VILLASMART: Wireless Sensors For System Identification in Domestic Buildings

Alexandru Caracaş, Fabian L. Mueller, Olle Sundström, Carl Binding, Bernhard Jansen
IBM Research - Zurich
CH-8803 Rueschlikon, Switzerland
Email: {xan, fmu, osu, cbd, bja}@zurich.ibm.com

***Abstract*—In this paper, we describe the design decisions, the implementation caveats, and the challenges faced while deploying a special-purpose wireless sensor network (WSN) at a domestic building that is part of a smart grid test environment. The sensor network is designed to collect high-quality data of the building's in- and outdoor climate, heating system, and energy consumption. This rich sensor data is analyzed in order to characterize the building's potential to act as a flexible energy consumer in a smart grid framework. In addition to the functional challenges, a continuous, low-power operation over extended periods as well as a plug&play, non-intrusive installation are required. Moreover, restrictions on the hardware costs and the development-to-deployment time had to be considered. Our simulation-driven application development and our highly modular design proved to be essential in meeting these challenges. This approach and its application to a real-world installation represent the key contributions of this work.**

I. INTRODUCTION

The recent drive to significantly increase the share of renewable energy sources poses many challenges to the existing electric grid. One major challenge is the highly fluctuating production of wind and solar power which requires effective means of dynamically balancing the grid in order to compensate for peak supply and demand.

In the context of the ECOGRID EU [1] project, our focus is on using the thermal inertia of domestic buildings as energy buffers with the goal of balancing the power grid. Domestic buildings do not need to constantly consume energy for heating purposes but can act as flexible energy consumers in the smart grid. However, in order to make the energetic flexibility of domestic buildings predictable and controllable, their energetic behavior needs to be understood and identified. Towards this end, we designed, developed, and installed a modular and extensible wireless sensor network (WSN) in a test and reference household called VILLASMART.

Based on the measurements from the sensor network, we derived and identified a mathematical model describing the energetic behavior of the building. On the one hand, the model needs to capture the fundamental thermal dynamics of the house depending on heat-pump operation and weather conditions. On the other hand, the model has to incorporate the behavior of the heat pump and its internal control system. The model is used to quantify and predict the flexibility of the system. Moreover, typical smart grid control systems rely on model-predictive control schemes when trying to find control signals that are optimal with respect to electricity costs or some objective capturing the grid balancing requirements. The effectiveness and performance of such methods fundamentally rely on the availability and accuracy of appropriate mathematical models.

The remainder of this paper is structured as follows. In Sec. II, we discuss related work combining WSN and model-based approaches in smart grid contexts. Sec. III introduces the VILLASMART test facility and the requirements imposed on the WSN. Subsequently, Sec. IV elaborates on our design decisions considering the given requirements. In Sec. V, we highlight the learning from the actual development and deployment of the WSN. Finally, we describe our approach of deriving and identifying a thermal building model in Sec. VI before concluding in Sec. VII.

II. RELATED WORK

In contrast to industrial building automation, we focus on domestic buildings, where wireless sensors can be used for retrofitting. In the area of home automation, several wireless systems have been developed based on various wireless technologies [2]. More recent efforts [3] include the identification of thermal models for domestic buildings based on temperature data. Our focus is on collecting a richer set of sensor data, e.g. detailed weather and power consumption information, in order to further improve the accuracy of thermal models. This results in more precise predictions and more efficient control.

A good summary on literature about deploying outdoor sensor networks can be found in [4]. Our work adds to the existing best-practices by providing insight into indoor WSN deployment in a real home setting. In addition to the list of "does" and "donts" compiled by [4], we contribute with the following aspects: i) simulation-based application development as a means to decouple and speed-up the software development, ii) hardware integration based on heterogeneous, modular, and extensible components for reducing costs, and iii) built-in management functionality for alleviating deployment efforts.

III. VILLASMART

The VILLASMART home represents the installation environment for our WSN. It is a fully functional and furnished building on the Danish island of Bornholm and is used as a reference home in the ECOGRID EU project [1]. As shown in Fig. 1i, the single-floor building is divided into seven rooms.

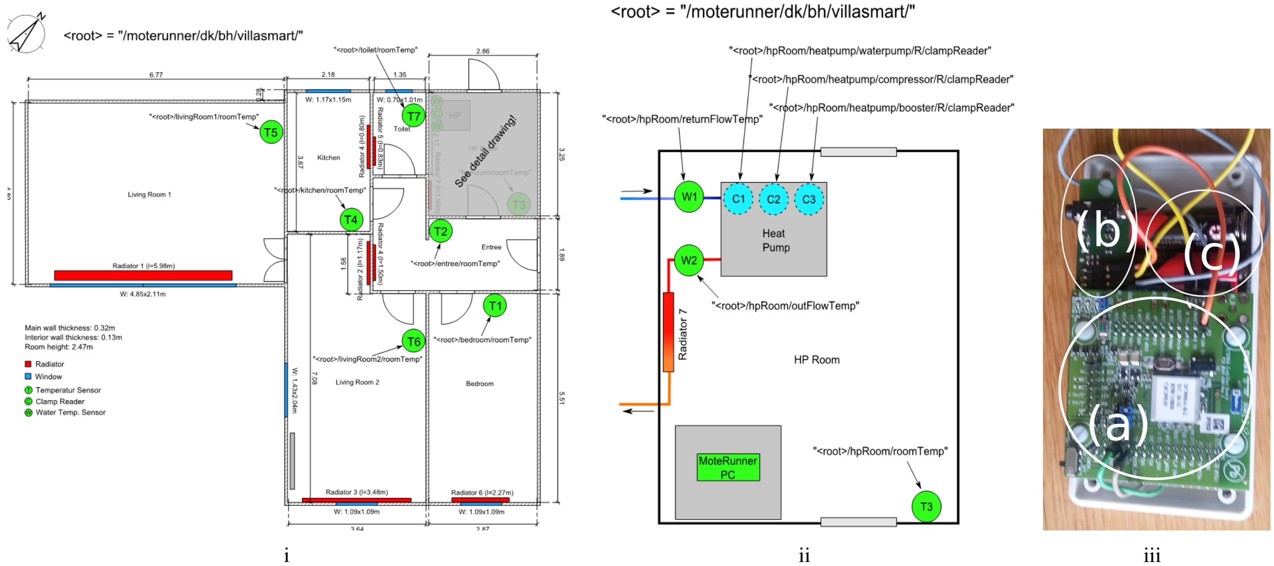

Fig. 1. The indoor sensor deployment at the VILLASMART reference home. The floor plan (i) shows the positions of the air-temperature sensors (T1-T7). The detailed view of the heat-pump room (ii) indicates the positions of the air temperature (T3), water-circuit temperature (W1, W2) and power (C1-C3) sensors. Data streams from each sensor are identified by URIs and are pushed to a messaging broker on a secure channel. Each indoor WSN node (iii) contains a mote (a) responsible for both computation and communication, an optional adapter board (b) for different sensors, and a replaceable AA battery pack (c).

An air-water heat pump heats the boiler water as well as the water of the heating circuit, cf. Fig. 1ii. Photo-voltaic cells on the building's roof enable local power generation.

Prior to our WSN deployment, several technologies ranging from smart meters, thermostats, and actuators, as well as wireless routers and several servers were already installed at VILLASMART. However, the existing sensor infrastructure does not provide the level of detail required for the identification of our thermal models. However, the existing ICT uses WiFi, Z-Wave, or ZigBee as a means of communication, which compete with our WSN for the wireless spectrum.

Our WSN infrastructure at VILLASMART comprises air and water temperature sensors[1], power sensors[2], a solar radiation sensor[3], as well as an outdoor weather station[4]. In addition to the monitoring capabilities, remote actuation allows to control[5] the operational state of the heat pump.

IV. DESIGN DECISIONS

To meet the rapid development schedule and a limited hardware budget, we relied on a heterogeneous set of both off-the-shelf and custom-built components. To enable the parallel development of hardware and software as well as a modular deployment, the WSN was designed as two independent, complementary sub-networks satisfying the different requirements for indoor and outdoor installation. An embedded PC, located in the heat-pump room, cf. Fig. 1ii, serves as the gateway between a secure, broker-based messaging service and the two wireless networks. The model analysis and the control logic interact with the WSN through queues provided by the messaging broker.

A. Note on Wireless Communication

The indoor and outdoor sub-networks have different requirements in terms of wireless communication and protocols. However, irrespective of the protocol, the common denominator for the physical layer and frame format is the well-established IEEE 802.15.4 standard in the 2.4 GHz[6] ISM band.

In a neighborhood, weather data is valid for the individual models of several households. Thus, the communication range of the outdoor sensors should cover a few hundred meters. A larger range also means that the outdoor network does not require a mesh topology. In this case, a star topology is easier to maintain and is more energy efficient as data rates are relatively low. Consequently, a carrier sense multiple access (CSMA) network protocol is well suited for this purpose.

By contrast, adjacent homes should be treated individually in terms of thermal behavior. Thus, the communication range of indoor sensors should cover only a few meters. Walls and metal enclosures disrupt wireless links. For this reason, a mesh topology is required for covering the entire house. In addition, the sampling rates of the indoor sensors are significantly

[1]Air and water temperature as well as power consumption exhibit fast dynamics and are, thus, sampled every 10 s.

[2]The power sensors should allow for a non intrusive installation. For this purpose, we use split-core current transformers (or clamp readers).

[3]On sunny days, the amount of solar radiation, when entrapped via large windows, can significantly influence room temperatures and is thus sampled in 30 s intervals.

[4]The dynamics of weather data are of minor importance. It suffices to sample in 2 min intervals for outdoor temperature, humidity, barometric pressure, wind speed, wind direction, and rain volume.

[5]For safety considerations, a local watchdog allows the heat pump to operate based on its own internal control if no external control was received for a certain time period.

[6]Using the 868 MHz band to escape the interference in the 2.4 GHz band introduces additional challenges. A lower frequency offers greater range, which increases the risk of interference between indoor networks from multiple homes. Furthermore, depending on the encoding, the bandwidth for the 868 MHz may not suffice for higher sampling rates.

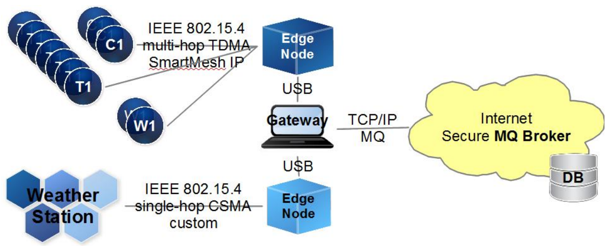

Fig. 2. Architectural overview for the WSN deployment.

higher. We employ an energy-efficient time division multiple access (TDMA) network protocol to meet the long life-time requirements while maintaining the higher sampling rates. Fig. 2 shows an overview of our system architecutre.

B. Choosing Off-the-shelf Hardware

To support a large variety of sensors, cf. Sec. III, it is desirable to have WSN nodes that easily integrate sensors and adapt to future modifications. As temperature is one of the key parameters for the thermal models, it is crucial to use the same sensing element for measuring both air and circuit-water temperature. For this purpose, digital and factory-calibrated sensors are an appropriate choice. We used a breakout board [5] of the TMP102 sensor which is sufficiently accurate and can be integrated using the I^2C bus.

For the indoor network, we selected the Linear nodes [6] to meet the communication and sensor requirements. They provide direct access to digital and analog GPIO pins, which facilitates integration. However, the nodes require custom indoor housing, cf. Fig. 1iii, for protection.

In contrast, all the electronic components for the outdoor network demand protection (according to the ingress protection standard the appropriate rating is IP67) against dust and water while being unobtrusive to the sensing elements. We mainly rely on Waspmote nodes [7] to collect weather data. The nodes provide a long range XBee radio, cf. Sec. IV-A, and appropriate housing for sensors, cf. left-hand side of Fig. 3.

Finally, the solar radiation sensor, cf. right-hand side of Fig. 3, is a low-cost custom design based on readily available components. The short-circuit current produced by the photovoltaic panel (d) is analyzed and converted by a corresponding WSN node (e). We relied on a high-end pyranometer for calibrating the conversion values.

C. Common Functionality for Sensor-specific Applications

In general, each WSN node runs a custom software application[7] tailored for sampling and processing the data from the attached sensor(s). Abstracting from the particularities of each sensor, a set of common functionality is required across all applications for maintenance reasons.

To ease deployment, all applications should provide information and statistics about the network topology, the quality of the wireless signals, and the battery level of the WSN nodes.

[7]The power sensing application is one example. It collects ADC samples at 2 kHz for all the three AC phases. The samples are collected for at least 80 ms to cover 4 periods of 50 Hz AC. Subsequently, the application computes the root-mean-square (RMS) of the voltage. The resulting consumed power is sent as a report every 20 s together with other statistics.

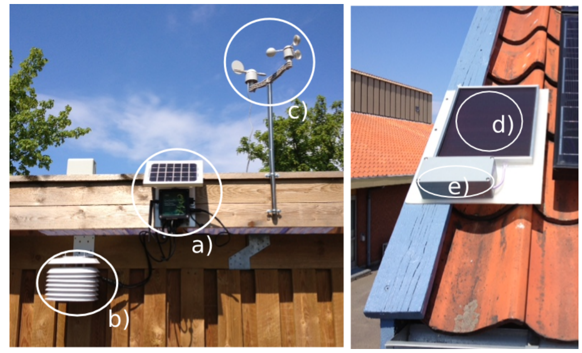

Fig. 3. The outdoor WSN at VILLASMART encompasses two nodes. The left-hand node (a) is installed in the courtyard and connects to the temperature, humidity, and barometric pressure sensors (b) and the wind speed, wind direction, and rain gauge sensors (c). The right-hand node is a custom solar radiation sensor (e) installed on the roof of the house, facing southwards.

The ability to reconfigure parameters at runtime is another important common functionality. This allows us to select different sampling rates, thresholds, buffers, and aggregation algorithms.

Anticipating future requirements, the sensor nodes should allow for over-the-air remote application maintenance, e.g. the loading, updating, and deleting of entire applications. Automatic energy management [8], e.g. powering off unused modules, is required for extended periods of operation on the initial set of batteries. In our case, these maintenance and management functions are provided by the Mote Runner [9] OS/VM running on the WSN nodes.

V. Development and Deployment Challenges

In the following we highlight the challenges faced during the development, testing, and the deployment of our WSN. As early on as possible, for a period of three months, we mimicked the actual deployment with a constantly-running testbed. The testbed was extended gradually to the full WSN as hardware components became available.

A. Writing The Software Without The Hardware

Due to procurement delays and a tight schedule, not all the required hardware components were available during the development phase. Even worse, many of the actual sensing elements were missing. In order to make progress with development it was vital to simulate the operation including warm-up times, communication, e.g. I^2C commands, and the reading of sensor values. The hardware specifications provided the details for the script-based simulation within the Mote Runner environment [9].

When compared to other WSN simulations, such as COOJA [10] and Avrora [11], our simulation environment is able to execute the same application code as is run on the actual hardware. Consequently, no source code modifications were required when moving from simulated to real WSN nodes. Moreover, this enabled us to inspect and debug the distributed WSN from within the simulation environment while executing directly against back-end systems. Thus, we were able to integrate the code for the database and message queues early in the development process.

B. Providing Protection for the Future Integration

An important aspect of any sensor network is the housing. It protects the electronic components from irreparable damage caused by transportation, handling, and operation.

At the same time, the housing should be flexible and allow for integration of different types of sensors. Irrespective of the attached sensors, all our indoor nodes use the same fire-repellent and shock-proof housing, cf. Fig. 1iii, which simplifies manufacturing. A sufficiently large aperture offers the flexibility to connect different sensing elements. For our current deployment, we attached up to three current transformers via TRS audio jacks, and temperature sensors via I^2C.

C. Communicating in Spite of Interference

One of the biggest challenges we faced during deployment was the wireless communication in the 2.4 GHz band. As described in Sec. III, the wireless medium is shared with existing infrastructure. To avoid collisions with other equipment, we opted for a channel-hopping, TDMA-based protocol [6] for the indoor WSN. The outdoor WSN is experiencing less interference and a CSMA-based protocol provides a viable solution in this case.

However, the CSMA approach worked well only for the weather station, cf. Fig. 3, which has enough transmission power available. In case of the solar sensor, a significant number of messages were lost due to a less powerful transmission and the vicinity of other equipment causing interference. Consequently, the solar sensor was reconfigured to act as a leaf node attached to the indoor TDMA network. This could be easily changed because of our flexible network and hardware design, cf. Sec. IV-B.

D. Anticipating the Extra Steps of Installation

Most of the installation steps, such as connecting current transformers and sensors, could be rehearsed in our testbed. In one such rehearsal, we were able to find and fix an intriguing mounting issue concerning the water-pipe sensors. The sensors have to be in physical contact with the pipe for accurate readings. However, improper mounting to the metal pipes caused sporadic short circuits leading to a node reset or a wrong behavior in the network protocol. An improved mounting design solved this issue.

Eventually, additional steps were required during the actual installation at VILLASMART. These steps could not be rehearsed beforehand. The current transformers required the special assistance of an on-site electrician to access the internals of the heat pump. The heat-pump enclosure turned out to be a Faraday cage and, thus, the corresponding WSN nodes sensing the power consumption had to be mounted outside of it. Additionally, the water pipe sensors are also placed on top of the heat pump, cf. Fig. 4. Such installation steps require extra flexibility in terms of both hardware and software, in particular when frequently attaching and reattaching sensors and cables, the WSN is expected to continue its operation.

During installation, unexpected situations can and will occur. For example, our outdoor temperature sensor suddenly

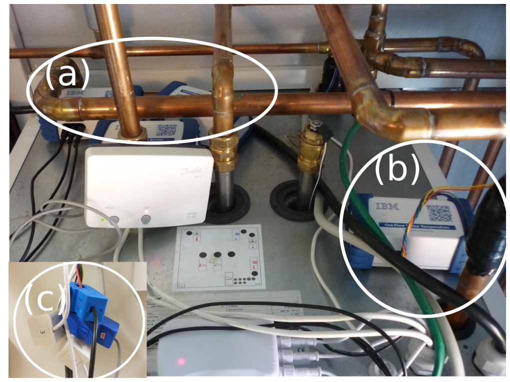

Fig. 4. The complexities of an actual installation as reflected by the heat-pump enclosure. Our WSN nodes (a,b) share space with existing infrastructure. The water-temperature sensors (b) are mounted directly to pipes. The current transformers (c) are attached to power lines inside of the enclosure.

failed during deployment. The same sensor had been working flawlessly on the first installation day. We later found that the failure was caused by excessive mechanical strain on the cable connecting the sensing element. This strain occurred when inserting the sensor into the solar shield. At a later stage, a replacement temperature sensor was shipped and installed. In spite of the sensor malfunctioning, the entire WSN was operational at all times, which shows the robustness of the modular approach.

VI. SYSTEM IDENTIFICATION AND EVALUATION

The main purpose of the WSN installed at VILLASMART is to provide the measurement data required for constructing and identifying a thermal model of the house as well as to give insight into the operation of the heat pump. In this section, we present initial results on the modeling of the thermal behavior of the house that was conducted based on sensor data.

A. Thermal Model of VILLASMART

The total thermal energy of VILLASMART, cf. Fig. 1i, is assumed to be stored in only two distinct energy buffers. The heavy structure of the house comprising walls and floor is defined to be the first energy buffer and contains the biggest portion of the house's energy. The second, much smaller energy buffer represents the energy stored in the building's heating circuit including the heating water itself, the water pipes, and the heating devices (radiators).

The behavior of thermal energy buffers as well as corresponding heat inflows and outflows can be conveniently described by means of a standard resistance-capacitance (RC) model as depicted in Fig. 5. Many other RC networks have been proposed to model the thermal dynamics of building, see e.g. [12], [13].

Our model consists of the two energy buffers mentioned above and represented by the capacitors C_1 and C_2 in Fig. 5. The corresponding energy levels are given by the temperature of the building's heavy structure, T_w, and the heating circuit temperature, T_c, respectively. Energy can flow from one buffer to the other only via the house's internal air, whose temperature T_{air} is an algebraic function of the two

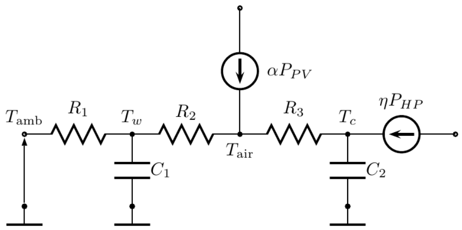

Fig. 5. The thermal model as an equivalent electric circuit.

buffers' energy levels. Conductive and convective heat flow resistances, lumped in R_1, R_2 and R_3, govern the exchange of energy between the house's solid structure and the in-/outdoor air, as well as between the radiators and the indoor air. For simplicity, the energy supply to the heating circuit is assumed to be directly proportional to the heat pump's power consumption, P_{HP}, where η is the proportionality factor. The energy influx due to solar irradiation is approximated by the power produced by the solar panels, P_{PV}, multiplied by a constant α. Measurements suggest that the solar energy should directly affect indoor temperature rather than the house's heavy structure. The thermal dynamics of the structure are too slow compared to the indoor air temperature that reacts to solar irradiation almost instantaneously.

Using Kirchoff's current law, we can derive the differential equations describing the thermal dynamics:

$$\frac{d}{dt}T_c(t) = \frac{-1}{C_2(R_2+R_3)}T_c(t) + \frac{1}{C_2(R_2+R_3)}T_w(t) + \frac{\eta}{C_2}P_{HP}(t) + \frac{\alpha R_2}{C_2(R_2+R_3)}P_{PV}(t) \tag{1}$$

$$\frac{d}{dt}T_w(t) = \frac{1}{C_1(R_2+R_3)}T_c(t) + \frac{-(R_1+R_2+R_3)}{C_1R_1(R_2+R_3)}T_w(t) + \frac{\alpha R_3}{C_1(R_2+R_3)}P_{PV}(t) + \frac{1}{C_1R_1}T_{amb}(t)\,. \tag{2}$$

By considering $[T_c(t), T_w(t)]^T$ as the state, $[P_{HP}(t), T_{amb}(t), P_{PV}(t)]^T$ as the input, and $T_{air}(t)$ as the output of the system, the dynamics (1)-(2) can be written as a linear time-invariant state-space system. The model's unknown parameters are the lumped heat flow resistances R_1, R_2 and R_3, the energy buffer's heat capacities C_1 and C_2, as well as the proportionality constants α and η.

B. Model Identification and Evaluation

Given the model (1)-(2), the goal of the system identification is to estimate the unknown model parameters based on data of the system input $u(\cdot)$ provided by the WSN.

We used a gray-box estimation routine of MATLAB's *System Identification Toolbox* [14] to calculate an estimate of the model parameters. Once the values for the parameters are known and an initial state $x(0)$ has been chosen, the system can be simulated and validated.

Fig. 6 compares the measured indoor temperature to our model predictions over a period of approximately 3 days. The maximum prediction error is $1.79°C$.

VII. Conclusion

Indoor and outdoor WSN are essential in future smart homes that are acting as flexible energy consumers in the power grid. The sensors provide the required information based on which energetic models of domestic buildings can be derived, identified, and evaluated. Accurate models are used to predict a system's energy consumption and the potential of balancing in the power grid. Moreover, models lie at the core of many predictive control schemes.

In this paper, we showed that a modular ICT design and a simulation-driven WSN approach offers the required flexibility and robustness for a successful deployment. Our solution can be easily integrated in newly-built homes and, alternatively, can be used to retrofit older homes. Furthermore, the practical experiences presented in this paper can be extrapolated and serve as a guide for improving future WSN deployments in smart grid contexts.

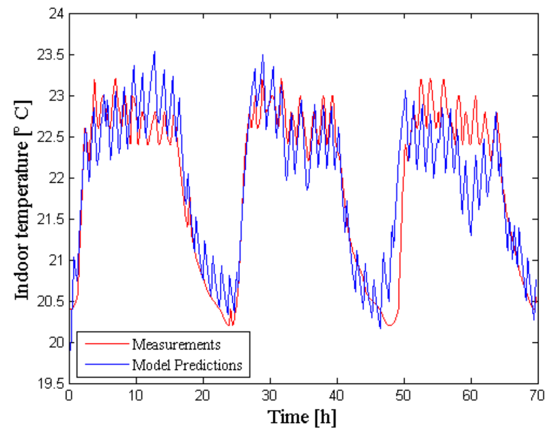

Fig. 6. Comparison of indoor air temperature measurements and model predictions over a representative period of approximately three days.

References

[1] EcoGrid EU, http://www.ecogrid-eu.net.

[2] L. Liang, et.al., "Design and implementation of wireless smart-home sensor network based on ZigBee protocol," in *ICCCAS*. IEEE, 2008, pp. 434–438.

[3] C. A. Carmody and T. O"Mahony, "System identification of a domestic residence using wireless sensor node data," in *MED*. IEEE, 2009, pp. 987–992.

[4] G. Barrenetxea, et.al, "The hitchhiker's guide to successful wireless sensor network deployments," in *SENSYS*. ACM, 2008, pp. 43–56.

[5] Sparkfun, https://www.sparkfun.com/products/9418.

[6] Linear, http://www.linear.com/products/smartmesh_ip.

[7] Libelium, http://www.libelium.com/products/plug-sense/.

[8] A. Caracas, et.al., "Energy-efficiency through micro-managing communication and optimizing sleep," in *SECON*. IEEE, 2011, pp. 53–63.

[9] Mote Runner, http://www.zurich.ibm.com/moterunner.

[10] F. Osterlind, et.al., "Cross-level sensor network simulation with COOJA," in *LCN*. IEEE, 2006, pp. 641–648.

[11] B. Titzer, et.al., "Avrora: Scalable sensor network simulation with precise timing," in *IPSN*. IEEE, 2005.

[12] J. H. Kämpf and D. Robinson, "A simplified thermal model to support analysis of urban resource flows," *Energy and Buildings*, vol. 39, no. 4, pp. 445 – 453, 2007.

[13] Z. O'Neill, et.al., "Model-based thermal load estimation in buildings," in *IBPSA*, 2010, pp. 474–481.

[14] "Mathworks MATLAB system identification toolbox," http://www.mathworks.com/products/sysid/index.html.