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Impressum
Published by

Publisher: Rector of the Ilmenau University of Technology
Univ.-Prof. Dr. rer. nat. habil. Dr. h. c. Prof. h. c. Peter Scharff

Editor: Marketing Department (Phone: +49 3677 69-2520)
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Editorial Deadline: 20. August 2010

Implementation: Ilmenau University of Technology
Felix Böckelmann
Philipp Schmidt

USB-Flash-Version.

Publishing House: Verlag ISLE, Betriebsstätte des ISLE e.V.
Werner-von-Siemens-Str. 16
98693 Ilmenau

Production: CDA Datenträger Albrechts GmbH, 98529 Suhl/Albrechts

Order trough: Marketing Department (+49 3677 69-2520)
Andrea Schneider (conferences@tu-ilmenau.de)

ISBN: 978-3-938843-53-6 (USB-Flash Version)

Online-Version:

Publisher: Universitätsbibliothek Ilmenau
ilmedia
Postfach 10 05 65
98684 Ilmenau

Home / Index:
http://www.db-thueringen.de/servlets/DocumentServlet?id=16739

DISTRIBUTED IN-HOUSE METERING VIA SELF-ORGANIZING WIRELESS NETWORKS

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ABSTRACT

Smart metering is a hot topic in building infrastructures. While smart meters enable improvements upon the transparency and efficiency of energy consumption for larger objects such as entire homes or apartments, advances in wireless and sensor technologies promise additional benefits through the implementation of sub-metering solutions.

This contribution details the experiences made in the setup and operation of a wireless sensor network for monitoring, i.a., power consumption at individual outlets in a pilot installation, discussing the network's hardware platform, software components, and lessons learned regarding practical issues of deployment.

The contribution furthermore contains a user report and outlines the increase of knowledge caused by the use of these additional sensors. Furthermore an approach is presented as to how these additional data can be integrated with a home energy management system in order to realize the Smart Home.

***Index Terms*—** smart grid, smart metering, smart home, in-house automation, energy management, wireless sensor networks, WSN, application frameworks

1. INTRODUCTION

Smart metering, the deployment of digital metering equipment measuring consumption at short intervals and communicating these data regularly to the utility for monitoring and billing purposes, is a hot topic in building infrastructures. While smart meters enable improvements upon the transparency and efficiency of energy consumption for larger objects such as entire homes or apartments, advances in wireless and sensor technologies promise additional benefits through the implementation of sub-metering solutions, i.e., the deployment of interconnected sensor nodes measuring energy consumption per consumer.

2. WIRELESS SENSOR NETWORKS

The concept of wireless sensor networks (WSNs) has been a topic of active research during the past decade. The term refers to networks of spatially-distributed sensor nodes communicating wirelessly. Topologically, these networks are usually star-, tree-, or mesh-shaped and self-organizing.

Research and development of WSNs have yielded a plethora of solutions with varying properties for a broad variety of application domains ranging from building automation to environmental monitoring to logistics and security. Despite the long time this technology has been in development, WSNs are only now being deployed in practical contexts on a larger scale.

Developing WSN solutions touches upon a broad spectrum of areas of expertise, such as development of sensors, digital and HF hardware design, embedded software development including operating systems and networking protocols, gateway applications possibly including user interfaces, and protocols for interfacing these with common IT infrastructures.

Particular challenges in the design of WSN solutions involve the mutually-dependent aspects of wireless sensor nodes' battery life, radio range, and granularity of data acquisition (both temporally and spatially, i.e., defined by the number of nodes) and transmission [1]. Together these aspects define a decision space in which a design is to be found that is optimzied for the requirements imposed by a particular application scenario.

3. A WIRELESS SENSOR NETWORK FOR APPLICATIONS IN ENERGY MANAGEMENT

In the combined domain of building automation and energy management, WSNs have been studied in the course of various research projects [2]. Building upon results from one of these projects[1], a pilot installa-

[1]*Customer Bautronic System (CBS)*, http://www.customerbautronic.de/, was publicly funded by German BMBF (project no. 03WKBD3C).

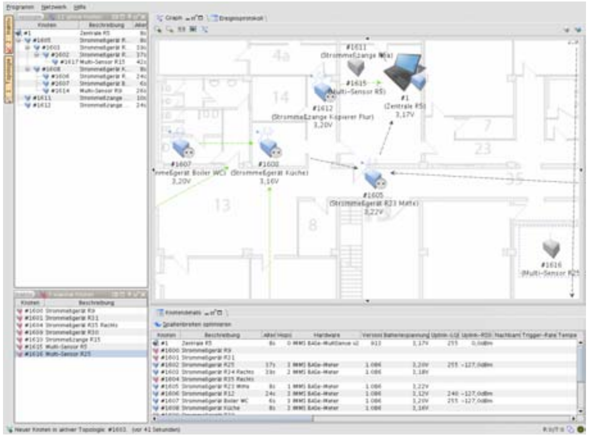

Fig. 1. The *BASe-Terminal* WSN gateway software visualizing the sensor network.

Fig. 2. *BASe-Meter* with an external current clamp.

tion of a WSN for applications in energy management has been set up at the Fraunhofer AST in Ilmenau, Germany. The goal of this installation has been to analyze the benefits gained from measuring energy consumption with per-consumer granularity—so-called sub-metering—on the one hand and the simultaneous consideration of additional sensory data on the other hand.

The pilot installation was deployed on a single floor of a larger building housing offices and laboratories. Figure 1 shows a section of the floor plan and the locations of wireless sensor nodes. The network comprised a total of 18 nodes of two types: electrical meters measuring power consumption and various other properties of the mains supply (frequency, voltage, current, phase), and environmental sensors measuring illuminance, temperature, and humidity.

3.1. Hardware Platform

The WSN deployed is based on an architecture, *BASe*, developed at IMMS which comprises a variety of components and has collectively been named *BASe-Net* [3]. The platform builds upon a low-power microcontroller system with an external RF transceiver and various interchangeable sensors. With some modifications, this design can be used to read out *Plogg* devices. *Ploggs* are smart metering plugs with a load controller and data logger, shipped with *Zigbee* or *Bluetooth* radios. Furthermore, they can be equipped with an external current clamp.

A *BASe* node integrated with a *Plogg* device has been named *BASe-Meter* (figure 2). In this case, all electrical circuits, the measurement system, the microcontrollers and the RF transceiver are mains-powered.

In addition to the energy meters, a number of *BASe-MultiSense* nodes are used to monitor humidity, temperature, and illuminance. In contrast to the *BASe-Meters*, these nodes are battery-powered and optimized for low-power operation to extend battery lifespan. Battery-powered nodes have the advantage of mobility.

3.2. Software Platform

The WSN solution's software platform can be viewed as comprising two parts: the sensor nodes' firmware dealing with the acquisition and wireless transmission of sensory data, and a gateway software interfacing the sensor network with external IT infrastructures.

3.2.1. Sensor Node Firmware

The sensor nodes' firmware is based on *TinyOS*—an open source operating system for wireless embedded sensor nodes—and the *ConSAS* [4] application layer, which enables the configuration and identification of sensor nodes of varying hardware designs by abstracting from different external sensors and actuators. System parameters, components included, and the routing layer can be configured using a graphical configuration tool.

The *BASe-Meters* are nodes with routing capabilities (routers). A multi-hop collection-tree-based routing protocol was chosen to transmit messages through intermediate nodes to a basestation. In contrast, the *BASe-MultiSense* nodes are so-called sub-nodes, transmitting their sensor values to the next, best-linked (based on received signal strength (RSSI) or link quality indicators (LQI)) router. Sub-nodes are not able to receive messages or act as intermediate nodes. This reduced functionality aims to reduce energy consumption and extend battery lifespan. Using this mode of operation, lifespans of months and even years are attainable, only depending on the sleep current and frequency of measurements and transmissions.

The combination of routers and sub-nodes results in a cluster-tree network topology converging on a central base node. The data received by the base node is forwarded through a serial (USB) interface to a gateway interfacing the WSN with external IT systems.

3.2.2. Gateway Software

A WSN gateway's primary responsibilities include configuring the network, monitoring its status, and obtaining data from the network and forwarding it to external entities.

In the installation being introduced, a compact PC—the *BASe-Gateway*—running a dedicated software serves as gateway. The gateway interfaces with the WSN using a base node attached via USB and is integrated with an existing IT infrastructure via Ethernet (figure 3).

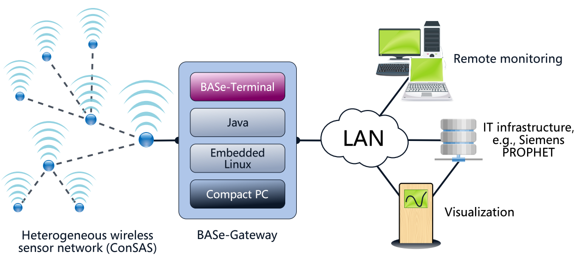

Fig. 3. Overall setup of the installation.

An application termed *BASe-Terminal* runs on the *BASe-Gateway* on top of Embedded Linux and a Java virtual machine (JVM). Additionally, it can also be run on regular desktop PCs, in which case it connects to a software stub (*TinyOS*'s *SerialForwarder*) running on the gateway in order to access the wireless network via the base node. While it offers a GUI when being executed on a PC, the gateway instance runs headlessly.

The *BASe-Terminal* software is a Java application built upon an application framework, the *Gateway Application Framework* (*GAF*). This software framework provides a base application, concepts, and infrastructures for realising the software portion of a WSN gateway. This basis is meant to be easily extensible and customizable to yield an application-specific gateway solution.

Customizability represents an important aspect of WSN gateway solutions as customer requirements may vary significantly, particularly with respect to both functional and data interface requirements. Also, over the course of time, due to both varying requirements (such as indoor vs. outdoor scenarios) and continuing development, a variety of WSN platforms (hardware and protocols) needed to be supported. A customizable, extensible software architecture thus significantly reduces the development efforts incurred from project to project.

The framework's extensibility and customizability are achieved through a number of specific means in addition to established software engineering techniques:

- Dependency injection (via *Google Guice*) is used—mostly for singletons—to make overriding framework classes easy.

- A plugin infrastructure, *JSPF*, is used, i.a., to decouple I/O components from the core of the framework to the greatest extent possible. Within this hierarchy, three types of plugins can be defined: network interfaces for accessing different WSN hardware platforms, data handlers for outputting data to a variety of media (such as files, serial interfaces, TCP/IP, UDP, SQL databases, JMS message brokers, etc.), and output formats taking care of formatting the output (in formats such as CSV, XML, etc.). The concepts for data output allow for both data aggregation and live data transfers to, e.g., data visualization solutions [5]; data handlers and output formats can mostly be combined arbitrarily.

- The framework employs a flexible build infrastructure using *Gradle* in order to create application archives (JAR). In the course of the build process, relevant resources are gathered into a single JAR while unused or undesired resources (such as plugins designated not to be part of a particular application) are excluded.

- Both the framework and all derived applications are thoroughly documented at the source code level. The documentation also explicitly points out how to extend or customize particular aspects. Application development is further facilitated by flexible debugging and logging infrastructures.

When run on a PC, the *BASe-Terminal* application offers a GUI displaying the network topology (as seen in figure 1) overlaid with a floor plan and status information concerning both the nodes and their wireless links. The nodes in the network are also listed hierarchically and in a tabular view displaying the current data reported by the various types of sensors. I/O plugins can be configured interactively, and it is possible to have data exported via several handlers simultaneously.

The framework and three gateway applications currently built on top of it collectively span approximately 105,000 lines of source code (including about 45% documentation), with application-specific code adding on average approximately 20% of code to that provided by the framework—underlining the high degree of reuse.

In the case of the pilot installation at Fraunhofer, the WSN was to be interfaced with a Siemens *PROPHET Solutions* energy management data system. To this end, a corresponding data handler and output format were implemented which output data to files in an XML format. These files are made available to a custom *PROPHET* input component via a CIFS (*Samba*) network share. The interface is request-driven: the *PROPHET* input component instructs the gateway to log the data of a selection of sensors at set intervals during a given period of time. Thanks to the software architecture detailed previously, the additional data interface could be implemented with minimal effort.

3.3. Practical Issues

After setting up the pilot installation at the Fraunhofer AST, both the overall network and the connections among the nodes were monitored and analyzed over an extended period of time. This revealed that some nodes exhibited very poor link qualities communicating with their neighbors and higher packet error rates than others. Almost all of these nodes had to bridge longer distances to their respective next hops. The structure of the building as well as absorption and reflection effects are likely to further contribute to the observed effects. Interference with Wi-Fi networks sharing the location could be ruled out after monitoring the used frequency band using a spectrum analyzer.

A partial solution to this problem consisted in the deployment of additional routers within the critical paths. Nevertheless some nodes continued to disconnect and reconnect intermittently without evident patterns. While this led to discontinuities in the acquisition of data, any particular node would continue to deliver data eventually. Also, thanks to the self-organizing nature of the mesh network, the consequences of a loss of connectivity of singular nodes prevented cascading effects as surrounding nodes were able to choose alternative routes.

Another lesson learned and a direct result of poor network connections was a lower-than-expected battery lifespan of the sub-nodes (up to four weeks at the most). In the original setup, sub-nodes dynamically adjusted their transmit power and had to retransmit route discovery messages in cases of link failures. Bad links could easily cause numerous retransmissions and thus longer operational times and shorter battery life. The sub-nodes were subsequently re-programmed with a modified transmit power adjustment and fewer retransmissions, which resolved the issue.

4. USER REPORT

4.1. Motivation

Within the framework of the project "Smart Grid Research and Development Platform," the Fraunhofer Application Center for Systems Engineering (AST) implemented a "Smart Grid Demonstrator" in enhancement of the *ICT-Energy-Lab* established since 2008 [6]. In addition to various distributed generation units, energy storage systems, and bulk consumers, it also contains systems utilized by private households. These systems include a smart metering system—metering the total consumption of a household and meant to replace conventional electromechanical meters in the future—, smart domestic appliances, and—last but not least—the previously-described distributed wireless sensor network.

This user report deals with the comparison and the mutual completion of smart meters and a distributed in-house metering application, respectively. First of all the common advantages and disadvantages of each system are shown. In addition, concepts for the integration of high-resolution in-house metering in private households into the Smart Grid approach are presented, aiming at a more efficient and sustainable energy usage.

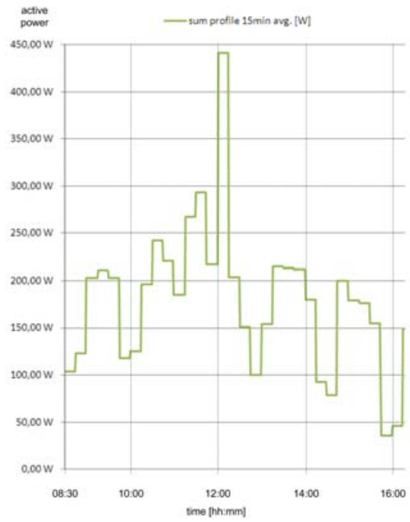

Fig. 4. Sum load profil of active power consumption of various appliances measured by a smart meter (15-minute mean values).

4.2. Smart Metering

As of January 1^{st}, 2010, it is mandatory to install meters able to visualize the consumption in a way appropriate for household residents in new buildings and total reconstructions. The main goal of the legislator is to sensitize residents to matters of energy efficiency and thereby achieve a reduction of the total energy consumption.

Existing solutions commonly visualize the data captured by smart meters via an Internet portal, which requires these data to be aggregated utilizing a wide-area communication network. Doing so, it is very important to guarantee secure data processing and storage to maintain the customers' privacy. To avoid these difficulties, other solutions communicate billing data only. Additional data are stored on a local web server and used to visualize the consumption on an in-house display or a smart phone connected to the local area network (LAN).

Both approaches are only able to meter the total consumption of a household. Conclusions on single appliances are hard to make, as can be seen in figure

4 (green graph). The displayed active power sum curve summarizes the consumption of a PC workstation, a printer, a refrigerator, and a microwave oven. Telling the share of each appliance is not feasible for a normal resident. Also the interval of measurement, a 15-minute mean value, makes the interpretation of the load profile difficult because, e.g., the switching of an appliance is not traceable.

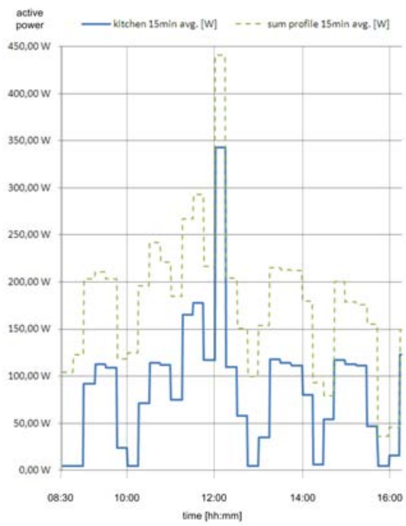

Fig. 5. Load profile of active power consumption of a refrigerator and a microwave oven (15-minute mean values).

In addition to the total consumption, the demand of individual consumers (e.g., workstations and appliances) at the Fraunhofer AST is captured by smart meters. Thus the behavior of the separately-metered consumers is retraceable. Figure 5, for example, shows the consumption of a refrigerator and a microwave oven (blue graph) plugged into the same electrical outlet. The disadvantage of measuring only a mean value at an interval of 15 minutes still remains. Yet equipping every appliance or electrical outlet with a smart metering device is not feasible and a very expensive solution—hence a solution which is cheaper and easier to install is needed.

4.3. Distributed In-house Metering System

A distributed in-house metering system is much better suited for capturing the consumption at different locations all over a household. The sensor system developed by IMMS described earlier in this paper uses a self-organizing wireless network to interconnect electrical outlet adapters and additional sensors distributed across a building and allows the measuring of the consumption of individual appliances or groups of appliances. Based on these measurements, the precise behavior of the different consumers can be analyzed and management strategies can be developed.

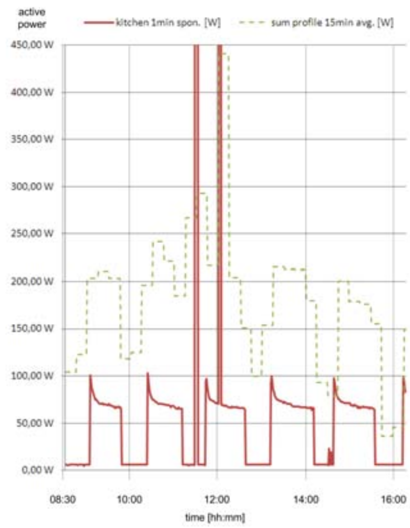

Fig. 6. Load profile of active power consumption of a refrigerator and a mircowave oven (1-minute spontaneous values).

The application implemented at the Fraunhofer AST enables a high-resolution measurement at an interval of one spontaneous value each minute. A shorter interval is also possible but will lead to a reduced lifespan of the battery-powered sensors. The quantity of data captured by these sensors is significantly higher than at the 15-minute mean values captured by a smart meter. Because of this and for reasons of data privacy, the communication of data to an external server is not useful; rather, it is preferrable for the data to remain at the costumer's whose privacy it concerns.

Figure 6 shows the load profile of a refrigerator and a microwave oven (red graph), but in contrast to figure 5 at a sampling time of one spontaneous value each minute. Obviously the profile illustrates the cyclical behavior of the refrigerator's compressor with its 45 minutes phase of cooling followed by 30 minutes of inactivity. The cooling phase starts at a peak power of nearly 100 W and stills to approximately 70 W. Between 11:15 and 11:45 as well as between 12:00 and 12:15, there are very high peaks in the load profile. The peaks represent the microwave oven operating at a power of approximately 1,200 W. It is impossible to extract this information from the 15-minute mean values.

4.4. Future Analyses and Developments

Based on the gained data, the Fraunhofer AST will develop concepts and algorithms for the optimization of the energy demand of private households and commercial buildings. To pick up the topic of the Smart Grid: a promising approach is the aggregation of a large number of consumers and take influence on their total demand to fit the current energy supply [7]. For this it is necessary to increase the degree of automation because common customers are either unable or unwilling to concern themselves with the challenges of in-house energy management.

To this end, smart domestic appliances such as a dish washer, a tumble dryer, and a washing machine have been obtained. Equipped with a communication interface, these appliances can be controlled by an in-house automation system following customer guidelines as well as guidelines given by external players (e.g., the local distribution grid operator or the energy supplier). An embedded PC or a controller unit operates the automation system and features an energy-saving design and a small form factor, enabling it to fit into the switch board.

The foremost aim is an efficient and environmentally friendly utilization of fossil energy sources as well as the sustainable integration of renewables. Therefore it has to be guaranteed that the control and automation systems employed help conserve more energy than they consume themselves.

5. CONCLUSIONS AND OUTLOOK

As has been shown in this paper, a pre-existing wireless sensor network developed at IMMS has been customized for a pilot installation at the Fraunhofer AST. Intrinsics of the WSN platform's hardware and software architecture enabled this with minimum development efforts; in particular, a flexible WSN gateway software architecture allowed for customer-specific extensions and customizations such as an integration with an energy management system.

The actual deployment at the Fraunhofer AST has shown that the functionality of the wireless sensor network depends on the conditions of operation. This means that individual sensor nodes that participate in the self-organizing network may lose their connection unpredictably without obvious changes in environmental conditions. Long-distance connections and the particular structure of a building may result in poor network connections with frequent packet errors. It is possible to reduce some of these effects through the deployment of additional, intermediate nodes. This shows that traditional network planning is necessary prior to setting up the network; automatic coexistence algorithms (such as frequency hopping or blacklisting) may help mitigate these effects further.

However, as no absolute guarantees as to the stability of wireless communications infrastructures can be made, dependent systems will have to take the possibility of temporary failures into account and provide for a certain degree of fault tolerance. In the context of smart (sub-)metering, the occasional loss of individual measurements is tolerable.

The current installation has lower retrofitting costs and achieves a high-accuracy energy metering. The measurement results can be used to create energy profiles, manage and schedule the active time of devices, reduce energy consumption, and reduce electricity costs. Furthermore, the next generation of electric outlets will be equipped with switching units in addition to the measuring equipment. This is needed because not every connected consumer has a communication interface which can be integrated with the home automation system.

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