher, depending on the sensing application and the TX power of the radio. If the device also has actuators, those also need to be powered. The sleep current is, in most applications, the current where everything is shut off, except for a small clock tree, which keeps the time and eventually will wake the system back up. In all other states, the sensor will consume a significantly higher current than the sleep current. This is due to the fact that generally, a fast processing means lower energy consumption [12]. While the sleep current is an important characteristic for a sensor device, it remains relatively constant over time. Therefore, it can be characterized by a stationary laboratory measurement setup, rather than by an in-situ approach.

To simplify the design of EG0N, the attention is put on measuring the active current and getting the power demand and other events in correct chronological order during the measurements. Next we will briefly discuss the goals we wanted to achieve with EG0N.

A. Design goals

As laid out, we focus on the active phases of the target devices. The measurements of the current should be precise enough in terms of amplitude and speed, so that distinctions between different active phases can be made, just by analyzing the gathered data. An example of this can be seen in Figure 3, where the phases of a bluetooth low energy (BLE) communication (sleep, wakeup, reception and transmission) can be clearly distinguished. Furthermore it should be possible to annotate the energy data with the state and events which happen on the target device. The basic idea is that EG0N can communicate with the target device. Either actively, for example by simulating a sensor and sending new data to the target device. Or it could stay passive, by just listening on peripheral buses and interrupts. These captured events are stored together with the energy measurements and timestamps onto the internal storage. This internal storage is easily accessible and is directly readable by standard software, like Matlab [13] or NumPy [14], for later analysis.

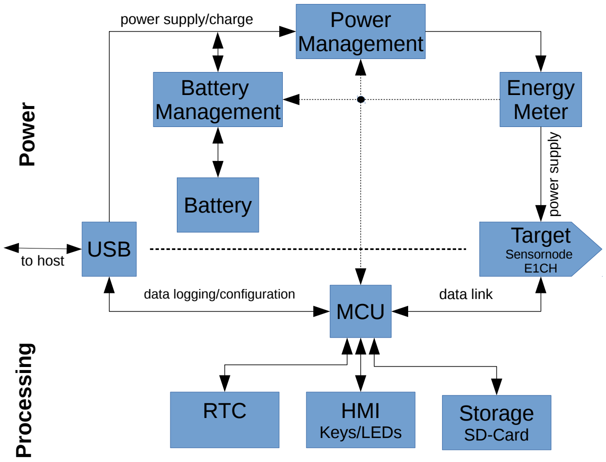


Fig. 2. Block diagram of the measurement platform EG0N. It is divided into the power and the processing domain. USB is used to for powering/charging and for communication.

B. Design Challenges

Of course, not all design goals mentioned before can be implemented equally well. Some are even contradictory to each other. For example, the system should be precise and accurate, while retaining a small size, low mass and low power consumption to be portable. These are the main challenges:

- Accurate and precise measurements of the energy used by the target device.
- Keeping the physical dimensions EG0N small and the mass low, to keep the device portable.
- Enabling long experiments, by having a long runtime, which means low internal power consumption.
- Interference free supply of the target device.
- Large internal data storage and communication facilities for experiment setup.

C. Hardware Design

A block diagram of our proposed system can be seen in Figure 2. It is split into two parts: the power domain and the processing domain with a microcontroller unit (MCU) controlling most of the parts.

Battery management: EG0N uses an internal battery, to power itself and the target sensor. This lithium polymer (LiPo) battery can be controlled via a built-in battery management. This provides basic measures to ensure a safe operation without damaging the battery with overcurrent and overvoltage. In case of a low battery voltage, the device can not only shut down the target sensor, but also completely turn itself off. It will then resume normal operation if the internal battery is charged again. Charging is done using the USB port. While charging is in progress and the battery is low on charge, the battery will be bypassed to keep the system operational. This also implies, that the rest of EG0N is always powered if the battery is charging or discharging. This allows the battery manager to measure the current to and from the battery, as well as the cell voltage. This can be used, together with the integrated temperature sensor of the MCU, to calculate the state of charge (SOC). All this data can also be stored on the internal storage, which is described later. While the design is not limited to a certain battery size, currently a LiPo with $950\,mAh$ is used. In typical measurement situations this lasts from several days to about a week. As mentioned before, it can always be recharged, without interrupting the running measurement.

Power management: The power management provides control over the power supplied to the target device. This enables EG0N to limit the supplied power. This can be useful if the sensor has an internal energy storage, like a super capacitor, and one would want to simulate an energy scarcity. So power would only be enabled under certain conditions or timings. Future improvements, amongst others, aim to improve the power manager. One idea is to modify it so it can basically give arbitrary impedances to the target device. This would enable the device to simulate energy harvesting sources, which are otherwise hard to reproduce. Another possibility is to apply different voltages to the target device to simulate different charge levels of its own battery. The power manager is also able to power cycle the target device for a full reset.

Energy meter: The energy meter is one of the most important parts of EG0N. This is the actual measurement circuitry, which allows to sense the current and voltage supplied to the target device. The current is sensed by a shunt brought into the high-side path to the target device. The shunt voltage is then sensed by an amplifier circuit [15]. Full scale range at the input shunt from $0\,\mu A$ to $30\,mA$ will be amplified to $0\,V$ to $3\,V$ at the output. The output is connected to the integrated $12\,bit$ analog digital converter (ADC) of the used MCU. This leads to a resolution of about $7\,\mu A$. As mentioned earlier in this chapter, we are interested in the active current of the target device. The used current sense IC amplifies the differential voltage at the high-side shunt resistor. It can work with a single supply voltage, but has, amongst others, the drawback of having a limited bandwidth. It effectively limits the bandwidth to about $10\,kHz$, which is well suited for measuring events in the typical time-scales of body worn sensors, as we will describe in Section IV. The voltage is measured using a high impedance voltage divider. This is then again connected to the internal ADC of the MCU for additionally measuring the supplied voltage. The target voltage is almost constant, since the target device is supplied with a regulated voltage from the power management. So the voltage measurement is more important for verifying that the system is working correctly.

Target integration: EG0N was designed with versatility in mind. Many different measurements on sensor devices can be conducted, just by loading a different configuration or reprogramming the embedded MCU of EG0N. But to make this device convenient, the PCB provides connectors, where the target sensor can easily be plugged in. (cf. Figure 1). To connect different targets, only a small adapter printed circuit board (PCB) is needed. This helps keeping the experiment setup robust, by avoiding wires and simultaneously keeping the traces short. This also improves the quality of the measurements, while still being able to connect a large number of internal and external signals of the target device to EG0N. EG0N can send data to and receive data from the target device, and log it to its storage. EG0N can also passively listen on peripheral buses of the target device, without interrupting it. This enables another possible feature: reflashing the firmware of the target device during measurements, to easily compare their energy consumption behavior.

Processing: The other side of EG0N is the processing domain, which at its center has a LPC1549 [16] MCU. It is connected to: The internal storage, which is implemented by a SD card; A simple human machine interface (HMI), which consists of some LEDs and buttons; The real-time clock (RTC), to keep a accurate timing; The target device, to communicate with the DUT; The power domain, to control it and capture the data from the energy meter, as well as the battery management; For setup and live logging it is also connected as a USB device.

All components of EG0N are designed to have reasonably low power consumption, especially in time periods in which they are not active. For example, the writes to the SD card are buffered. If there is no write or read for a certain amount of time, the SD card will be powered off. These measures to conserve energy are also reflected in the software, which will be discussed next.

D. Software Design

The software of EG0N includes a real-time operating system (RTOS) to manage the different tasks. Some tasks are dedicated for internal ”housekeeping”, while others are used for the actual measurements and data capture.

Internal: The internal tasks include doing the battery management for EG0N itself. This is important, to not deep discharge the internal battery to avoid damage to it. Also here the SOC calculation is implemented. If a low charge, or respectively voltage, is detected, EG0N will shut down. Further internal tasks include writing to the SD card, including a file system, buffering and powering the SD card. Data is written to the storage as conventional ASCII comma-separated values (CSV) files. This requires more storage space, but, because storage space is available in abundance, this saves later processing efforts during data import and simplifies sharing the data with others. An USB task provides communication functionality, like setting up measurements and getting live data. This also allows EG0N to be used as a stationary measurement device. One important feature here is setting the internal RTC, so that the measurements are correctly timestamped. This is only necessary if the internal battery had to be cut off due to low state of charge. Otherwise, the RTC will remain operational over long time periods, if no measurements take place.

Measurement: The other side of the software handles the actual measurements and data processing in relation with

TABLE I
KEY CHARACTERISTICS OF EG0N.

Current sense		
Resolution	7.0	μA
Bandwidth	10	kHz
Sampling rate	25	khZ
Min. current	0	mA
Max. current	30	mA

(a) Current sense specification.

Voltage sense		
Resolution	1.5	mV
Bandwidth	10	Hz
Sampling rate	25	Hz
Min. current	0	V
Max. current	6	V

(b) Voltage sense specification.

Battery capacity	$950\,mAh$
Battery lifetime	4 - $7\,days$ (full sample rate)
RTC accuracy	$20\,ppm$
Storage capacity	$32\,GB$ (SDHC)
Physical dimensions	$80\,mm \times 50\,mm \times 20\,mm$
Mass	$75\,g$

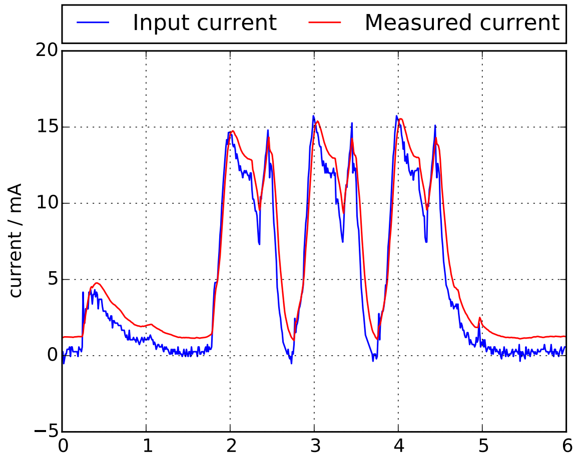
(c) General specification.

the target sensor. Since basic facilities are provided by the internal tasks, the measurement tasks can be kept quite simple, depending on the desired data. The measurement task can incorporate basic HMI on EG0N. This allows for easy work flows for experiments, like starting a new measurement with the press of a button. Measurement tasks can range from very basic ones, like sampling energy data with a fixed rate and saving it, to complex applications which interact with the target device extensively. Since the RTOS is statically linked, the MCU of EG0N has to be reflashed if another measurement task should be used. An improvement of this, by using code interpreters for getting more flexibility, is proposed in Section V.

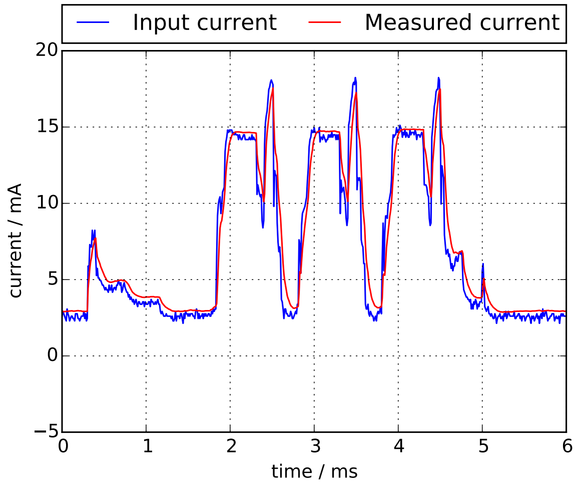
When designing such measurements, one should be attentive to the amount of gathered data. Processing gigabytes of data will take a significant amount of time and is, in many cases, not necessary. It is advisable to only keep data which is relevant for the later examination. For example, long sleep periods of the target device can be described with very few data points. This shows another advantage of this system: by adapting the measurement task to the specific problem at hand, one can make the later analysis significantly easier by preprocessing and elimination of unneeded data. One possible usecase for this might be: whenever the target device wakes up to send a packet, there is a steep edge in the current draw, which can be used to trigger an increase of the sampling rate.

IV. EVALUATION

Some key evaluation results and characteristics of EG0N are summarized in Table I. Figure 3 shows a typical current consumption plot for a Bluetooth Low Energy sensor. In this particular case, the target sensor had a rather large buffer capacity of $100\,\mu F$. This lead, together with the shunt and connectors, to a low pass behavior, which in turn smoothed out interesting details in the current plot. Figure 3a shows the resulting plot with a large capacity, while Figure 3b shows much more details after removing this capacity. So here a trade-off is necessary: if one is interested in details of the power consumption curve, then some modifications to the target device may be necessary. If only the mean consumption over a longer period of time is of interest, then it can be left as is, since the consumed energy will stay the same.



(a) Current with a high capacitance on the target sensor/



(b) Current with a low capacitance on the target sensor.

Fig. 3. Typical example for the current consumption of a DUT with an active Bluetooth Low Energy (BLE) connection. The measurement allows to distinguish the active states of the DUT. In the first two milliseconds the DUT wakes up and does some sensor sampling and processing. The BLE transmission starts in the third millisecond. The transceiver of the DUT then listens to the BLE Master and transmits a reply. This is then repeated two more times. The input current is measured with a precise stationary instrument, while the measured current is the current as seen by the EG0N circuitry without calibration.

V. FUTURE WORK

A big advantage of EG0N is its versatility, due to a flexible firmware. By being adapted to new measurement setups, it can be used in many experiments. Configurations can be loaded from the SD card or via USB, but recompilation is necessary for larger changes. While EG0N has an integrated USB bootloader to alleviate this effort, we think this can be done even more comfortable. We propose putting a code interpreter on the MCU, to make adaption easier but still keep the full versatility. For example, the PicoC project [17] provides a lightweight implementation of an interpreter with extensive functionality.

Another helpful feature would be to make EG0N reprogram the target device. The idea is to have several firmware files on the SD card and loading them on the target device, for example after pressing a button. This would allow to test several firmware variants on the same hardware.

The following suggestion would actually require a major redesign of the power management provided by EG0N for the target device: We plan to enable EG0N to be able to set a certain impedance or voltage for the target device. In some situations, especially when energy harvesting is involved, one could use this to simulate such cases. This would allow to not only measure the energy, but also to limit the available energy to the target device.

A problem which can arise in long-term measurements is the large amount of recorded data, which might exceed the memory capacity of the device and makes the data processing computationally complex. Therefore, we are planning an adaptive sampling system in further versions. In idle periods, in which the sensor is sleeping, the system might lower the sampling rate. A hardware module should automatically detect a device wakeup and quickly increase the sampling rate. A measurement lowpass automatically adapts to modified sampling rates, such that the data integrity is always guaranteed. With such an extension, the amount of recorded data can be greatly reduced.

Another interesting option is adding a wireless interface to EG0N. It could transmit the measured data directly to a laptop. Therefore, the energy consumption could be studied interactively.

With these proposed extensions, EG0N will become even more versatile in the future and will therefore become well suited for an increasing set of applications.

VI. CONCLUSION

In this paper, we have presented EG0N, a miniaturized measurement system for on-body electronics. We have shown that such a system can be realized having the area of a credit card. Further research will further shrink the dimensions and increase the functionality. We believe that such devices will become a useful tool for researchers for evaluating their energy-saving techniques in a systematical manner.

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