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# Integrating Wireless Sensor Nodes and Smartphones for Energy-Efficient Data Exchange in Smart Environments

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***Abstract*—To effectively exploit the potential of smart environments, an energy-efficient data exchange between the smart environment infrastructure and its users is necessary. Usually, a major building block of smart environments are different sensors, which typically communicate making use of the IEEE 802.15.4 standard. Opposed to this, users in a smart environment are nowadays most often equipped with smartphones, which do not support IEEE 802.15.4-based communication, but offer other standards for wireless local communication, like Bluetooth. Consequently, a major challenge in this context is the efficient integration of wireless sensor network and smartphone technology to provide users with smart environment data in a seamless fashion in real-time. To realize the necessary interconnection of sensors deployed in a smart environment and users' smartphones, different possibilities exist, which can basically be divided in extending sensors to support the communication standards offered by smartphones, or vice versa. We analyze different integration possibilities in this context and realize them prototypically. Based on real-world measurements, we evaluate the energy-efficiency of the different approaches, in particular providing a comprehensive analysis of their energy consumption.**

## I. INTRODUCTION

Wireless sensor networks (*WSNs*) possess the sensing as well as the computing and data transmission capabilities to establish smart environments in people's homes or within a container or a truck's load area and are thus often employed for realizing such smart environments. To provide users with data from these deployments, energy-efficient data transmission technologies are needed, which address the characteristics of smart environments. With a focus on the users as consumers for the data provided by smart environments and against the background of the high penetration of smartphones in today's society, the logical consequence is to integrate wireless sensor nodes (*motes*), as the basic building blocks of smart environments, and smartphones to enable an easy access for users to the environment data. But, as on the one hand motes typically use IEEE 802.15.4-based communication which is not supported by smartphones and on the other hand smartphones employ standards for wireless local communication, like Bluetooth, which are usually not supported by motes, means to efficiently bridge this communication gap are required. Therefore, we focus in the work at hand on the analysis, prototypical realization, and real-world evaluation of different possibilities to interconnect motes and smartphones. Thus, the contributions of this paper are:

- Prototypical implementation of different means to integrate motes and smartphones;
- Evaluation of different technologies to interconnect motes and smartphones with real-world measurements with respect to their energy efficiency.

The remainder of this paper is structured as follows: Section II presents related work. Our analysis of possibilities to interconnect motes and smartphones and their prototypical implementations are described in Section III. Section IV presents the evaluation of the different technology platforms to integrate WSN and smartphone technology. With section V, we conclude the paper providing a summary of our findings and an outlook on future work.

## II. RELATED WORK

The transmission of environment data gathered in a WSN to users and thus the connection between WSNs and users' systems is a common problem in several application domains for smart environments. It is essential to provide a possibility for an energy-efficient data exchange between a WSN deployment in a smart environment and users in real time to enable early reactions to detected critical situations, for example temperature violations during transport processes or users leaving their smart home having left their oven turned on. Thus, several possibilities have been already investigated in this context. Most often, these solutions are employing an autarkic gateway component, which mediates between WSN and users' end systems.

Within the 'Intelligent Container' project, WSNs are deployed in containers creating a smart environment to monitor the transport of temperature sensitive goods [1], [2], [3], [4]. In the prototypical realization of the intelligent container there, TelosB-based motes [5] are used and each container is equipped with a dedicated communication gateway, responsible for collecting the data from the WSN, processing it, and transmitting it to the users' systems. The gateway is realized as an ARM-based embedded system mounted in the container. It is supplied with power from a truck's engine or the power supply from a reefer container's cooling aggregate.

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As well in the domain of real-time monitoring of transport processes with WSNs, Traulsen et al. [6] and Valente et al. [7] rely totally on self-developed system components. Traulsen et al. use their in-house developed S3 mote platform [8] complemented with an in-house developed mobile gateway. The gateway is based on an individually modified mobile embedded Linux PC, which offers different communication interfaces and takes care of transmission from motes to users' systems. Valente et al. use customized ZigBee-based motes in combination with a customized embedded system as central node. This central node is permanently powered via cable and is responsible for data gathering from the motes and the subsequent transmission to user systems.

Decker et al. employ customized motes based on the Particle sensor node platform to monitor a storage area [9]. Their approach to provide data from motes to users is to employ an off-the-shelf WLAN router with correspondingly connected Particle nodes to the router's USB ports. Thus, the WLAN router acts as bridge between the WSN and the local area network providing the data to users' systems.

A different approach, explicitly targeting at mobile technologies is provided by Jiang et al. [10], [11]. The authors design an extension card which fits into a standard or a mini SD slot and is equipped with a transceiver for wireless communication. It allows to transmit and receive wireless data by different read and write commands to a virtual file system on the card, which the authors developed.

Nearly all of the described approaches use dedicated hardware as intermediates to realize a data exchange between WSNs and users' systems. Consequently, no direct data exchange between users and the deployed motes is realized. With the utilization of the mentioned mediators it becomes necessary to maintain a corresponding backend infrastructure, which receives the data from the motes and forwards it to users' devices. This incurs additional costs and creates critical points of failures which can lead to the situation where users' cannot be provided with data, for example due to the failure of a mediator or a problem in the backend system. Consequently, we looked for a possibility to provide direct data exchange between users and deployed motes and realize such a data exchange by exploiting current smartphone technology and complementary technologies to provide for a direct integration of motes and smartphones. Jiang et al. created as well a base technology for direct communication between motes and smartphones, but their card design is not usable in today's phones. However, we employ a similar technology, which makes use of the microSD extension slot of today's smartphones to enhance them with IEEE 802.15.4-based communication possibilities (cf. Sec. III-A).

## III. SYSTEM DESCRIPTION

In order to realize a system, which exploits a smart environment, e.g., in people's homes or in a container or a truck's load area, constituted by motes to provide users with real-time data of the monitored space, efficient means to make this data available to users are needed. As smartphones have gained a significant market penetration nowadays providing a huge variety of devices, already available at very low prices and thus already possess a wide dissemination in the general public, our goal is to exploit this technology, which offers not only a powerful interface, but as well an interface users are accustomed to. Consequently, the establishment of a common communication channel between deployed motes and a user's smartphone is required instead of connecting to backend systems through gateways. The prevailing communication in smart environments exploiting motes is usually IEEE 802.15.4-based, which is not supported by smartphones. However, smartphones typically employ Bluetooth for short-range wireless communication on the one hand, which is on the other hand not very widespread in the mote platforms used today. In consequence, to enable these two base technologies to bi-directionally transmit data bridging approaches are required. On the one hand, these can rely on the enhancement of the mote-side to enable Bluetooth-based communication and on the other hand, these can rely on the enhancement of the smartphone-side to enable IEEE 802.15.4-based communication. In the following, we examine possibilities to realize both options and describe our prototypical implementations. Section IV provides an analysis of the energy efficiency of the different approaches.

### *A. Interconnecting Motes and Smartphones by enabling IEEE 802.15.4-based Communication on Smartphones*

To enable IEEE 802.15.4-based communication on a smartphone, a corresponding hardware extension is required, because current phones do not natively support the IEEE 802.15.4 standard. There exist several possibilities, which can be employed. One option is to use the USB-port of a smartphone to connect external devices to the phone, which are capable of communication using the IEEE 802.15.4 standard. The specific data transfer between the phone and the external device can then be realized via the USB connection. A second option is the usage of the extension slots of smartphones for inserting different memory cards. An inserted card can realize the IEEE 802.15.4-based communication with motes and can be accessed from the smartphone via read/write commands.

We realized the first option with two different external devices. At first, we employed an X-Tick module, which is based on the XBee mote platform and possesses an FT232 USB-UART bridge, which takes care of converting messages between the X-Tick's internal UART and its external USB interface. So, the X-Tick could be connected to a Google Nexus One smartphone using a USB On-The-Go cable, which leads to a configuration as depicted in Fig. 1.

On the opposite side, we employed two different mote platforms with the TelosB mote platform [5] and the

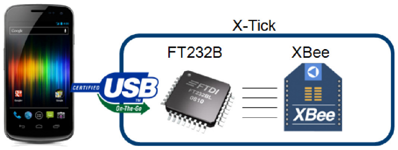


Figure 1: Schematic illustration of X-Tick to Smartphone connection

SunSPOT platform [12], [13]. The TelosB mote platform constitutes a lightweight sensor platform, which is already very established in WSN research and is explicitly tailored to the need of low power consumption in WSNs. It has for example been already applied to establish smart environments in logistics [1], [14]. The SunSPOT motes are as well established motes in the WSN community, but compared to the TelosB platform, they focus rather on flexibility, processing power, and ease of development and do not explicitly focus on energy efficiency to reach high node lifetimes as the TelosB platform. The main characteristics of the two employed platforms are outlined in Tab. I.

Table I: Feature comparison TelosB and SunSPOT

| | Processor | Clock Rate | RAM | Flash | Radio |
|---|---|---|---|---|---|
| TelosB | TI-MSP430 | 8MHz | 10KB | 48KB | CC2420 |
| SunSPOT | ARM926EJ-S | 400MHz | 1MB | 8MB | CC2420 |

Finally, the connection of the X-Tick module to the Google Nexus One via its USB-interface (Fig. 2) allowed us to establish an IEEE 802.15.4-based bi-directional communication channel with different mote platforms supporting IEEE 802.15.4-based communication.

Figure 2: X-Tick-based prototype

To realize the described second option of exploiting the memory card extension slots of smartphones, we used the SDZ-539 microSD ZigBee card from Spectec [15].

The SDZ-539 microSD card possesses an integrated CC2530 transceiver from Texas Instruments, which realizes the IEEE 802.15.4-based wireless communication. Additionally, it provides 8KB of RAM and 256KB of flash memory. Furthermore, 2GB of memory storage as usual memory card are offered to the smartphone equipped with the card and explicit support of Android and Windows operating systems, including Windows Mobile, is provided. Its functionality is based on using the SD-interface for data exchange with the smartphone. Thus smartphone apps can interact with the card by write and read operations. The microSD card itself takes care of transforming and transmitting the data it received from the smartphone and vice versa provides the data received from a mote to the smartphone application. However, the Spectec development kit comes with a dedicated receiver to be attached to a PC. So, again as already described in the context of the usage of the X-Tick platform, the SDZ-539 microSD card supports IEEE 802.15.4-based communication, but depending on the motes to be communicated with adaptations have to be performed to harmonize the individual standard parameters employed on the different platforms and then a bi-directional communication channel between the smartphone via the microSD card to the deployed motes can be established.

### *B. Interconnecting Motes and Smartphones by enabling Bluetooth Communication on Motes*

After having described different ways to extend smartphones to being able to communicate in an IEEE 802.15.4-based network, we now put the focus on means to extend standard IEEE 802.15.4-based motes with Bluetooth communication possibilities. Again, our investigations are based on the already described TelosB and SunSPOT mote platforms. For enabling a mote with Bluetooth-communication capabilities, several extension modules are available, which can be attached for example to the USART pins of a mote platform. We employed different extension modules, varying in price and correspondingly in their capabilities, for example regarding transmission range, customizable options, security means, etc. Specifically, we employed the GP-GC021 module from SURE electronics, which can be bought for ca. 20USD and the BlueSMiRF Gold-platform, which can be bought for ca. 50USD. Thus, with the rather cheap SURE module, we explicitly catered for domains, where cost efficiency is a major requirement and could compare this simple and cheap solution to a rather sophisticated, but significantly more expensive solution employing the BlueSMiRF platform.

The GP-GC021 Bluetooth-to-UART adapter from SURE is compliant with the Bluetooth 2.0 standard and possesses a 9600baud UART interface. The module handles the specifics of the Bluetooth protocol autonomously. This means that data which is written to the serial interface is automatically transmitted using Bluetooth's RFCOMM protocol, which emulates an RS-232 serial connection. Exploiting the expansion connectors provided by the TelosB platform, respectively the SunSPOT platform, the SURE module can be attached to both mote platforms. Consequently, for data transmission via the SURE module, data is written and read not anymore from the motes' transceivers, but rather through the provided UART, respectively USART, interfaces. The connection with the BlueSMiRF module works similar. On the smartphone side, we identified Bluetooth's Serial Port Profile (SPP), which makes use of RFCOMM, as the appropriate profile to establish a communication with the Bluetooth extension modules used on the two mote platforms. Employing SPP, allows smartphone applications to directly connect to motes via their Bluetooth extension modules using the Universally Unique Identifier (UUID) assigned to SPP while bypassing Bluetooth's Service Discovery Protocol (SDP). Thus, the extension of the considered mote platforms each with one of the modules and restricting the communication with the motes to their USART interfaces, with corresponding usage of the attached Bluetooth module, allowed us to establish a Bluetooth-based bi-directional communication channel between mote and smartphone.

To realize the communication between the different mote platforms and the smartphone not only the hardware extensions had to be provided, but specifically customized software had to be developed as well, to cater for the platform-specific realizations of the wireless communication on the different platforms.

## IV. EVALUATION

### A. Evaluation Setup

In order to assess the energy demand for the different presented options under realistic conditions, we have conducted practical measurements of the sensor devices' supply voltages and power consumptions. As described in the previous section, we have used two different mote platforms widely used in research, namely the TelosB platform [5] and the SunSPOT motes [12], [13], both of which feature built-in IEEE 802.15.4-based radio transceivers. On the TelosB, we employed TinyOS V2.1.0. Our SunSPOT implementations are based on SDK v6.0. On both platforms, we employed the standard communication stack as shipped with the specified versions of the operating system. We have furthermore attached the two presented Bluetooth extension modules to each of these nodes in order to enable Bluetooth-based communication. Therefore, we assessed both motes without Bluetooth extension modules using only their built-in IEEE 802.15.4-based transceiver and the combinations of each mote with a SURE GP-GC021 module and a BlueSMiRF Gold module. The actual measurements were conducted in two ways. Firstly, we have employed a boost converter powered by a supercapacitor as energy source for the motes in our experiments (Fig. 3), following Ritter et al. [16]. To enable comparable measurements, the same charge has been put on the supercapacitor before each new iteration of the experiment, with all experiments having been conducted in the same lab environment. This solution provides the motes with a fixed energy budget and the differences between their operational times can then be used to deduce an indicator for the relative energy efficiency of the different realization options. In order to assess when the energy budget has depleted, we have employed a receiver mote to monitor the communication channel and measure the time during which packets were still received. Secondly, a Hitex PowerScale with ACM Probe [17] has been used, which is capable of sampling voltage and current synchronously at sampling rates of up to 100kHz. The PowerScale was configured to confine its measurement interval to the wireless communication, this time without a receiver mote, using trigger outputs in order to determine the exact amount of energy required for each individual communication.

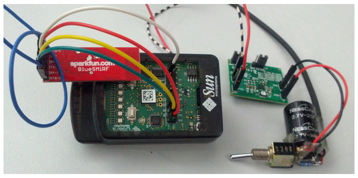
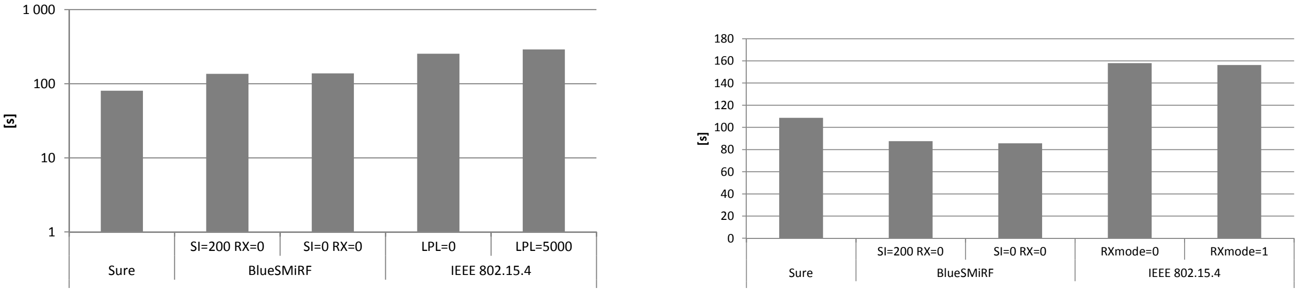


Figure 3: Setup of boost converter and supercapacitor connected to a SunSPOT with a BlueSMiRF module

### B. Evaluation Results

For the measurements with the boost converter and the supercapacitor to assess the mote lifetimes with and without the different extension modules and communication standards, we used a program on the motes which sends a data packet with a payload of 1 Byte each 50ms. Furthermore, we employed different parameter settings: The BlueSMiRF module offers the ability to configure its inquiry scan window. This SI-parameter sets the amount of time, the device spends on enabling inquiry scans per duty cycle to influence its discoverability in a network. We employed two different parameter settings for SI. In one series of our experiments, we employed a value of 200ms, in another series of experiments, we set the parameter to zero, which means disabling inquiry scans and making the device de facto undiscoverable from other Bluetooth devices. Furthermore, to avoid problems concerning inaccuracies during the measurements, we did not connect the receive pin (RX). The TelosB mote offers furthermore the possibility to set an LPL-parameter, which influences the duration of deep sleep phases between consecutive checks for incoming messages. We set the parameter to zero to disable the deep sleep phases in one series of our experiments and to 5000 in another series of our experiments to assess the consequences of a relative long deep sleep phase compared to disabling it. The SunSPOT platform provides its users with the possibility to explicitly turn off the receiver by setting its RXmode parameter to zero. So, we conducted experiments with the receiver turned off (*RXmode=0*) and turned on (*RXmode=1*). The experiments for each combination of mote platforms and modules with the different described settings have been repeated three times. As outcome of the experiments, we present the average mote lifetimes in Fig. 4.

It can be clearly seen that the usage of the motes' internal



(a) Average mote lifetime TelosB

(b) Average mote lifetime SunSPOT

Figure 4: Measured average mote lifetimes

Table II: Power and energy measurement results

| Mote | Radio Module | Min Power During Transmission [W] | Max Power During Transmission [W] | Avg Power During Transmission [W] | Energy Consumption for Transmission [J] |
|---|---|---|---|---|---|
| TelosB | SURE | 0.14729 | 0.26132 | 0.19305 | 0.002652507 |
| | BlueSMiRF | 0.01155 | 0.44218 | 0.16716 | 0.00163984 |
| | IEEE 802.15.4-based | 0.002 | 0.0642 | 0.05523 | 0.00040869 |
| SunSPOT | SURE | 0.08576 | 0.44579 | 0.24416 | 0.0029494528 |
| | BlueSMiRF | 0.08849 | 0.71829 | 0.40273 | 0.0046475042 |
| | IEEE 802.15.4-based | 0.09538 | 0.33664 | 0.16465 | 0.00125 |

IEEE 802.15.4-based transceivers provides significant longer mote lifetimes. For the TelosB mote even without employing deep sleep (LPL=0), a mote lifetime of 253.9 seconds is reached, prolonged by 36.9 seconds when enabling deep sleep phases (LPL=5000). However, as we employed regular transmissions every 50ms, we do not gain the full benefit of the LPL=5000 setting, because the deep sleep phase does not persist 5000ms as set in the LPL parameter, but only roughly 50ms, namely the time between two subsequent transmissions. The best Bluetooth-based solution on the TelosB with the BlueSMiRF module reaches only a mote lifetime of 137.7 seconds. Thus, the best IEEE 802.15.4.-based communication provides a lifetime more than 210% longer. However, the influence of the mote platforms as well as the Bluetooth platforms can be clearly seen, too. On the SunSPOT platform with the BlueSMiRF module only a lifetime of 87.6 seconds is achieved, which is ca. 36% shorter than the TelosB's lifetime with this configuration.

To assess the energy expenditure for individual transmissions, we conducted experiments with the same setup of motes and extension modules, but transmitting only one message and measuring the energy costs for this transmission using the Hitex PowerScale described above. The results, we gathered concerning the energy expenditure of one transmission can be found in Tab. II.

The measurement results show again a significant dependency on the underlying mote platform. So, it can be noticed that both the data transmission via Bluetooth as well as the data transmission using IEEE 802.15.4-based communication on the TelosB mote require less energy than on the SunSPOT. In direct comparison between the Bluetooth-based communication and the IEEE 802.15.4-based communication, the significant less energy expenditure for a data transmission via IEEE 802.15.4 can be seen. For the TelosB, the communication with the SURE module requires more than six times the energy, respectively more than four times the energy for the BlueSMiRF module, that the communication with the built-in IEEE 802.15.4-based transceiver takes. In comparison to the IEEE 802.15.4-based communication on the SunSPOT, the Bluetooth communication requires more than twice the energy using the SURE module, respectively nearly four times the energy using the BlueSMiRF module. This underlines the findings we made concerning the lifetime measurements with the boost converter and the supercapacitor, which clearly highlighted the advantages of IEEE 802.15.4-based communication in the examined context compared to Bluetooth-based communication.

## V. CONCLUSIONS AND FUTURE WORK

Conveying data from motes to users in an efficient way is a major challenge in the context of smart environments. Thus, we investigated different means to interconnect motes and smartphones to establish a direct data exchange between a sensor deployment in a smart environment and users. In order to overcome the communication gap between motes usually relying on IEEE 802.15.4-based communication and smartphones, which only support other standards for short-range wireless communication, we identified possibilities for extending smartphones with IEEE 802.15.4 communication capabilities on the one hand and on the other hand enabling motes for Bluetooth communication. We provided proof-of-concept realizations for both approaches. On the basis of these prototypical implementations, we conducted different experiments to provide a real-world analysis of the energy efficiency of the different approaches. We evaluated the energy efficiency with regard to mote lifetime and energy to be spent for data transmissions. The evaluation results have shown that using Bluetooth communication via the different extension modules we employed leads to a significantly reduced mote lifetime in comparison to restricting communication to IEEE 802.15.4. Furthermore, making use of the different low power listening options on motes enhances the lifetime advantage provided by IEEE 802.15.4-based communication even more, as the comparable options for the Bluetooth extension modules do not prove to be similar efficient. These results have been underlined by our energy expenditure measurements for individual data transfers, which have been proven to be significantly higher using Bluetooth-based communication compared to IEEE 802.15.4-based communication in our real-world tests.

In the next steps, we will conduct more experiments employing additional extension modules to investigate more detailed the influence of different hardware on the energy efficiency of the presented approaches. Furthermore, the operability of the approaches on other smartphones will be evaluated to analyze their transferability. In the work at hand, we have provided energy analyses focused on motes. Consequently, as future work we will examine the energy consumption on the smartphone against the background of the presented solutions.

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