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SmartMeter.KOM: A Low-cost Wireless Sensor for Distributed Power Metering

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***Abstract*—Most current smart metering solutions aim at increasing user awareness for their household's electrical energy consumption. Although some smart meters make use of wireless data transfers between their sensor and display units, their integration into existing wireless sensor networks is hampered by proprietary communication interfaces and their lack of reprogrammability. Furthermore, the sole availability of aggregate consumption values renders current meters insufficient for novel application scenarios like smart home automation, for which information at device-level granularity and high resolution is vital. We address these shortcomings of existing solutions by presenting SmartMeter.KOM, our wireless sensor node capable of determining the current consumption of individual electrical appliances at high resolution. The platform is based on low-power hardware and incorporates a reprogrammable microcontroller which allows developers to easily deploy new algorithms. Its IEEE 802.15.4-compliant radio transceiver makes its integration with existing sensor networks possible, and thus enables their integration in smart buildings. We demonstrate the versatility of SmartMeter.KOM by presenting prototypical implementations of smart applications and identifying further research directions.**

I. INTRODUCTION

The ability to monitor the power consumptions of electric appliances and switch their mains connection is a major enabler for smart environments. Fine-grained knowledge about the currently active consumers enables various smart services, e.g. a detailed analysis of the individual contributors to a household's energy bill or the detection of a user's presence or location. By correlating energy consumption readings with contextual information, user comfort and energy expenditure can be improved, e.g. by automatically switching off unused appliances or turning devices on without explicit user interaction. The availability of embedded systems with metering and actuation capabilities is thus essential in order to realize the vision of smart environments.

Existing commercial metering devices typically lack the functionality to monitor consumers at device-level granularity, and rarely provide the function to control the mains connection to the attached appliance. Their integration into existing Wireless Sensor and Actuator Networks (*WSAN*s) is additionally complicated, because proprietary radio communication protocols are predominantly used, which render protocol translation necessary at all times. The lack of reprogrammable hardware also restrains the prototypical evaluation of processing functionality on the nodes, e.g. the realization of algorithms to extract patterns of device activity recorded over extended time intervals or the inference of information about the type of the attached device and its current status.

We directly address the shortcomings of existing solutions by presenting the design of the SmartMeter.KOM platform in this paper. It combines capabilities for taking high resolution measurements of the electrical current flow, switching the mains connection of the attached load, and a wireless communication device to exchange readings and actuation commands with other nodes in the WSAN. SmartMeter.KOM nodes are based on low-power reprogrammable hardware, enabling additional functionality to be easily incorporated. In order to ensure interoperability with widely available sensor nodes, such as the TelosB [1], the radio transceiver device used on SmartMeter.KOM complies to the IEEE 802.15.4 standard [2], which has been widely adopted in WSANs. Besides providing fine-grained current measurements at device level, SmartMeter.KOM can be configured to generate events whenever an appliance is attached, activated, changes its state, or behaves erroneously. The low delay between measurement and transmission of according event messages to the WSAN represents a clear benefit of SmartMeter.KOM over existing solutions. The contributions of this paper are as follows:

- We present design decisions and implementation details of the SmartMeter.KOM platform.
- We evaluate the platform with regard to its accuracy as well as its resource and energy consumption.
- We demonstrate its versatility by presenting an application that automatically discovers and disconnects faulty devices.

We summarize related work in Sec. II, followed by outlining the design considerations and implementation details of SmartMeter.KOM in Sec. III. We evaluate our platform and present experimental results in Sec. IV, and conclude this paper in Sec. V.

II. RELATED WORK

Along with rising energy prices, user demand for awareness of their energy consumption has increased. In consequence, smart metering devices have received wide attention in recent years, and resulted in a range of both research prototypes and full-fledged commercial products. Metering equipment is available for different granularity levels, ranging from the presence of a single meter for complete households up to individual meters for each attached device.

Capturing a household's overall energy demand and creating user awareness for their consumption is target of many existing commercial units, such as Wattson [3], CurrentCost [4], or Cent-a-Meter [5]. Common to all of these solutions, the sensor units are mounted within a building's distribution board. A separate display provides a view of the total building consumption, but does not allow the user to identify and analyze consumers individually. A finer resolution can be achieved by attaching meters to every circuit individually [6, 7], effectively enabling energy metering at the granularity of floors or even rooms. Finally, dedicated metering equipment can also be attached to consumers individually, allowing users to drawing fine-grained portraits of their consumption, which is especially valuable when devices with variable energy consumption are being measured. A plethora of device-level measurement devices without radio transmission capabilities are widely available, such as Kill A Watt [8]. Proprietary wireless data communication protocols are being used in the RWE SmartHome Zwischenstecker [9] and the Homematic series [10], which enable, but at the same time complicate, their integration into existing WSANs. Both the Plogg [11] and the Plugwise Circle [12] devices communicate over the Zigbee Smart Energy standard [13]. However, the unavailability of implementation-specific documentation makes adaptation difficult, and the bundled software either does not provide access to power consumption readings at all, or at reduced resolution only.

Apart from interfacing the electrical installation directly, indirect monitoring of power usage is based on capturing the magnetic field surrounding the power cables of appliances. Conclusions about a device's current consumption can thus be extracted without the need to unplug or physically modify the appliance [14]. Similarly, an approach to exploit the side-effects of device usage is presented in [15], in which a sniffer device listens to noise on the mains voltage on in-house electric cables. The activity of appliances is then inferred from the presence of characteristic noise patterns on the mains line.

Besides commercially available solutions, ACme-B [16] is a research prototype for current metering, based on the existing Epic mote platform [17], which enables monitoring appliances individually and communicates over IEEE 802.15.4. It performs peak tracking to assess the power consumption, which it reports wirelessly at a rate of one packet per minute. Similarly, Plug is an extension cord equipped with sensors for electrical power consumption [18], but utilizes a 2.4GHz radio that does not comply to IEEE 802.15.4. An extension to ACme is proposed in [19], which takes voltage and frequency measurements only at a single location, and extracts power values from correlating this *virtualized* voltage line with the current readings taken in a distributed fashion.

In summary, only per-device monitoring enables the unambiguous detection of appliances and their activity states. However, most existing per-device metering solutions are either based on closed systems, hard to obtain, or lack the integration possibility with IEEE 802.15.4-based WSANs, which complicates their use in research.

III. SMARTMETER.KOM: DESIGN AND IMPLEMENTATION

The identified lack of suitable and available systems to take power measurements in a distributed fashion has inspired us to create a flexible low-cost solution for researchers.

A. Design Considerations

We have considered several requirements during the design of SmartMeter.KOM, which we outline in the following list.

- **Device-level sensing granularity**: In contrast to "non-intrusive appliance load monitoring" (*NILM*) [20], which is based on the installation of a single metering device inside a household's distribution board, the capability of drawing a fine-grained portrait of the contributors to a household's energy consumption is only possible when power consumptions are measured on a per-device basis. SmartMeter.KOM has thus been designed to operate on device-level granularity, and thereby eliminates possible ambiguities when several devices of identical consumption are present. Especially when actuation of individual appliances is required, a measurement and actuation unit operating on a per-device basis in inevitable.
- **Actuation capabilities**: Besides the functionality to measure the current consumption of attached appliances, their actuation enables the realization of manifold smart services. Possibilities include the deactivation of consumers when users are absent, the generation of events when operating modes change, or the autonomous disconnection of faulty devices. SmartMeter.KOM thus provides a controllable switch to enrich conventional electrical appliances by smartness.
- **Reprogrammability**: The integration of reprogrammable hardware into smart metering prototypes is inevitable in order to evaluate the capabilities and limitations of smart metering. The possibility to easily modify a node's functionality allows researchers to integrate new functions, i.e. logic evaluation or autonomous event generation capabilities, and thereby explore the achievable degree of smartness and intelligence. In consequence, the decision to integrate a user-programmable microcontroller on the platform has been made.
- **Sensor network integration**: The proprietary radio protocols and closed-source software used on existing commercial hardware solutions for device-level monitoring complicate their integration into existing sensor networks. Directly addressing this limitation, we have decided to design SmartMeter.KOM with an IEEE 802.15.4-compliant communication interface for seamless integration into existing sensor networks.

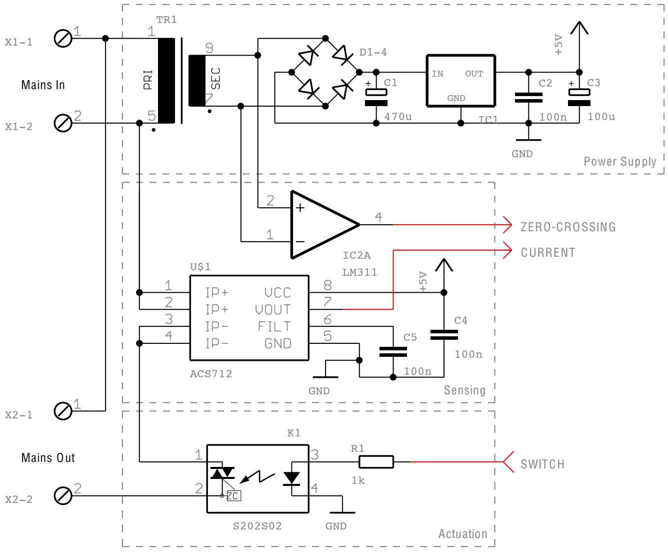

Fig. 1. Schematic of the 5V power supply (top), current and zero crossing sensors (center), and consumer actuation device (bottom). Connections marked in red are directly interfaced to the microcontroller.

- **Low energy consumption**: Besides creating awareness for the power consumption of the attached appliance, the metering node should ideally require less energy for its operation than can be saved by turning the connected appliance off at phases during which its operation is needless. We therefore use low-power components to maintain a low energy consumption of the platform.

B. Sensor Selection

With electrical power being defined as the product of voltage and current, both of which are measurable physical quantities, an appliance's power consumption is basically proportional to the electrical current flow and the phase offset between voltage and current under the assumption of a constant mains voltage (nominally 230 volts ±10% at 50Hz in Europe). In the first development stage, we have thus decided to confine our measurements to the current flow as well as the phase shift with regard to the zero crossing of the voltage level. The accuracy of the power calculation can however be increased by incorporating an additional voltage sensor or applying the concept of a virtualized voltage channel [19].

To measure the current consumption of appliances connected to SmartMeter.KOM, we have selected the Allegro Microsystems ACS712 [21], a precise low-offset current sensor based on the Hall effect. It can measure currents up to five amperes, i.e. loads of up more than 1,000 watts, which exceeds the consumption of most household appliances. Operating on a supply voltage of five volts, the ACS712 outputs a voltage U_{out} linear to the input current I_{in}, according to Equation 1. Its own power consumption in operation mode is stated as 50mW in the data sheet.

$$U_{out} = 2.5V + I_{in} \cdot 185\frac{mV}{A} \quad \text{if } |I_{in}| <= 5A \tag{1}$$

Despite its size, we have used a transformer-based power supply unit (cf. Sec. III-E) to detect the zero crossings of the input voltage. A National Instruments LM311 comparator [22] is directly connected to the unrectified output voltage of the power supply and interfaced to the microcontroller such that an interrupt is fired whenever a zero crossing is detected. According to its data sheet, the LM311 has a power consumption of 17.5mW. The circuits for both current and voltage zero crossing sensors are depicted in the center part of Fig. 1.

C. Actuator Selection

A relay is necessary in order to make the activation of the attached consumer controllable from a low-voltage output pin of the microcontroller. While mechanical relays often require several hundred milliwatts to drive the electromagnet that closes the switch, solid-state relays employ semiconductors to perform the actual switching operation and hence require significantly less power to operate. We have integrated a Sharp S202S02 [23] solid-state relay (*SSR*) in SmartMeter.KOM, which is capable of switching loads of up to eight amperes, although additional cooling is required when loads in excess of 500 watts are active over longer time intervals. The SSR additionally features an integrated zero crossing detector, which delays the activation of attached devices until the next zero crossing of the input voltage has occurred, leading to less interference on the mains line and repeatable conditions for successive switching operations. Similar to mechanical relays, the switched mains voltage is galvanically decoupled, such that no risk of injury exists on the low-voltage part. The relay is controlled by a digital input signal and consumes 10mW when the consumer is switched on. Its position in the schematic drawing is depicted in the lower part of Fig. 1.

D. Communication Device

To cater for the integration into existing WSANs, the selection of an IEEE 802.15.4-compliant hardware solution for wireless communications is necessary. We have selected the Microchip MRF24J40MA [24], because it combines a radio transceiver chip with an on-board antenna and all required external components on a single circuit board. The device is interfaced over a three-wire Serial Peripheral Interface (*SPI*) bus, and features an additional interrupt pin which signals incoming traffic to the microcontroller. The module is widely configurable and can be set up accordingly to make use of the packet format used in TinyOS [25], as outlined in TEP 111 [26]. By complying to the TinyOS header format, SmartMeter.KOM nodes can also take further roles in TinyOS-based WSANs, e.g. act as router or repeater nodes for radio traffic. The module's typical power consumptions are quoted as 80mW while transmitting, and 63mW while in reception mode, which can be reduced even further by using the integrated sleep modes.

E. Power Supply

Smart metering devices have been designed to capture power consumption data of electrical appliances, and are in consequence always located in positions where connection to the mains is available. In consequence, SmartMeter.KOM nodes are supplied by a small transformer, as

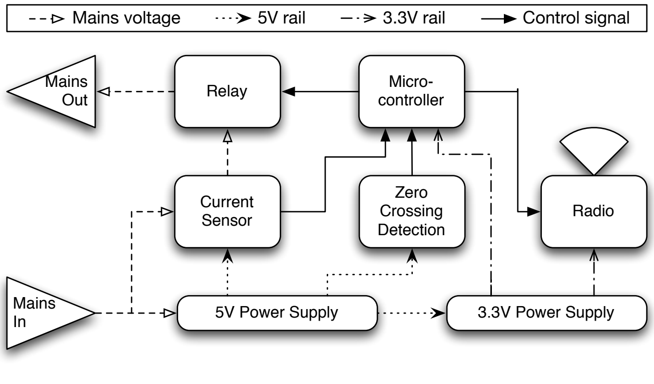

Fig. 2. Block diagram of SmartMeter.KOM

shown in the upper part of Fig. 1, obsoleting the need to rely on batteries, which would need to be changed regularly. After rectification of the voltage, it is passed through voltage regulators which emit constant operating voltages of 5V for the sensors and 3.3V for the microcontroller and the radio transceiver. Simultaneously, the unrectified transformer output voltage is tapped in order to provide the voltage zero crossing signal to the microcontroller, in order to measure the phase shift between voltage and current and thus enable the determination of real, reactive, and apparent power.

F. Integration and Interfacing to the Microcontroller

To control the components, we have used the low-power Atmel ATtiny44 8-bit microcontroller in our design, which is equipped with 4kB of program memory and 256 bytes of RAM. It has eight built-in analog-digital converters with a resolution of 10 bits, and thereby provides the functionality required to perform the conversion of the analog signal input from the current sensor into the digital domain. An integrated Universal Serial Interface (*USI*) provides hardware-supported communication routines to flexibly interface peripherals, e.g. over the SPI bus, in order to communicate with the radio transceiver. The ATtiny44 is available in 14-pin DIP and SOIC packages, which simplify the assembly process of the circuit boards, and can be programmed via In-circuit Serial Programming (*ISP*). With regard to its energy consumption, the ATtiny44 consumes 9.5mW in active mode, 2.3mW when idle, and less than 15μW in sleep mode.

The resulting node architecture is depicted in Fig. 2, and our custom SmartMeter.KOM printed circuit boards, measuring 3.6cm by 3.0cm excluding the transformer-based power supply board, are shown in Fig. 3. The wireless transmission module is dedicatedly placed above a ground plane to be shielded from signal lines, while the antenna intentionally protrudes over the edge of the board to achieve best performance. All pins of the microcontroller, which are currently not in use, were routed to the edge of the board and connected to pin headers for improved debugging and future expansion purposes.

IV. EVALUATION AND EXPERIMENTATION

We evaluate SmartMeter.KOM with regard to the design considerations established in Sec. III-A by showing that SmartMeter.KOM design fulfills the requirements of low energy consumption and seamless integration capabilities with existing sensor networks. Additionally, we assess the performance and usability of SmartMeter.KOM by conducting practical experiments and portraying our experiences with the platform.

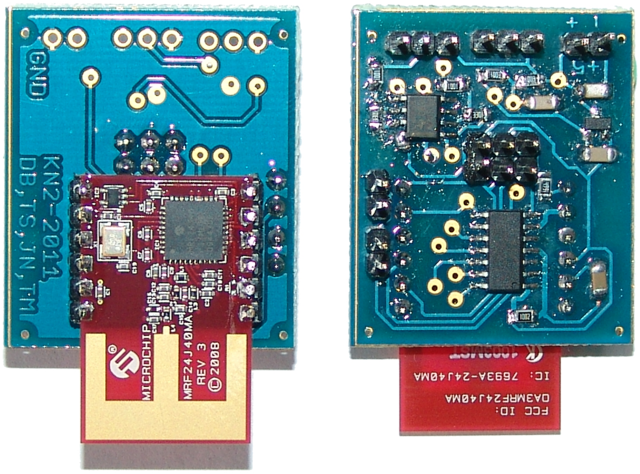

Fig. 3. Back (left) and front (right) view of the SmartMeter.KOM prototype

A. Power Consumption

Based on the component selection presented in Sec. III, we assess the power consumption of SmartMeter.KOM with regard to the design decision of low-power design. According to the values stated in the components' data sheets, an electrical power consumption of 167mW was expected when all components are active and packets are being transmitted on the radio. This number however excludes the dissipation of the power supplies for the 5V and 3.3V rails, which can be estimated to range between 10μW when both MCU and radio are in sleep mode up to 44mW with active MCU and ongoing radio transmissions. In contrast to dedicated solutions like the energy measurement circuit [27] developed for the TWIST testbed [28], we have attached a SmartMeter.KOM node to a calibrated Fluke 8050A digital multimeter and measured the current consumption values of SmartMeter.KOM under real-world conditions. Our measurements are shown in Fig. 4 and indicate that at most 188.1mW are consumed by Smart-

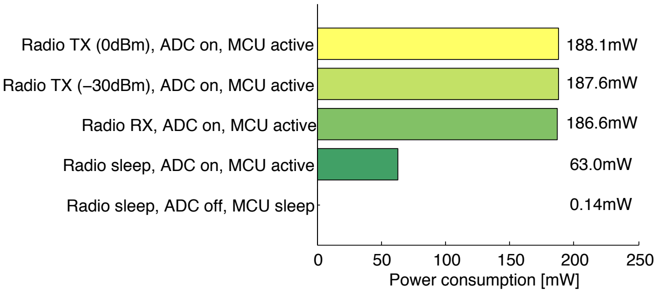

Fig. 4. SmartMeter.KOM power consumption in different modes of operation

Meter.KOM when the radio transceiver is active, while only 63mW are required when no radio communication takes place. With all components in sleep mode and the Hall sensor detached, the overall consumption drops to 140μW. In summary, the power consumption analysis has shown that SmartMeter.KOM successfully follows a low-power design.

B. Current Metering Accuracy

Because the consumption traces of appliances with linear current draw (e.g. conventional light bulbs) follow sinusoidal waveforms, their total power consumption can easily be extrapolated from the peak current draw. However, the increasing presence of switch-mode power supplies with according non-linear current consumptions (a selection of traces measured using SmartMeter.KOM is shown in Fig. 5) necessitates alternative sampling techniques to capture accurate representations of the current flow. We directly address the limitations of peak tracking by implementing the current measurement on the SmartMeter.KOM nodes using the root mean square (*RMS*) method. Its calculation shown in Equation 2, where n is the number of samples taken during a full-wave of the current (20ms for a mains frequency of 50Hz) and I_k represents the current value measured at sampling point k.

$$I_{RMS} = \sqrt{\frac{\sum_{k=1}^{n} I_k^2}{n}} \tag{2}$$

In order to determine a sampling frequency and an according number of samples n that leads to accurate metering results and at the same time does not exceed the capabilities of the employed MCU, we have conducted a preliminary measurement and compared the RMS values for consumer devices with known current consumption for sampling frequencies ranging from 100Hz to 2,000Hz. The measured relative errors (comparing the calculated RMS current against the measured ground truth) are shown in Fig. 6 and confirm the trend of an increase in accuracy for higher sampling frequencies. Especially for devices with switch-mode power supplies (like the LCD monitor), a high sampling rate is required to accurately capture the non-sinusoidal features of the attached appliance's consumption and thereby reduce the measurement error. Based on the observations from the previous experiment, we have therefore configured SmartMeter.KOM to sample current readings at a rate of 1.6kHz, which results in n=32 sampling points per full-wave of the input voltage. We have furthermore assessed the maximum measurement error for a larger selection of devices. The comparison of the values determined by our SmartMeter.KOM implementation and reference measurements using the calibrated multimeter are indicated in Table I. They show that SmartMeter.KOM slightly overestimates the current consumption in all experiments, but also indicate that the encountered measurement error is below 4% in all cases.

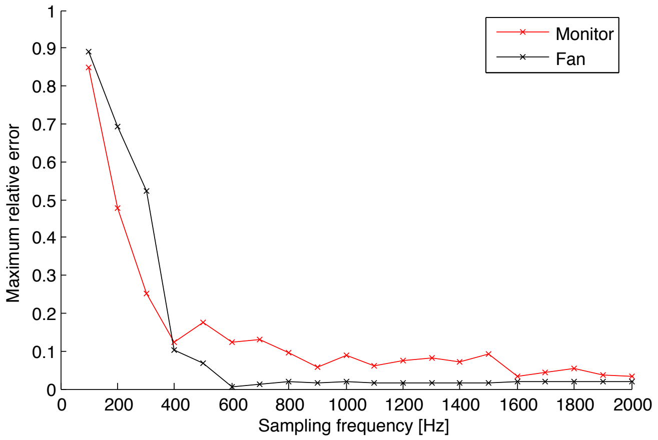

Fig. 6. Relative measurement error at different sampling frequencies

TABLE I
ACCURACY OF THE RMS CURRENT MEASUREMENTS

Device	Measured RMS current		Error
	Fluke 8050A	SmartMeter.KOM	
8 port Ethernet switch	43.5mA	44.3mA	+1.8%
24 port Ethernet switch	157mA	163mA	+3.8%
Pedestal fan	173.9mA	176mA	+1.2%
20" LCD monitor	231mA	233mA	+0.9%
24" LCD monitor	350mA	351mA	+0.3%
Desktop computer	530mA	534mA	+0.7%

C. Integration into WSANs and Resource Consumption

We verify the practical integration of SmartMeter.KOM into existing IEEE 802.15.4-based sensor and actuator networks by configuring the SmartMeter.KOM nodes to provide a set of functions over the network. In our experiment, a TelosB mote with the TinyOS BaseStation application has been used as gateway between the WSAN and a desktop computer. All requests have been issued using a command line application on the computer.

The following functions have been implemented and tested in our prototype:

1) Single sample request: When this function is executed, the latest RMS current reading as well as the corresponding power estimation (assuming 230 volts mains voltage) are transmitted in reply.
2) Continuous sample request: After the invocation of this method, the node transmits average current and power readings every ten seconds until configured differently.
3) Threshold-based event generation: By configuring an upper and lower threshold value, event notifications are generated when the measured RMS current exceeds the given thresholds.

All functions were executed on the SmartMeter.KOM node in a proper and timely manner, which thereby successfully confirmed its seamless integration into IEEE 802.15.4-based sensor and actuator networks. In order to provide a sense of the according resource demands, we have implemented different combinations of transmission channel (serial link or wireless interface) and power estimation (peak detection, accumulative

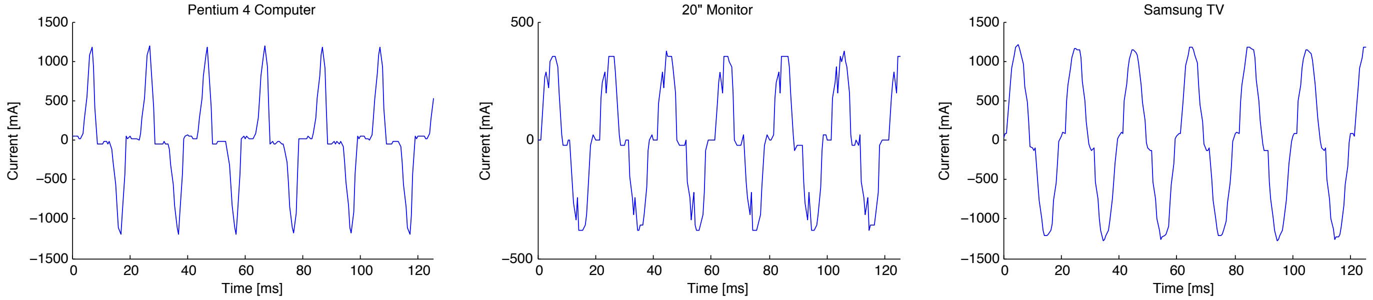

Fig. 5. Steady-state current traces of different attached electrical consumers

RMS calculation, and sliding window RMS calculation), and show the according resource demands in Table II. In all cases, further resources are available on the microcontroller, which enable the integration of additional processing algorithms, such as capabilities to detect the type of the attached appliance.

TABLE II
MEMORY CONSUMPTIONS OF THE IMPLEMENTED APPLICATIONS

Application	Program memory	RAM
Peak detection serial transmission	1260 bytes (30.8%)	23 bytes (9.0%)
Accumulated RMS serial transmission	1302 bytes (31.8%)	23 bytes (9.0%)
Sliding window RMS serial transmission	1484 bytes (36.2%)	92 bytes (35.9%)
Peak detection wireless transmission	2144 bytes (52.3%)	25 bytes (9.8%)
Accumulated RMS wireless transmission	2206 bytes (53.9%)	26 bytes (10.2%)
Sliding window RMS wireless transmission	2326 bytes (56.8%)	95 bytes (37.1%)

D. Practical Experimentation Experiences

We conclude our evaluation of SmartMeter.KOM by demonstrating its applicability in smart buildings through a practical experiment. The goal of the experiment was to autonomously determine unexpected device behavior based on an appliance's expected current consumption. Many electrical appliances typically only consume electrical currents ranging between fixed bounds. Their demand for unusually high or low currents is often an indication for upcoming device faults or malfunctions. In order to determine violations of typical current ranges, we have configured a SmartMeter.KOM node to automatically learn the typical operating currents of an attached consumer, and emit an event message over the wireless channel whenever the determined bounds are violated. We have selected a lightweight learning algorithm based on the recognition of operating regions which are established when similar currents have been measured for more than eight periods of the input voltage (i.e. a time frame of 160ms, equalling 256 sampling points), using a sliding window RMS calculation which calculates the RMS value over the latest 32 current samples. The learning algorithm is presented in Algorithm 1.

Algorithm 1 Operating current learning algorithm

```
Initialization $I_{ref} \leftarrow$ latest sliding window RMS current
 1: $count \leftarrow 0$
 2: $I_{\chi} \leftarrow$ latest sliding window RMS current
 3: if $|I_{\chi} - I_{ref}| \leq 5mA$ then
 4:     $count \leftarrow count + 1$
 5:     if $count = 256$ then
 6:         Store $I_{ref}$ as valid operation current
 7:         Goto line 1
 8:     end if
 9: else
10:     $I_{ref} \leftarrow I_{\chi}$
11:     Goto line 1
12: end if
13: Goto line 2
```

After having determined the normal operating regions of the device, the values are arranged in form of a binary search tree enabling the fast storage of learnt regions in an organized manner. The tree structure also caters for fast searching in order to validate whether a device is within its normal operating region. In the experiment, we have connected a pedestal fan to SmartMeter.KOM and monitored its typical operating regions and the according transitions, which resulted in the state tree (annotated by the operating modes) shown in Fig. 7. Each state denotes a learnt valid operating region of the device. If the device deviates from the normal operating regions for a period greater than 1024 samples (equalling a time interval of 640ms), an event is generated and transmitted to the base station to allow for user notifications. Additionally, the solid state relay is turned off to reduce the risk of permanent device damage. The resource consumption of the implemented functions is still within the resource limitations of the employed microcontroller, where it occupies 3574 bytes (87.3%)

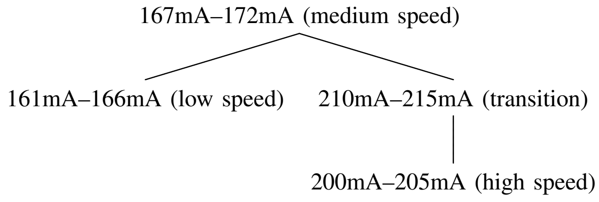

Fig. 7. Determined operating currents of the used pedestal fan

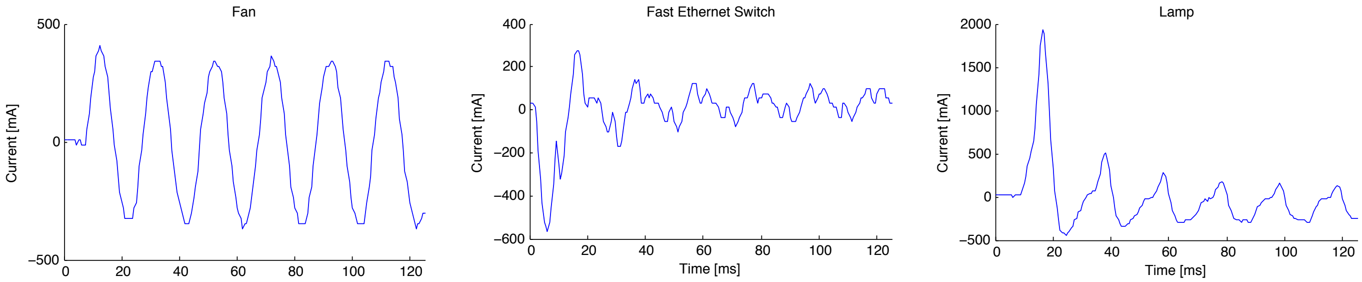

Fig. 8. Inrush current traces of different attached electrical consumers

of program memory and 109 bytes (42.6%) of RAM, with additional RAM being dynamically allocated depending on the tree size. We have validated the according functionality by attached a secondary consumer to the SmartMeter.KOM outlet, which immediately turned off the solid-state relay when the overcurrent condition was detected.

V. CONCLUSION

In this paper, we have presented the design and implementation of SmartMeter.KOM, a wireless sensor and actuator node which can monitor current consumptions of attached appliances and control their mains connection. Based on low-cost reprogrammable components, SmartMeter.KOM has been designed as a versatile experimental platform. Specific sensing or actuation behavior can be easily integrated through the reprogrammable character of the used microcontroller, e.g. to raise user awareness for their energy consumption or provide functionality for the realization of smart environments. Seamless integration with existing wireless sensor and actuator networks is given through the presence of an IEEE 802.15.4-compliant radio transceiver. The selection of low-power components has resulted in an energy consumption of less than 200mW for the developed platform, and a correspondingly low usage cost. Our evaluation and practical experiments have confirmed the versatility of SmartMeter.KOM and demonstrated its applicability in smart environments.

A. Future Work

We plan to use the available resources on the microcontroller in order to include further processing capabilities on the node, e.g. the integration of device type classifiers through power signature analysis, such as proposed in [29, 30, 31]. We have taken traces of device inrush currents using SmartMeter.KOM, which are shown in Fig. 8, and already indicate potential to infer device types from their characteristic inrush currents. In the long term, we are also planning the indoor deployment of power metering nodes at large scale to get a fine-grained portrait of the consumers within the building, similar to the experiment conducted in [32]. We anticipate the deployment to help us locate the major energy consumers in the building and to provide context-aware building automation.

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