Such Title, much education

Författaren

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Co-supervisor : Min hanledare

Faculty of Science, Technology and Media
Department of Electronics Design
Thesis for the Degree of Doctor of Technology
Mid Sweden University, SE-851 70 Sundsvall, Sweden

Sundsvall **2020**

Akademisk avhandling som med tillstånd av Mittuniversitetet i Sundsvall framläggs till offentlig för avläggande av doktorexamen i electronic den **28 maj 2020 kl. 09:30 i sal cs01, Mittuniversitetet Sundsvall.** Seminariet kommer att hållas på engelska.

Such Title, much education

Printed by Mid Sweden University, Sundsvall 2020
ISBN 123456
ISSN 1652-893X

Faculty of Science, Technology and Media
Mid Sweden University, SE-851 70 Sundsvall
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Mid Sweden University Doctoral Thesis 1

Abstract

The abstract resides in file `Abstract.tex`. Here you should write a short summary of your work.

Sammanfattning

Acknowledgments

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Introduction

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1.1 Motivation

[2]

Table 1.1: Piezoelectric Stack

Parameter	Value
C_p	$3.5\,\mu F \pm 15\%$
d_{33}^{eff}	$230\,nCN^{-1}$
tgδ	0.02

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1.2 Aim

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1.3 Research questions

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1.4 Delimitations

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Figure 1.1: Miun Logo

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Part II

Papers

PAPER I

Sebastian Bader, Matthias Krämer, and Bengt Oelmann. “A Domain-Specific Platform for Research in Environmental Wireless Sensor Networks”. In: *SENSORCOMM 2013, The Seventh International Conference on Sensor Technologies and Applications :* 2013, pp. 200–207. ISBN: 978-1-61208-296-7. URL: http://www.thinkmind.org/index.php?view=article&articleid=sensorcomm_2013_8_30_10078

A Domain-Specific Platform for Research in Environmental Wireless Sensor Networks

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***Abstract*—Wireless Sensor Networks have the ability to improve a multitude of existing application domains. These networks are built up from a number of sensor nodes with sensing, communication and processing capabilities and the performance of the networked system is defined by the performance of the node platform it is based on. In this paper, we present SENTIO-em, a hardware platform for research in the environmental monitoring application domain. Based on the application domain requirements, the architecture and implementation of SENTIO-em is optimized for environmental monitoring constraints, while it is sufficiently flexible to be reused for different applications within the domain. The architecture of the platform is presented and evaluated under both laboratory and different environmental conditions. The obtained results are compared to a number of existing node platforms, demonstrating that SENTIO-em provides high energy efficiency with increased processing performance, short state transition times, and low quiescent currents.**

***Keywords*-Sensor Node Platform, Environmental Monitoring, Domain-specific Design**

I. Introduction

Sensor nodes are the basic building blocks of any wireless sensor network. It is therefore of great importance that the platform on which the sensor node is based, supports the application requirements for the usage of the the intended system. Furthermore, the required tasks for the sensor node should be carried out as efficiently as possible, in order to prolong the lifetime of the system, to constrain the development time, as well as the system costs.

In final product solutions this will typically result in an application-specific hardware design, supporting the task execution without unnecessary overhead. In research applications, however, hardware platforms have to be reusable and hence make application-specific solutions inefficient. To allow for reusability, the platform has to be sufficiently flexible for it to be adjusted for requirements of different applications. Nevertheless, the system should perform well in each of the different use cases and thus, should not be hindered by its own flexibility.

A common approach to achieving reusability of sensor node hardware is the design of general-purpose hardware platforms, such as those presented in [1]–[4]. These platforms typically have no specific application in mind, but are designed to be usable as a prototyping platform for a wider area. On the downside, general-purpose nodes require more development time once they are used in specific applications. Additionally, they may not allow the performance of certain application tasks or are inefficient in their execution.

In this paper, we are introducing SENTIO-em, a hardware platform that is specifically intended for wireless sensor network applications in the environmental monitoring domain. By designing the sensor node platform in an application-domain-specific manner, we are able to include typical domain-specific requirements, while maintaining a flexible platform for operations in different applications within the domain. In this way, the platform becomes reusable without any loss in application focus or increase in overhead.

II. Related Work

The application domain of environmental monitoring presents requirements that are well matched by wireless sensor network technology. This has led to the adoption of this technology in a number of field-trial evaluations, such as those presented in [5]–[7], where a network of sensor nodes has been utilized as a measurement instrument. Despite their differences in the application constraints, a similar fundamental platform architecture remains.

Since the beginning of wireless sensor network research, a large number of node platforms have been introduced. As these represent too many different systems, only a subset of solutions are mentioned. A more detailed presentation of existing hardware platforms can be found in [8].

The systems proposed in [1]–[4] represent general-purpose research platforms, which are mainly targeted for wireless sensor network prototyping. While the general architecture of these nodes is similar, different device choices have been made for system implementation. The platforms contain processing, storage, communication and power units, but require sensors and other extension to be attached via an expansion interface.

A different architectural choice has been made in [9]. While still a general-purpose platform, the whole system can be constructed of a variety of building blocks and therefore suits different scenarios. Although this building

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block approach allows for very flexible use of the different modules, it is not suited for fast development times, because, in the majority of cases, an application-specific design will be required in order to assemble the building blocks into a complete platform.

In order to provide platform access to a wider community, several companies have made sensor nodes commercially available. Examples of these platforms include Libelium's Waspmote, Zolertia's Z1 and the Shimmer node. The majority of these platforms, however, have only limited application focus in order to be usable by a wider community.

With the SENTIO-em platform we propose an application-domain-specific design. Instead of basing the design choices of the platform on general-purpose constraints or on the requirements of a single application, the design of the platform has been based on typical requirements found in the application domain of environmental monitoring. Thus, the platform remains flexible to variations between different applications in environmental monitoring, while showing a higher domain specific performance as opposed to completely general-purpose platforms.

III. System Design

After an analysis of typical characteristics in environmental monitoring wireless sensor networks, we describe how these characteristics have been taken into account in the design of SENTIO-em, and present the resulting hardware and software architectures of the platform. A final overview on the system's implementation is given at the end of the section in Table III.

A. Environmental Monitoring Requirements

Environmental monitoring is typically performed by collecting sample data in the natural environment [10, chap. 2]. As wireless sensor networks enable for new measurement instruments with high spatial and temporal resolution without the requirement of a fixed infrastructure, they have been used in a plethora of different environmental applications, ranging from the monitoring of glaciers in Iceland [11] to the observation of rain forests in Australia [12].

Environmental monitoring wireless sensor networks typically operate in a time-driven manner, which means that they are collecting data at preordained intervals. The collected data, or information extracted from it, is in the majority of systems transfered to a central gathering point, which leads to a simple *sample-and-send* operation for individual sensor nodes. Due to the monitoring of slowly changing parameters, such as temperature, humidity or gas concentrations, the resulting sampling rate of sensor nodes in environmental monitoring is rather low as well. The number of nodes within the network, on the other hand, is commonly large in order to cover a given terrain with a desired spatial resolution.

This has two effects. On the one hand, the low sampling rate poses only limited processing power demands on the computational unit within the sensor node. On the other hand, the possibility of a large number of sensor nodes within the system requires the individual sensor nodes to be of low cost and the maintenance requirements to be kept at a minimum in order to make the system utilization economically feasible. In order to minimize maintenance, the lifetime of the sensor nodes must be long. As the sensor nodes, however, typically operate on capacity-limited energy storage devices, the lifetime is bound by the energy capacity available. An increase in capacity, however, also leads to an increase in cost and size of the sensor node. Thus, energy efficient operation is the principal requirement for the successful application of wireless sensor networks in the environmental monitoring domain.

Furthermore, the target setting for environmental measurement systems are typically outdoor environments, which means that the final system has to withstand harsh weather conditions and operate reliably under varying ambient conditions. Because these conditions are difficult to reconstruct in laboratory environments, the development of an environmental wireless sensor network requires outdoor test deployments. As it is often necessary during the development stage to make changes to already deployed sensor nodes, the underlying platform should support easy deployment, reconfiguration and recovery.

Finally, due to the long system deployment periods and the desire for low per-node cost, platform overhead is a parameter to be kept at a minimum. With platform overhead we describe components, modules and functionalities, which are included in a node platform although they are not required for the intended task to be accomplished. Typical examples of these are functionalities that are added in order to simplify system development.

B. SENTIO-em Hardware

The SENTIO-em hardware architecture has been designed with the requirements, as previously mentioned, in mind. A block diagram of the overall system architecture is presented in Figure 1. The detailed description of the design concepts and implementation is divided into sub-categories, which are organized according to computation, communication, sensing, power, form-factor and interfaces.

1) Computation: As is the case with the majority of existing sensor node platforms, the computational unit of SENTIO-em is built around a microcontroller. Due to the low processing capabilities, which are generally necessary and the requirement for low energy consumption, earlier systems are based on simple 8-bit or 16-bit processors, such as the Atmel ATMega family and the series of MSP430 controllers. However, as semiconductor technology has advanced since the introduction of these platforms, more recent microcontroller cores offer higher processing power with

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Table I
COMPARISON OF TYPICAL MICROCONTROLLER CHOICES FOR THE IMPLEMENTATION OF HARDWARE PLATFORMS IN SENSOR NETWORKS

	ATMega1281	MSP430F1611	AT32UC3L	EFM32G280
Manufacturer	Atmel	Texas Instruments	Atmel	Energy Micro
Architecture	8-bit	16-bit	32-bit	32-bit
Clock Frequency [MHz]	0–16	0–8	0–50	0–32
Flash [kB]	64–256	48	16–64	32–128
SRAM [kB]	8	10	8/16	8/16
Operating Voltage [volt]	2,7–5,5 (<8 MHz) 4,5–5,5 (>8 MHz)	1,8–3,6 (<4 MHz) 2,7–3,6 (>4 MHz)	1,62–3,6	1,8–3,8
Current Draw				
Active [mA MHz^{-1}]	1	0,5	0,2	0,18
Sleep [µA]	5–100	1,1–75	5–45	0,6–0,9
Off [nA]	250	100	9	20

Table II
COMPARISON OF CONSIDERED RADIO TRANSCEIVER CHOICES FOR THE IMPLEMENTATION OF SENTIO-EM

	CC1101	SX1233	CC2520	XBEE 802.15.4
Manufacturer	Texas Instruments	Semtech	Texas Instruments	Digi International
Frequency [MHz]	315/433/868/915	433/868/915	2400	2400
Max. Data Rate [kbps]	500	600	250	250
Sensitivity [dBm]	-116	-120	-98	-100
Output Power [dBm]	-30 to +12	-18 to +17	-18 to +5	-10 to +18
Current Draw				
TX [mA]	12–34	16–95	25–37	45–250
RX [mA]	14–17	16–17	18–25	50–55
Sleep [µA]	0,2	0,1	<1	<10
Implemented Protocols	none	none	low-level	low / high-level

similar or even lower power consumption, thus increasing the energy efficiency dramatically. For this platform an Energy Micro EFM32 controller was chosen, which is based on an ARM Cortex-M3 processor core. Table I provides a comparison of previously used low-power microcontrollers and the EFM32 controller on SENTIO-em. The parameter comparison shows that the EFM32 microcontroller outperforms the other listed processor choices in almost all regards.

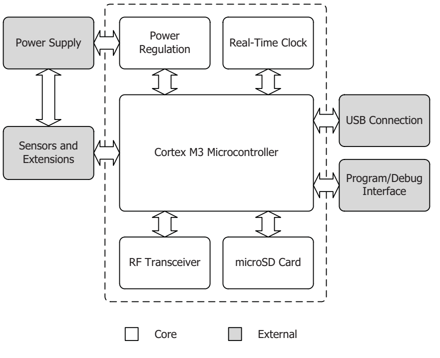

Figure 1. Block diagram of the SENTIO-em hardware architecture. The core node is shown in center, supported by application-specific extensions (left) and development functionalities (right).

The EFM32 controller is driven by a 32 MHz Q-MEMS crystal and has a connection to a Real-Time Clock (RTC) for accurate time-keeping. The RTC has an integrated crystal with temperature compensation, which improves the time-keeping accuracy in outdoor applications due to reduced environmental influences. In comparison to other controllers, the EFM32 stands out particularly because of its high energy efficiency.

2) Communication: The de-facto communication standard in research and commercial sensor networks are IEEE 802.15.4 based transceivers. These transceivers are available for both $868/915$ MHz, as well as 2.4 GHz, both being part of the license-free ISM bands. Although this transceiver choice comes with some advantages, such as compliance with other systems, an existing community (i.e., available protocol solutions) and comfortable usage, its drawbacks are its limited flexibility and the considerable packet overhead. This plays a role, especially when payload sizes are low, as is typically the case in environmental monitoring applications. In environmental monitoring, moreover, lower frequency bands are preferable, as attenuation is reduced and hence longer communication ranges can be achieved with the same output power. On the other hand, low-frequency radio transceivers come without protocol implementations and thus require more development time.

Table II provides an overview of radio transceivers

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(a) (b)

Figure 2. Pictures of the implemented SENTIO-em platform (a) mounted on the laboratory dock; (b) mounted in a protective enclosure. These two scenarios demonstrate the usage of the platform during development and deployment, respectively.

that have been considered for the implementation in the SENTIO-em platform. In addition to the standard transceiver chips, the XBee, a transceiver module with higher processing capability, has been listed. This module enables the implementation of high-level protocols (i.e., routing and networking) directly on the transceiver, but at the cost of higher overhead (e.g., energy consumption).

Due to the difficulty of predicting the exact communication requirements of individual applications, for the architecture of SENTIO-em a flexible solution has been chosen, which allows for the exchange of radio modules. The interface is based on the XBee transceiver module, which is available with different protocol implementations (e.g., 802.15.4, Zigbee or 802.11). Furthermore, low-level, low-frequency transceivers based on the Semtech SX1233 and TI CC1101 have been designed with the same interface in order to provide a flexible solution for custom protocols. By this means, it is possible to choose between general, easy to implement communication modules for rapid prototyping, or customized modules with optimized performance characteristics.

3) Sensing: Sensors are the modules which have the greatest variability between applications within the same application domain. While in environmental monitoring typical sensor types reoccur (e.g., temperature, humidity or barometric pressure), the amount, combination and requirements placed on the sensors can differ tremendously.

Due to this uncertainty in relation to sensor requirements and the targeted reusability within the application domain, SENTIO-em does not contain any sensors on its core module. Instead, sensors are connected to the platform via a 22-pin sensor interface, which provides a variety of microcontroller connection possibilities, including I2C, SPI, UART, as well as analog and digital I/O pins. In order to reduce overhead, the conversion to other interfaces, such as 4-20 mA or IEEE 1451, must take place on the sensor extension, if necessary.

4) Power Supply: In a similar manner to that for the sensor interface, a power interface has been implemented to allow for the usage of different power sources. While it is the case that during development platforms are usually powered from the grid, a laboratory power supply or an USB port, during deployments energy is typically taken from batteries or ambient energy sources.

The power interface provides a 16-pin connection to the designated power source module, which includes, in addition to the power path, communication and monitoring capabilities. The output from the power supply unit should lie between $3\,\mathrm{V}$ and $5.5\,\mathrm{V}$, but can be unregulated as a power regulation unit is part of the core platform.

5) Form-Factor: Although the form-factor of a sensor node platform is typically not its first design criteria, it has a major influence on usability, size and cost of implemented systems. Initially, platforms were supposed to be tiny and inexpensive, but more recently usability has gained a greater focus. In the physical design of SENTIO-em we have attempted to incorporate the usability, in particular in relation to the environmental monitoring constraints as presented in Section III-A. While previous solutions have demonstrated form-factors that have enabled easy development by creating a USB-stick structure [2], or providing extreme reconfigurability from building blocks [9], in this platform both laboratory and deployment constraints were considered.

In the resulting physical implementation, modules that are only used in the laboratory development of the system are divided from the general platform core. As a result, a docking station-like board has been designed, whereon the SENTIO-em platform can be mounted during development. Because this laboratory docking solution is usually not deployed with the system, it is not restricted by size. Furthermore, as not every node platform requires its own docking station, price is also not a major concern. As a result, extra functionality can be provided for laboratory development, which, in a normal setting, would be omitted due to the hardware overhead. Moreover, the size and cost of the actual node platform can be reduced, as modules that are only required during development can be removed. Figure 2a depicts such a laboratory docking solution, which in this

Table III
OVERVIEW OF THE SENTIO-EM PLATFORM IMPLEMENTATION

Microcontroller	Energy Micro EFM32	
Clock Frequency	32 MHz	
RAM/Flash	16/128 KB	
Local Storage	SD card	
Time Keeping	Temp. compensated RTC	
Radio	CC1101/SX1233	XBee 802.15.4
Frequency	433 MHz	2.4 GHz
Data Rate	500/600 kbps	250 kbps
Development	USB, ARM 20	
Extension	Sensor, Power, Debug (72-pin)	
Size	75 mm × 49 mm	
Sleep-mode Consumption	<2 µA	

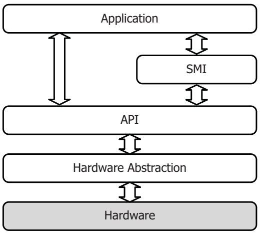

Figure 3. Layered software organization from hardware to application for SENTIO-em. The figure shows all available software layers, which do not have to be implemented in every application

case includes a USB interface, programming connection, a complete debugging interface, multiple LEDs and push buttons, as well as a selection of power supply connections.

Furthermore, the form-factor of the SENTIO-em core module has been chosen with simple deployability in mind. The module has a physical size of 75 mm × 49 mm, which allows for a screwless mounting of the platform in a Hammond 1591T plastic enclosure, as shown in Figure 2b. In the same way a sensor extension module (also shown in the picture) and a power supply unit can be stacked within the same box in a matter of seconds.

6) Interfaces: The SENTIO-em architecture includes several input and output interfaces. As previously mentioned, the core module provides interfaces for sensor extension, power supply connection, docking, as well as radio module integration. Furthermore, the module contains an SD-card slot that allows for local storage of large amounts of data in a size and cost-efficient manner. The user interface of the platform is rather simplistic, consisting of a reset button, a single programmable push button and a few status LEDs. In addition, the platform has been equipped with two magnetic switches, which allow user interaction with the sensor node without opening its physical enclosure. This, for example, allows to set the packaged system to a shipping mode, in which the node conserves energy until it has finally been deployed. For the usage of additional user interfaces, the platform can be placed on its laboratory docking solution.

C. SENTIO-em Software

For the development of the applications, a software stack, as depicted in Figure 3, has been implemented. For this, standard operating systems, such as TinyOS or Contiki, have been avoided, but the development of application code mainly relies on a C++ API. This allows for a uniform code, wherein individual hardware modules are interfaced via class instances, while keeping the overhead of the software stack at a minimum.

In order to support the development of larger applications, a state machine interface (SMI) has been developed on top of the platform's API. The SMI allows for the definition of application states in an abstract manner, as well as the state transition conditions. The state transitions can occur directly at the end of the current state (e.g., based on some condition), but are typically triggered by some external event, such as a timer, sensor or user interrupt. Furthermore, the state machine interface allows for the implementation of hierarchical finite state machines, which increases code readability and reusability in more complex applications. For more detailed information on the fundamentals of the SMI framework, we refer to [13].

IV. EXPERIMENTAL SETUP

For the evaluation of the SENTIO-em platform several tests have been conducted, which can be grouped into the following categories.

1) Platform evaluation under laboratory conditions
2) Platform evaluation with environmental influences
3) Platform comparison with existing solutions

While some previously presented system properties can only be described qualitatively (e.g., easy deployability), because of objectivity reasons, the presentation of results mainly focuses on quantitative data. Design decisions in compliance with qualitative constraints have been described in the previous section.

The primary quantitative parameter of interest is energy efficiency, which includes energy consumption, timings and computational performance. Additionally, the communication range is of interest in many outdoor sensor network deployments. However, as the communication range is dependent on the operational environment, and hence objective measurements are difficult to obtain, the radio module output power is analyzed instead, which allows for the estimation of the range in different environmental settings.

For energy consumption measurements, a fully implemented SENTIO-em platform (equipped with an SX1233 radio) is supplied from a constant voltage source and is configured for the respective system state under test. The current consumption of the platform is measured in the

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supply line by means of an Agilent 34410A digital multimeter. The consumption measurements are conducted under laboratory conditions to estimate ideal behavior, as well as under different environmental influences. For the tests under environmental influence, a TestEquity 1000H environmental test chamber has been used in order to generate defined environmental conditions.

In a similar setup, platform timings have been evaluated. These measurements include the time for the system-wakeup, as well as transition times between different operating states. A TechTools logic analyzer has been used in order to conduct the measurements of the time periods. This logic analyzer provides a resolution of 10 ns.

In order to compare the energy efficiency of the SENTIO-em platform with that of existing platforms, we have analyzed the maximum clock frequency and the sleep-mode power consumption of a set of popular sensor nodes. While for SENTIO-em its obtained measurement results have been used, the data on the other nodes is extracted from the respective datasheets or research publications.

Finally, the RF output power of the Semtech SX1233 module implementation has been measured using an Anritsu MA24106A power meter.

V. RESULTS

The evaluation results are presented separately in respect to energy efficiency and communication performance. All the presented results on the SENTIO-em platform are based on measurements.

A. Energy Efficiency

Energy efficiency in low duty-cycle applications, such as those that typically occur in the environmental monitoring domain, is determined by two platform parameters. These parameters are the power consumption of the sensor node during inactive periods and the time period the node has to remain active. In order to reduce the active time, in turn, the state transitions and the processing tasks have to be performed as quickly as possible.

Because the SENTIO-em platform is always operated at a constant supply voltage, the measurement of power consumption is performed by measuring the current consumption. The operating voltage of the platform is 3 V, which can be used to compute the power consumption, if this is necessary.

Table IV shows the results of the current consumption measurement for different operating states under laboratory conditions. All values represent the complete platform consumption and are measured as described in Section IV. During the measurements of the microcontroller consumption, the radio module is set to sleep mode, while the microcontroller is asleep (EM3) for radio measurements.

Overall the measured values comply with the expectations from the theoretical datasheet numbers. For example, in energy mode 3 (EM3) a current draw of 1.2 µA was measured, which is in accordance with the expected value (600 nA MCU + 500 nA voltage regulation + 100 nA radio transceiver). Special attention should be paid to the operating state *EM3 + RTC*, which represents the microcontroller in energy mode 3 operating with an external RTC. This state is the one most often used during sensor node inactive periods (i.e., between sensor samplings and radio activities). Due to the typically low duty-cycle in environmental monitoring applications, this value determines the lifetime of the sensor node, and thus closely correlates to that of the system lifetime. During transmission, the node's power consumption depends tremendously on the RF output power to be used, which, in turn, is defined by the distance between the transmitter and the receiver. The measured relationship between these two parameters is depicted in Figure 4.

Table IV
ENERGY CONSUMPTION OF SENTIO-EM IN ITS DIFFERENT OPERATION STATES (LABORATORY CONDITIONS)

State	Current	Condition
Active	6.1 mA	14 MHz
	8 mA	32 MHz
Low-Power	2.3 µA	EM1
	1.6 µA	EM2
	1.2 µA	EM3
	1.8 µA	EM3 + RTC
Radio	11–50 mA	TX
	16.5 mA	RX

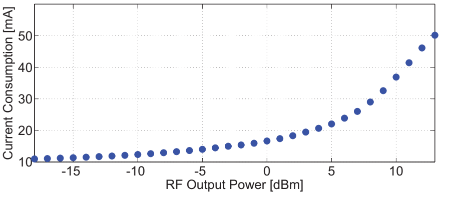

Figure 4. Current consumption of the Semtech SX1233 radio transceiver operating at different output power levels. Output power can be configured from −18 dBm to 13 dBm in 1 dBm steps

Because the majority of environmental monitoring applications take place in outdoor environments, the sensor nodes will be exposed to different environmental conditions. Therefore, conducting evaluations purely under laboratory conditions is insufficient. Figures 5 and 6 depict the results of measurements conducted under different temperature conditions. Figure 5 shows the platform's leakage current over a wide temperature range, whereas Figure 6 displays the temperature influence on active communication. All measurements have been conducted using a constant humidity setting of 40 %. In addition, the influence of different relative humidity conditions has been tested, but is ignored in this paper as its impact was found to be minimal. The

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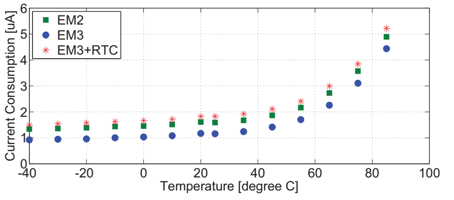

Figure 5. Current consumption of the SENTIO-em platform in its low-power modes over its entire temperature range. Humidity levels have been constant at 40 %

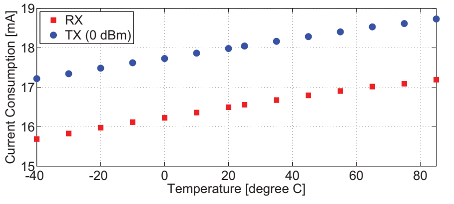

Figure 6. RF transceiver current draw during transmission (0 dBm output power) and reception under varying temperature conditions. Humidity levels have been constant at 40 %

measurement results show the expected increase of current draw with increasing temperature. While the temperature influence in the active communication shows a linear effect, in low-power modes the typical temperature dependency of leakage currents at a pn-junction can be observed. The leakage current in the platform remains low over the entire temperature range, but shows a drastic increase in relation to the laboratory conditions at temperatures above 40 °C.

Table V shows the transition times between the different operating states of the SENTIO-em platform. As many applications within the environmental monitoring domain follow a *sample-and-send* scenario with low duty-cycles (i.e., nodes periodically read sensor values and transmit them, while staying in low power modes as much as possible), transition times can play a significant role for the overall power consumption. The measurement results show that SENTIO-em can wake-up from low-power modes in less than 6 µs and be ready to transmit or receive in a few hundred µs. In combination with the typically low amounts of sensor data to be transmitted, these short transition times allow SENTIO-em to operate on very low duty-cycles.

Figure 7 indicates the energy efficiency of the presented platform in respect to popular existing sensor node platforms. In this figure, the sleep-mode power consumption of each platform is plotted against the maximum clock frequency, at which the respective platform can operate. The resulting location on the grid indicates how fast the platform can accomplish its tasks, and at which cost the processing performance comes.

Table V
TRANSITION TIMES BETWEEN DIFFERENT OPERATION STATES OF THE SENTIO-EM PLATFORM

From	To	Transition time
Sleep	Active	1.8 – 5.8 µs
Radio sleep	TX	150 µs
Radio sleep	RX	380 µs
TX	RX	390 µs
RX	TX	70 µs

B. Radio Performance

As mentioned previously, a parameter of interest concerning the radio transceiver is its communication range. This is particularly true in environmental monitoring applications, as the sensor networks might cover large outdoor areas. If the network does not have to simultaneously offer high spatial resolution, then long communication range can limit the system cost, as nodes with a purely relaying functionality can be omitted.

However, communication range is not a value that can be objectively measured. While it mainly depends on two transceiver parameters, the output power of the transmitter and the sensitivity of the receiver, several system external parameters will also influence the communication range. These parameters include the physical environment (i.e., objects in or close to the communication path, which result in multipath propagation, signal scattering or increased attenuation), as well as interference sources. As the external parameters are not under the direct control of the network/system operator and will vary from one location to the other, the evaluation of radio performance has been limited to the evaluation of transceiver properties.

Figure 8 shows the relationship between configured and measured output power of the SX1233 transceiver implementation, which indicates that no power is lost in the transmission line or the matching network.

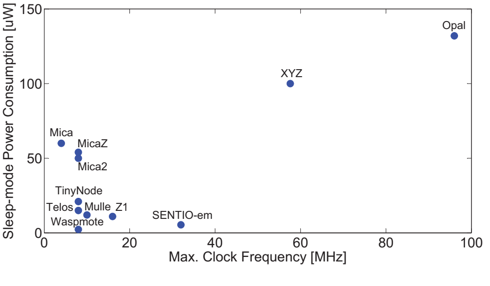

Figure 7. Comparison of different sensor node hardware platforms in respect to their energy efficiency. Energy efficiency is here measured by max. clock frequency and sleep-mode power consumption.

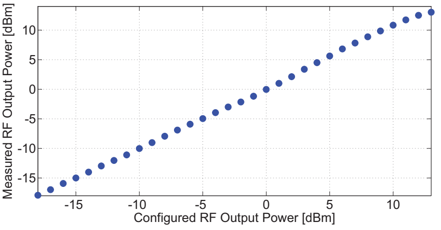

Figure 8. Comparison of theoretical and measured RF output power as an evaluation for radio transceiver implementation

VI. Conclusions

With SENTIO-em, we have presented a wireless sensor node platform particularly designed for the environmental monitoring application domain. While typical application-specific solutions limit the reusability of the node platform, which is hindering the research process, general purpose designs often lack the performance for the specific applications at hand. The application-domain-specific design of SENTIO-em, combines the advantages of both fields, which results in a platform that is optimized for a specific application domain, but which can be reused in different applications within the domain.

We have described the system architecture of SENTIO-em, which has been based on the typical application requirements of the environmental monitoring domain. These include long operating times, outdoor deployment, coverage of large areas, and low sampling rates. For the node platform, these requirements have been translated into system demands, such as energy efficiency, low quiescent current, long communication range, low hardware overhead, and simple deployability.

The implemented platform has been evaluated under both laboratory and different environmental conditions. The results show a reliable operation even under extreme temperatures, but also the typical temperature-dependent current draw of the involved semiconductor components, which will influence the lifetime of the system in different environments.

In comparison with typical existing platform solutions, SENTIO-em shows a high energy efficiency. The combination of fast processing times due to its 32 MHz clock frequency, short state transition times, and low power consumption in inactive states, proves the high energy efficiency of SENTIO-em, which determines the long system lifetimes desired in low duty-cycle applications within the environmental monitoring domain.

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PAPER II

Javier Aranda. "Super Article". In: *Super Mega Watt Energy Harvester* (2020)

“Super Article”

Abstract

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4.1 Introduction

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4.2 Acknowledgements

This work was sponsored.

References

[1] Sebastian Bader, Matthias Krämer, and Bengt Oelmann. "A Domain-Specific Platform for Research in Environmental Wireless Sensor Networks". In: *SENSORCOMM 2013, The Seventh International Conference on Sensor Technologies and Applications :* 2013, pp. 200–207. ISBN: 978-1-61208-296-7. URL: http://www.thinkmind.org/index.php?view=article&articleid=sensorcomm_2013_8_30_10078.

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