POVOMON: an Ad-hoc Wireless Sensor Network for Indoor Environmental Monitoring

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***Abstract*—Wireless Sensor Networks (WSN) are a versatile technology that offers the ability to monitor real-world phenomena in detail and at large scale in scenarios where wired infrastructures are inapplicable or expensive. In this paper we present an ad-hoc WSN deployment for indoor environmental quality monitoring in office buildings. The indoor environmental quality and balance between inhabitant comfort level and power demands are the main objectives of this network. The presented system consists of 19 sensor devices continuously measuring vibration, temperature, humidity, light, and carbon dioxide levels in working areas. The power load of the building is measured by dedicated current sensor devices. Preliminary laboratory tests and data sets collected during 4 months of real world operation show that our system provides an accurate monitoring of indoor environmental parameters delivering high data reliability with an estimated lifetime exceeding 1.5 years, without the gas sensors. The paper presents the HW/SW architecture, the network infrastructure of the deployment and analyzes real measurement data.**

I. Introduction

Wireless Sensor Networks (WSNs) are commonly recognized as a versatile technology that offers efficient and easy-to-deploy facilities for monitoring applications [1]. Autonomous, self-powered and wire-free devices (nodes) can be distributed over a broad space providing large amount of real-time data while operating for a long period of time (up to several years). The key features and connectivity of WSNs enable users and researchers to easily access the data and experiment with various configurations of the sensing infrastructure.

In this paper we present an ad-hoc wireless sensor network developed and deployed at the Department of Information Engineering and Computer Science at the University of Trento. This network, named POVOMON, performs real-world, long-running monitoring of indoor environmental quality and conditions in the office building. The efficiency of the heating, ventilation, and air conditioning (HVAC) system, information about the presence of people, and the energy consumption of the building are the main subjects for analysis of the presented deployment. The ultimate aim is to infer occupant comfort level based on the indoor climate conditions, assess HVAC efficiency and unwanted heat loss, and eventually find the optimal balance between the former two.

Monitoring of environmental and physical quantities in civil buildings has been an extensive research topic for more than ten years [2], [3], [4]. Most research focuses on appropriate sensor placement [5], allowing the networks size and sensor redundancy to be minimized, and reduce overall system cost. We address the complementary aspect of providing long-running monitoring in the most inhabited areas of the building and collect comprehensive sensory data sets inferring indoor ecology and people comfort level over a long period of time (different seasons of the year). Currently, the POVOMON network consists of 19 sensor devices placed in the corridors, working and rest areas. In our system we utilize a rich set of cutting edge (off-the-shelf) sensors that allow us to go beyond classic temperature analysis. The presented deployment provides monitoring of ambient humidity, temperature, illumination, carbon dioxide (CO2) and methane gas level, and vibration (acceleration). Additionally, monitoring of the building load and power utilization is performed by dedicated current sensors attached to the power lines. This will allow us to correlate power demands with indoor atmosphere conditions and habitat comfort. Extra node metrics, such as peer to peer signal strength (RSSI), link quality, nodes residual battery level and packet loss statistics are collected in order to assess the performance of the WSN.

The network topology and communication architecture is developed for a long-term operation with minimal level of power consumption. The most important design factors that were addressed in this project included high reliability of network communication, tolerance to existing WLAN infrastructure, real-time access, and visualization of sensory data history. All sensory data gathered by the system are persistently stored in a database. Access to this information is provided by an interactive web-based graphical user interface that displays the current network topology and data logs for each individual sensor device. This information is publicly available and can be accessed at http://povomon.disi.unitn.it. Based on 4 months of deployment operation, we can conclude that POVOMON delivers high communication reliability, accurate and comprehensive sensory data representation, and minimum level of power consumption. Excluding the contribution of the gas sensors, the predicted network lifetime is 520 days that is confirmed by real-life experiments and simulations.

The paper is organized as follows. After reviewing the related work in Section II, Section III introduces the experimental WSN platform presenting the hardware architecture and sensor devices. The application, communication protocol and the network infrastructure are reported in Section IV. Finally, we evaluate the performance of the sensor network in Section V, by presenting measurements for various quantities.

II. Related Work

Environmental monitoring has been traditionally one of the main application fields for wireless sensor networks [6], [7], [8], [9]. For more than a decade, a wide range of real world deployments have been developed and presented by

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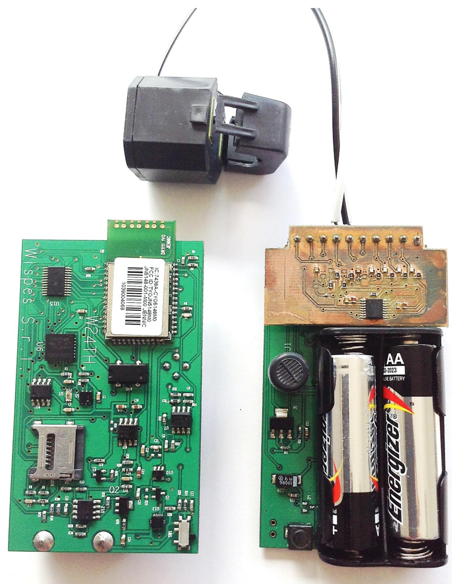

Fig. 1. W24TH node platform with current and gas sensors (top and bottom)

the WSN community [2], [3], [4]. Beutel et al. [1] give a comprehensive overview of the most prominent wireless sensor network installations deployed in the period from 2002 to 2008. Additionally, the authors focus typical real-life problems and issues encountered during WSN design and deployments in a real environment. In this section we focus specifically on recent WSN monitoring deployments and research areas related to indoor climate monitoring and control.

Rodriguez et al. [10] present a small-size network consisting of 10 nodes that was developed for environmental conditions monitoring (temperature and humidity) in a data center building. This deployment was designed to study and mitigate the challenges of cooling the environment in datacenter, and optimize the HVAC performance. The obtained results revealed significant temperature variation in different data center areas. Some zones were cooled too much while others were overheated. Similarly, Bhattacharyaet al. [11] present a small-size deployment for indoor air quality analysis. Various air quality parameters, including gases (CO, CO2), aerosols (PM2.5, PM10) along with other environmental quantities like temperature and humidity were collected.

Methods for optimal sensor placement have been widely studied for enhancing coverage, minimizing network redundancy, installation and overall system costs. For instance, Jaeseok et al. [5] demonstrate a method for placing and minimizing a number of sensor nodes in a network for environmental applications. The network consists of 13 ZigBee-based sensor nodes running for a one week period. Measured quantities included temperature, humidity, and illumination in indoor environment. In order to reduce the number of nodes needed in the deployment, the authors grouped the sensor nodes into coherent clusters, and selected a representative node with maximum RSSI level in each cluster and then removed neighboring sensors. The final deployment used only 6 nodes, while the monitoring accuracy decreased by only 13 percent, compared to the initial setup with all 13 sensor nodes in place. Similarly, Gouy-Pailler et al. collected a temperature data set for 10 days from 25 sensor nodes installed in a house and calculated distance and similarity measures for sensor selection in highly instrumented buildings [12]. The authors present a method to organize data into coherent clusters based on distance and similarity measures from homogeneous and heterogeneous sensors. These clusters can be used for dimensionality reduction by representing cluster of sensors as a single virtual measurement.

Hardware platform design for an extensive indoor air quality monitoring [12], [13] is widely represented research topic in the literature. These offer energy efficient low-cost heterogeneous sensor devices for various environmental quantities. A number of commercial products are also available for indoor climate analysis, power control and energy optimization. The most popular products on the market to date include EcoWizard by XBow, e-Homewireless system by e-Home Automation and ioBridge.

Several factors distinguish our work from the existing literature. First, we provide data on the collected indoor environmental quantities over a long time period. Importantly, this data is made available to third parties through a user friendly web based application for easy access and further analysis and research. The deployment incorporates a number of non-conventional sensors. Advanced sampling techniques are being investigated to achieve long term operation for these specialized, power hungry, measurements.

III. System architecture

The system and application requirements demanded us to utilize nodes featuring low-power consumption, an extensive set of integrated peripherals components and a customizable sensory configuration. We have used the Wispes W24TH node platform[1], shown in Figure 1. The core of the platform is based on the Jennic NXP JN5148 SoC, which incorporates a 32-bit high performance RISC processor and a 2.4 GHz IEEE802.15.4/ZigBee PRO complaint transceiver module inside a single chip. Peripherals include several timers, ADC and DMA channels, DACs and a number of serial interfaces. Integrated low-power features such as scalable CPU clock speed, multiple power-down modes and individually selectable peripheral components make this platform an attractive hardware solution for a wide range of WSN applications.

The W24TH board power sub-system includes an energy source (2 AA-size batteries), a step-up DC/DC 3.3V converter and a battery level control loop. The power management subsystem is designed to provide facilities to separately switch off on-board components, enabling ultra-low power consumption (8 μA MCU in a deep sleep mode). The sensory subsystem consists of on-board digital sensors, which include a $\pm$6g 3-axis accelerometer (LIS3LV02DQ), an ambient light sensor (BH17), and a temperature-humidity sensor (SHT21). In addition, the platform can be equipped with replaceable analog modules for MOX gas sensor for VOC, O3, NOx, NH4, CO, and CO2 measurements, and non-invasive current sensors. This modular architecture allows us to configure individual sensor nodes based on the location and information of interest.

The software application is based on the available platform-native API framework. The application running on the sensor

[1] http://www.wispes.com

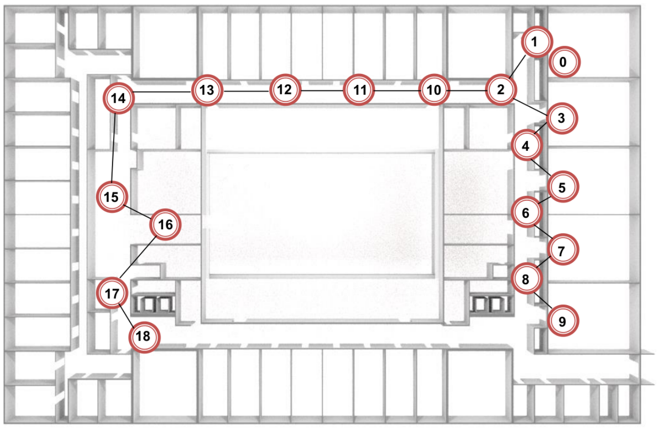

Fig. 2. POVOMON topology

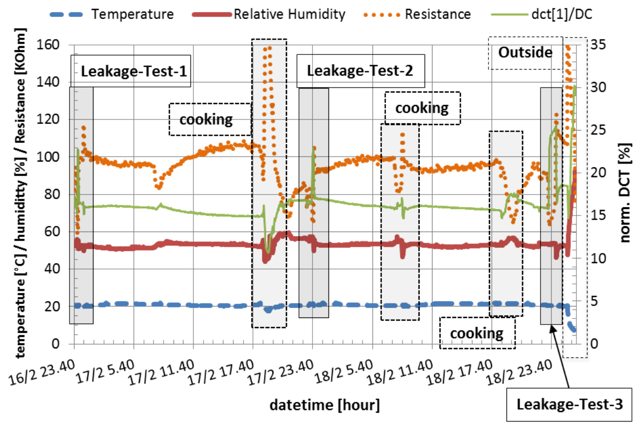

Fig. 3. Evaluation of gas sensor measurements

nodes implements various sampling algorithms for different types of sensors. Temperature, light, humidity and gas conditions are measured once every 5 minutes, which is also the period between two communication events. Conversely, acceleration and current sensors are sampled continuously within the same period of time. The acceleration information of interest includes minimum, maximum and mean levels of vibrations detected in the period between two consecutive communications. For the current sensor, we have implement an Equivalent-Time sampling algorithm in order to obtain the effective (RMS) value of the electrical load over the same time interval, without having to keep the node continuously in the on state.

IV. Deployment

We deployed our network on the office floor of the university building, which is a typical indoor environment with shared 2.4Ghz ISM radio band, and substantial RF reflection due to walls and occupants action disturbances. The network topology (deployed February 2014) consists of 19 sensor nodes distributed on one floor of the building (60 by 40 meters). Nodes are placed in working areas (doctorate students open spaces), corridors, kitchen and chill areas as showed on Figure 2.

The network implements a hierarchical two-branch communication topology where each individual node is connected only to its closest neighbors as depicted on Figure 2. Lines represent logical connections and hierarchy between nodes. It should be noted that the nodes output power and sensitivity levels would allow them to be connected to more than one node. This allows us to add new sub-branches to the network without applying changes to the existing topology, and increases the network reliability.

The communication protocol is designed on top of the IEEE802.15.4 standard extended with an ad-hoc TDMA-based communication algorithm [4], designed to achieve an efficient multi-hop data passing on tree-based topologies. Communication between nodes is enabled during short periods at regular time intervals known as Frame Intervals (FI). Data packets from the most distant nodes are passed to the central data gate (node 0) throughout a set of intermediate nodes. Each node acts as a data router and as parent for the nodes with higher id number in a branch. The key part of the communication model is an inter-node time synchronization that gives a global time reference and prevents inherited nodes clock drift. Specific messages (beacons) containing global time are broadcasted periodically by the central node and propagated throughout the network to align node clocks. When not communicating, nodes keep radios in low power mode, perform sensing routines and spend the rest of the time in dormant state waiting for the next network event. The distance between nodes in the deployment ranges from five to fifteen meters depending on the proximity to WLAN routers that interfere and corrupt nodes signal. Additionally, in order to prevent accidental physical damage, all the nodes are placed inside a plastic enclosure and attached to the walls at a height of 2 or 2.5 meters.

All sensory data gathered by the sink node (node 0) is persistently stored in a SQL database. Access to this information is provided by an interactive web-based graphical user interface that displays the current network topology and data logs for each individual sensor device. All sensory data is displayed in real-time and can be exported in various formats including CSV format. The project website is available at http://povomon.disi.unitn.it.

V. Evaluation

In this section we evaluate the core system components and study their performance in a real world installation. The accuracy of the air quality monitoring is studied by carrying out experiments in the lab and real-world environments. Network performance is assessed by analyzing RSSI level deviation, packet loss ratio and nodes energy consumption. Our analysis is based on the preliminary lab tests and 4 months of network operation.

A. *Air Quality Monitoring*

We begin with the evaluation of the air quality monitoring, which is the core function of our system. Monitoring air quality is made problematic by the typical high power consumption of the sensors, which adversely affects the node lifetime. We address this problem with embedded chemoresistive (MOX) sensors, targeting CO, VOCs and Natural Gas monitoring,

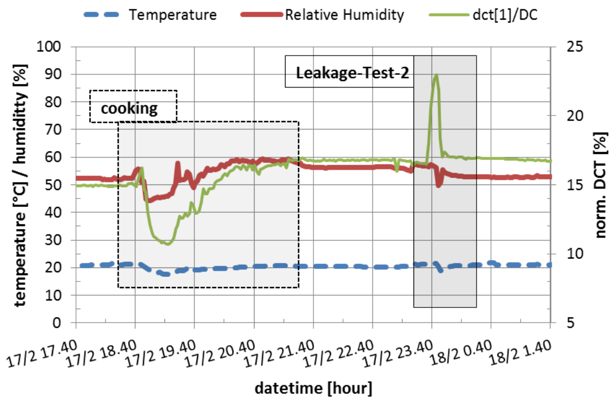

Fig. 4. Second leakage test using the `DCT[1]/DC` algorithm

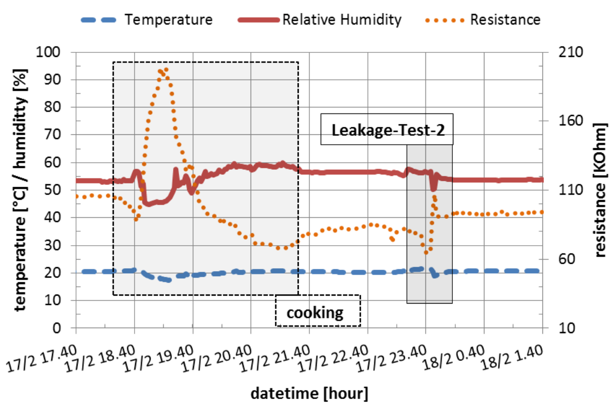

Fig. 5. Second leakage test with standard sampling technique

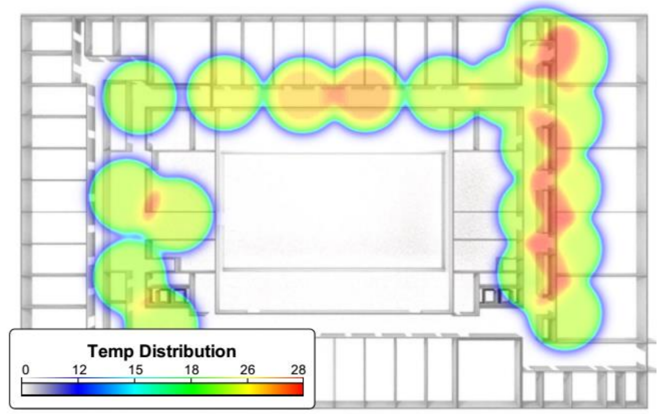

Fig. 6. Temperature heat map

which are of particular interest for Indoor Air Quality (IAQ) assessment. Chemoresistive sensors exploit a reversible chemical reaction, triggered by heat, which results in a variation of their inner resistance. MOX sensors take a few seconds to heat-up and reach a steady signal response, so their energy consumption is very high (e.g., AS-MLK requires 41 mW for at least 5 seconds). On the other hand they are robust, lightweight, they exhibits low cross sensitivity to non-target volatiles compounds and they have very long lifetime without maintenance nor refilling of reagents, which are winning features for WSN applications.

In order to reduce the power consumption, we have used and tested non-conventional sampling and processing strategies, introduced in our previous work [14], [15]. The idea is to reduce the amount of energy required to perform a measure by limiting the time the sensor is switched on (from 5 to 0.5 s). The volatile compound concentration is assessed using a Discrete Cosine Transform (DCT) based algorithm (denoted as `DCT[1]/DC`) that processes the variation of the resistance during the transient sensor response. We tested the performance of this technique - using the same AS-MLK[2] sensor targeted to Natural Gas - in a real kitchen using three of the wireless nodes presented above. We report the case where a measure is collected every 2 min to compare with the characteristic response in [14]. Figure 3 shows the temperature, relative humidity and natural gas concentration evaluated as `DCT[1]/DC` measured by one node, and ground truth (as sensor resistance) measured by another node using standard sampling (5 sec sensor switch on time). The two nodes where placed next to each other, 5 meters from the gateway node (the third). We performed three tests of controlled gas leakages using a custom sealed chamber - containing nodes, placed on top of a kitchen's gas nozzle - while standard kitchen activities (e.g., cooking) were taking place. In the final part of the test we placed the node outdoors, to test the speed of the sensor response to abrupt concentration changes.

Due to space limitations, we report the details of the second leakage test only (the other cases are similar), shown in Figure 4 for the `DCT[1]/DC` algorithm, and Figure 5 for the conventional sampling technique. In both cases, all the reported parameters change simultaneously during standard activities (cooking in this case): a change in temperature and relative humidity (RH) results in a decrease of the `DCT[1]/DC` response and in an increase of the resistance, in accordance with the sensor characterization. In case of natural gas leakage, instead, the `DCT[1]/DC` (Fig. 4) and the resistance (Fig. 5) change earlier than temperature and RH. This is due to the cleaning of the sealed chamber (used to simulate the leakage) since fresh air is injected 10 minutes (5 gas samples) after the gas. Finally, we observe that the `DCT[1]/DC` response is more stable (less variations due to other activities) than the resistive response.

These results show that it is possible to obtain an immediate feedback on the air quality. The adoption of the `DCT[1]/DC` algorithm allows us to greatly reduce the power consumption, and increase the lifetime of the node from 3 to 6 months, using a 5 min. sampling period. Despite these encouraging results, further work is therefore necessary before gas sensors can be integrated in the current deployment, to maintain an overall balance in the network and avoid point failures.

Our network setup is able to provide instantaneous data on temperature and humidity, which is useful in evaluating the HVAC efficiency over time. As an example, Figure 6 displays an instantaneous snapshot of the temperature condition in the building, in the form of a heat map. Similarly, humidity distribution at the same time instance is shown on Figure 7. It

[2]https://www.appliedsensor.com/

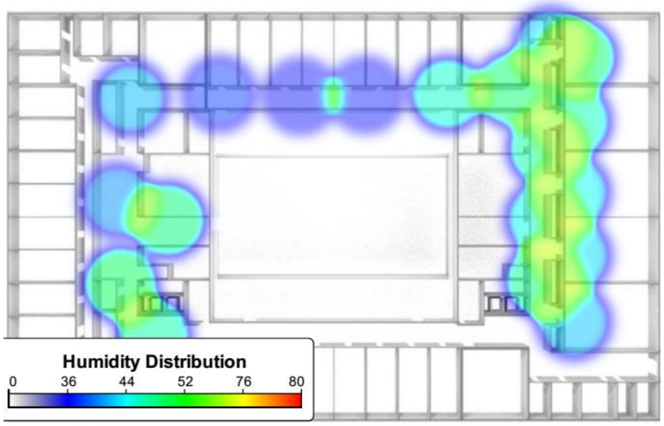

Fig. 7. Humidity heat map

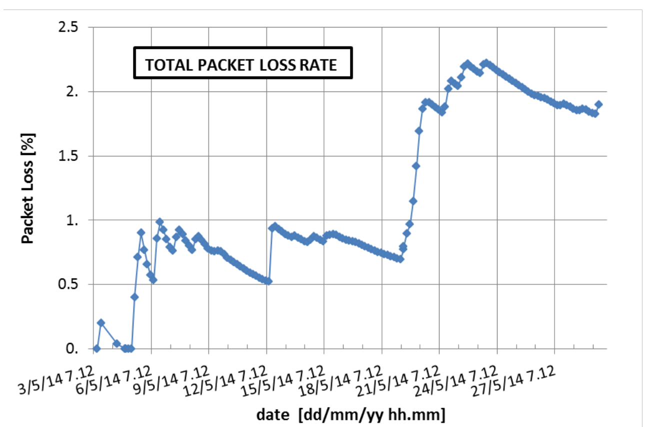

Fig. 8. Total packet loss ratio

is noticeable that the level of both temperature and humidity are higher in working areas and office rooms, and lower in corridors and rest areas. Currently, we are working on correlating this information with the HVAC load measured using one node equipped with a current sensor.

B. Network Evaluation

Network reliability and communication performance is one of the most important aspects for an efficient long-term WSN deployment. We assess communication reliability by studying packet loss statistics over a long period of time. Figure 8 presents the *total* average network packet loss ratio collected for the last month of network operation. The data reveals some real-life issues related to the shared 2.4 Ghz band and RF spectrum occupancy in the building. As it turns out, nodes from number 14 to 18 interfere with recently installed RF equipment that appeared after the POVOMON network had been deployed. The effects of the interference results in the spikes of packet loss rate visible on Figure 8. These effects are localized: while one side of the network experiences elevated packet loss rations, the nodes deployed on the opposite side of the floor exhibit a ratio below 0.5%. Our current work focuses on optimization network reliability and reduction of the total packet loss below 0.2%.

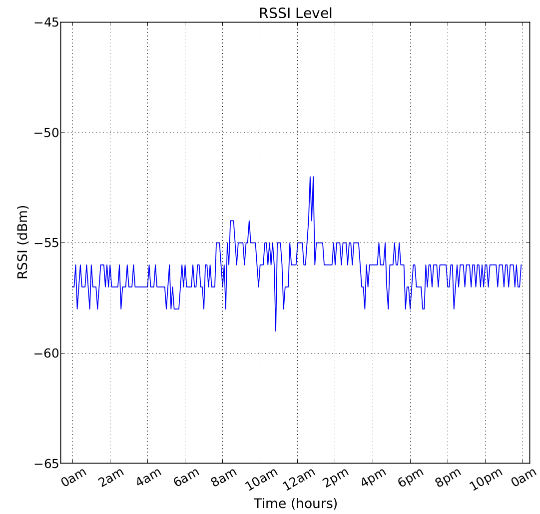

Fig. 9. One day RSSI level

Figure 9 presents the RSSI level history during one day for node 7 (see Figure 2 for the topology) located in an office room with 15 occupants. An interesting pattern in signal level can be detected from this figure. The signal quality is generally higher (-55 dBm) during the day time and lower (-57dBm) during the night. This appears to be due to the RF signal obstacles such as the door of the room, which is kept closed during non-business hours. This pattern repeats from day-to-day for this particular node. Other nodes exhibit similar RSSI level patterns depending on the location and occupant behavior. The network, as well as the air quality measures and the accelerometers (which we do not discuss here for space reasons), can be used for indirect estimates of other metrics, such as building occupancy and activities.

The energy efficiency and network lifetime optimization is an important and challenging design objective in our system. We address these by combining the low-power modes available on the platform with appropriate scheduling and inter-node synchronization algorithms. The residual battery level collected during 4 months of operation for 10 installed nodes is showed on Figure 10. A noticeable difference in the initial battery levels and depletion curves can be detected from this figure, which could be due to different environmental operating conditions. Along with real-world experiments, we also performed a number of system simulations to predict system lifetime and validate the choice of the key application algorithm settings prior to the actual deployment. Figure 11 shows the simulated battery depletion (black curve) overlaid to the real-world 4-month data presented above. All simulation were carried out in the PASES framework [16], which is specifically designed for power-aware design space exploration of embedded systems and WSNs. Simulations show that the expected POVOMON lifetime in the current configuration exceeds 520 days.

VI. Conclusion

In this paper we presented a real-world long-running WSN installation for indoor climate monitoring. The presented setup

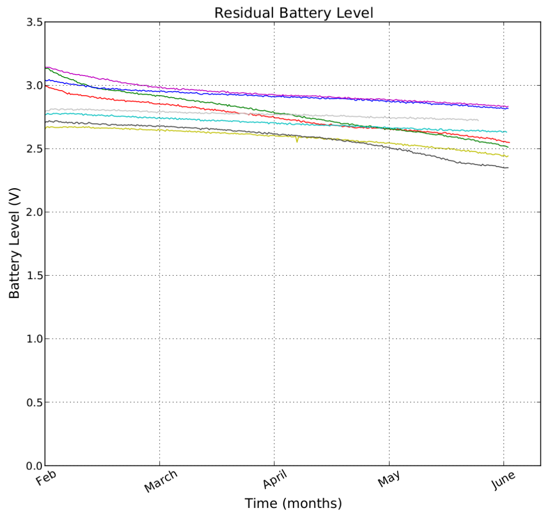

Fig. 10. Residual battery levels during 4 months of network operation

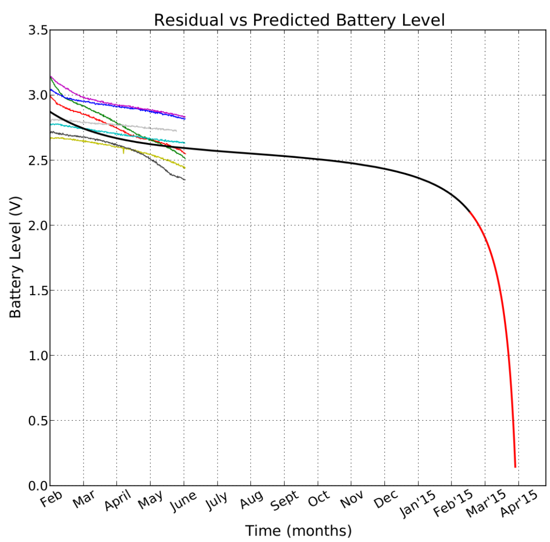

Fig. 11. Simulated battery discharge curve

includes 19 nodes located in office rooms, corridors and rest areas. A rich set of sensors is incorporated in order to assess the efficiency of the HVAC system, deduce occupant comfort level and measure electric load of the building. Experimental results and several months of network operation proved efficiency and applicability of the presented system. However, some real-world issues have been detected such as increased packet loss due to existing and newly installed WLAN RF equipment. Currently, we are focusing on improving the network reliability, and on the optimization of the node energy efficiency with regard to gas sensing. The evaluation of the current sensor to asses the overall building power load is also ongoing. Our future work includes the extension of the network with new nodes to cover more space in the building. Additionally, we are developing algorithms for automatic analysis of the collected sensory data-sets for classification of indoor climate, occupant comfort, and activity detection.

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