Smart monitoring for sustainable and energy-efficient buildings: a case study

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***Abstract*—Steadily raising standards for indoor environmental quality in living and office spaces lead to an extensive utilization of high performance and power-demanding climate control systems. An increasing utility and energy cost for buildings operation, in turn, pushes researchers and manufactures to explore new strategies to reduce energy waste and minimize ecological impact. The key enabler for an efficient energy management is accurate measurement and assessment of buildings operation that contribute to the total load. In this paper we present an ad-hoc Wireless Sensor Network deployment that performs monitoring of electricity load and occupants comfort level in a university building where more than a hundred students and employees are present every day. The system consists of 27 sensor devices continuously measuring vibration, temperature, humidity, light and the air conditioning system electrical load. An accurate analysis of indoor conditions, recognition of inhabitant comfort level, automatic forecasting and recommendations on optimal balance between environmental quality and power demands is the main objective of the presented system. Preliminary laboratory experiments and following 15 months of continuous real-world operation demonstrate that the presented system provides accurate monitoring delivering a valuable insight into the building operation.**

I. INTRODUCTION

According to the report [1], buildings operation accounts for about 40% of the global energy use. With rising utility costs and limited/declining/shrinking operational budgets, it is getting vitally necessary for householders and organizations to reduce their energy bills. The bottom line for any energy optimization is a clear understanding of how a particular building and separate building blocks consume and waste energy. A dominant part of the energy budget (up to 50% [2]) for a typical commercial or civil building is presented by the heating, ventilation, and air conditioning (HVAC) system. The same holds for advanced and specialized buildings such as datacenters [3], [4]. However, despite the great efforts done in recent years to reduce energy usage, many existing buildings continue to operate inefficiently. Energy waste often comes from the heating and cooling when nobody or almost nobody is present. University facilities, such as lecture and meeting rooms, present a vivid example where regular patterns of activity are given. Students enter the lecture auditorium for a class, however after the lecture time, the auditorium is empty but still might be intensively heated or cooled. By providing an efficient energy distribution that matches the occupancy and activity in a particular building, the potential savings can be substantial in terms of the economic cost and environmental impact [2]. People health, well-being, and productivity of employees are directly determined by the performance of the climate, light and other control systems, and should not be overlooked while optimizing energy load. Hence, a clear understanding of all indoor components interactions including the building's electricity load and people comfort level is a groundwork for energy-efficient and sustainable building operations.

This paper presents a practical case study on a smart monitoring system for sustainable and energy efficient buildings. In our previous work [5] we introduced an open-data IoT sensor network, named POVOMON, deployed at the Department of Information Engineering and Computer Science at the University of Trento. Since February 2014, our deployment has been performing continuous in-depth monitoring of various ambient quantities in the university building with more than a hundred employees and students present every day. The network consists of multiple wirelessly interconnected tiny sensor devices continuously tracking temperature, light, humidity, vibration and other network related metrics.

In this paper we present a further functional extension of the POVOMON network. Along with the environmental quantities, we added extra sensor devices to measure the HVAC electrical power load at the scale of the building floor and separate building blocks, using wireless power meter equipped with energy harvesting circuits [6], [7]. Currently, our network consists of 27 sensor devices covering an indoor area of 60 x 40 meters, including office and service rooms, walking halls and chill areas. The ultimate aim of the project 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. The POVOMON deployment offers an open-data access to all data logs collected since the beginning of operation (February 2014). All sensory data gathered by the system are persistently stored in both a local database and a cloud-based IoT platform. All information is publicly available and can be accessed at http://povomon.disi.unitn.it. The site presents an interactive web-based graphical user interface displaying the current network topology and data logs for each individual sensor device. Based on more than a year of continuous operation, we can conclude that POVOMON delivers accurate monitoring in the scale of spacious building blocks and provides valuable information of building operation.

The paper is organized as follows. After reviewing the related work in Section II, Section III introduces the sensor platform, the wireless architecture, communication protocol

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and SW application. Section IV presents the obtained data sets and discusses trends and correlation of various quantities. Finally, Section V provides conclusion remarks and discusses future work of the project.

II. RELATED WORK

Building automation and indoor environmental monitoring have received considerable attention in scientific and industrial communities over the last two decades [8], [9], [10]. Energy efficiency and indoor ecology are set at the heart of the EU Europe 2020 Strategy to support sustainable and inclusive growth of a resource efficient economy. The main research objectives in this field include design exploration of monitoring and control tools, advanced analysis of multi-sensory data and intelligent control of electrical outlets. The pivoting technological enabler for monitoring applications is the advent of Wireless Sensor Networks (WSN) that join ultra-low-power communication with miniaturization of sensors and actuators. The state of the art in indoor monitoring is presented by a wide range of experimental studies, WSN deployments [11] and sensors used in conventional way [12]. These explore various technical aspects of hardware and network implementation [13], sensors sampling methods [14] and nodes placement [15]. Mainstream research on indoor ecology and people health performs analysis of indoor air quality and concentrations of volatile organic compounds [16], [17], [18], comfort thermal and humidity conditions [19]. Buildings energy monitoring is studied to a great extent in a number of scientific and industrial projects [20], [21]. The main strategy for energy reduction in residential and commercial buildings is an adaptive scheduling [21], [22] of power demanding electrical outlets including the HVAC. Experimental studies on adaptive climate control report up to 20 % savings on energy bills [2]. Past research works [23], [24] have also examined the relationship between occupancy and building energy use. These have shown that people behavior greatly affects the variation in energy consumption in different households, but the extent of such influence still requires further exploration [23].

A number of commercial products for indoor climate analysis, power control and energy optimization are also available. The most popular products on the market to date include Nest by Google, 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

A. Wireless sensors

The low power Wireless Sensor Network (WSN) technology is a key enabler for the POVOMON network topology allowing flexible arrangement of sensor devices at the places of interest. In our deployment we utilize the Wispes W24TH hardware node platform[1]. This platform integrates a SoC that includes an ARM-based computing unit and a 2.4 GHz IEEE802.15.4/ZigBee complaint transceiver module, a power sub-system and a set of sensors. Available peripherals include several timers, ADC and DMA channels, DACs and a number of serial interfaces. A dedicated power management subsystem enables us to separately switch off on-board components, allowing ultra-low power consumption (8 μA MCU in deep sleep mode). Environmental monitoring is enabled by a set of on-board sensors, e.g., accelerometer, ambient light sensor, and a temperature-humidity sensor. This modular architecture allows us to configure individual sensor nodes based on their location and information of interest. In such a way, the platform features an universal analog interface to connect with wide range of MOX gas sensor e.g VOC, O3, NOx, NH4, CO, and CO2 [25]. The platform is also interfaced with inductive current sensors, which can be attached to a power line for current measurement, and is read through an external 8-channel ADC module. Since our HVAC system requires a three-phase supply, we use 3 separate sensors to measure the total electrical load. The total power is computed as the arithmetic sum of the active power measured on each individual line. The in-line power, in turn, is calculated as the RMS current measured by the sensor multiplied by the RMS voltage relative to the neutral (230 Volts) point.

The software part implements various sampling algorithms for different kinds of sensors. Environmental data, such as temperature, light and humidity, is sampled once every 5 minutes, which is also the period between two consecutive communication events. Conversely, acceleration and current sensors are monitored 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.

An Equivalent-Time sampling (ETS) algorithm is implemented in order to obtain the effective value of the in-line current. The ETS algorithm allows the effective sampling rate of the acquisition system to be increased by representing a complex signal waveform from multiple samples taken at different clock timing. For accurate results, the algorithm requires the signal to be perfectly repetitive. In our application, however, we assume that the in-line signals stay stable over a single acquisition interval which is 200 ms.

B. Wireless network

The POVOMON network is deployed on the office floor of the university building, where more than a hundred students and employees work every day. Currently, the network topology consists of 27 sensor nodes (one sink and 26 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 shown on Figure 1. The covered area represents 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 is configured as a hierarchical two-branch communication infrastructure where each individual node is connected only to its closest neighbors as depicted on

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

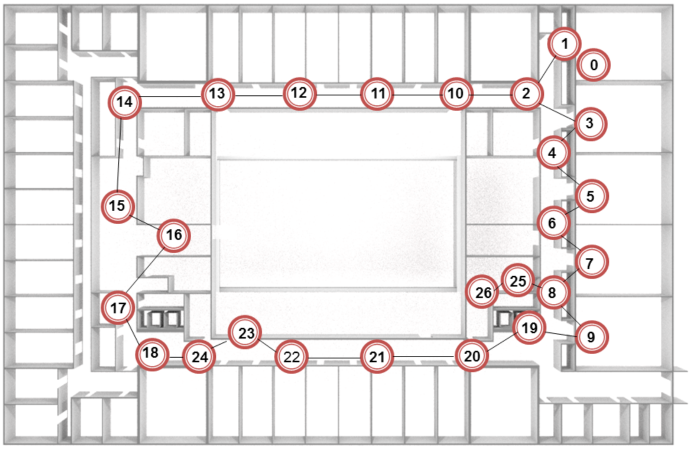


Fig. 1: POVOMON topology

Fig. 2: POVOMON deployment

Figure 1. Lines between nodes represent logical connections and hierarchy among nodes. The nodes output power level and sensitivity, however, allow nodes to be connected with multiple neighbors. The distance between nodes in the deployment, depending on the proximity to WLAN routers, ranges from five to fifteen meters. Additionally, in order to prevent accidental physical damage, each node is placed into a plastic enclosure and attached to the walls at a height of 2 or 2.5 meters.

The communication among nodes is based on the IEEE802.15.4 standard extended with an ad-hoc TDMA-based communication algorithm [26], designed to achieve an efficient multi-hop data passing on tree-based topologies. Communication between nodes is only enabled during short periods of time at regular intervals known as Frame Intervals (FI). Each node is assigned with unique time-slot intervals within global FI during which node is allowed to communicate. The rest of the time, nodes stay in a low power state, performing sensors sampling and waiting for the next communication event.

C. *Data aggregation*

Data packets from the most distant nodes are passed to the central data sink (node 0) throughout a set of intermediate nodes along the branch. All sensory data is persistently stored in both the local database and on a cloud IoT service platform. The latter one allows us to remotely keep an eye on the current building conditions with cloud-based live widgets, IFTTT-like (If This Then That) algorithms for real-time alerts and notifications on abnormal states. Among other features, POVOMON offers an open access to the data sets with full sensory history collected over the year of continuous network operation. All sensory data is displayed in real-time and can be exported in various formats including CSV format. This information provides a valuable insight into the building operation and might be interesting for anyone involved into data analysis for buildings automation, indoor environment, people comfort and smart power grids. The project website is available at http://povomon.disi.unitn.it.

IV. EVALUATION

In this section we evaluate the core system components including communication efficiency and the environmental and electrical load monitoring accuracy, and study their performance in a real world installation. The network performance is assessed by analyzing the RSSI level, the packet loss ratio and the nodes energy consumption. The environmental data analysis relies on the data sets obtained during experimental laboratory setups and 15 months of real world network operation. The HVAC electrical load study is based on a short term (one week) experimental setup by analyzing its correlation with ambient conditions obtained during the same time period.

A. *Network Performance*

A reliable and fault-tolerant communication infrastructure is the basis for any kind of distributed monitoring system. While being an attractive technology for a great variety of applications, wireless communication for low power devices poses certain challenges for developers. In particular, the interference from nearby RF equipment leads to an increasing packet loss, that in turn causes the loss of time synchronization between nodes, which might lead to extensive power consumption. Our system, installed into a typical indoor environment with shared 2.4 GHz band, demonstrates moderate to good communication reliability and tolerance to interference. The average packet loss estimated over 15 months of operation is 6.6%. The packet loss in our deployment shows seasonal dependency and varies during the day time, occupants activity and load of nearby Wi-Fi equipment. The packet loss leads to the degradation of nodes lifetime, which appears 30-40% worse than that estimated in simulation [27]. Another issue that we revealed during network operation is that direct sun light during the summer months can cause extensive heat inside the nodes boxes, dramatically increasing battery drawn/shortening battery capacity and even damage the nodes.

B. *Power load measurements*

The electrical power load analysis is based on the pilot setup that was deployed for a one week period in order to estimate the accuracy of the utilized sampling algorithm. The HVAC system in the building consists of four independent three-phase lines supplying each side of the floor. Each three-phase line is split into three conventional single-phase 230 Volt lines, each delivering electrical power to a subset of air conditioning devices, such as fans and pumps. Our experimental setup covers one side of the building floor with the most dense concentration of sensor nodes (Node0 - Node19). Prior to the installation, all current sensors were calibrated by applying a known load in order to remove existing DC biases and profile noise levels.

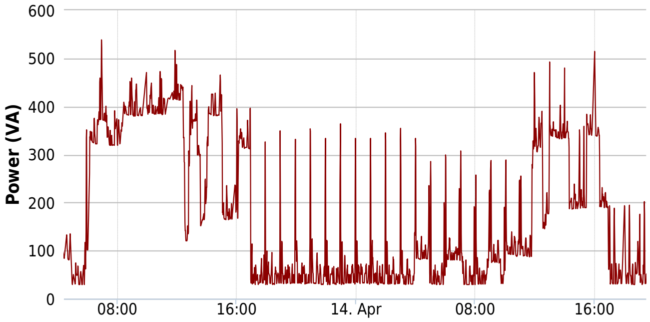


Fig. 3: One day power load profile

Figure 3 shows the power load profile of one weekday with all 3 separate three-phase lines combined. Data are taken with the device presented in [28]. The power signal displayed on the figure is apparent power measured in VA (Volt-Ampere) units. Since the phase of voltage relative to the current is not detected by the utilized sensors, active power can not be measured directly. The magnitude of the active power can be computed as the magnitude of measured apparent power presented on Figure 3 multiplied by the cosine of the angle (in degrees) between current and voltage.

As it was expected, the main load comes at day time hours between 6 am to 4 pm when the HAVC system is most active. In the evening and night time, the system follows a periodic pattern of HVAC activation for short 5-minute intervals. Figure 4 presents the power load break down for each three-phase line. A considerable differences in loads can be noticed between the phases. That makes the three-phase line unbalanced, and should be avoided in order not to generate disturbances on the power grid.

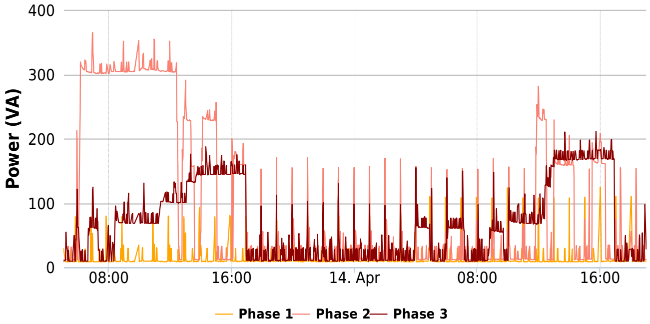


Fig. 4: One day power profiling. 3 phases breakdown

C. Power & Environment

An ambient conditions profile obtained in an office room (Node 9) over a four-week period is presented on Figure 6. It can be noticed that all quantities, e.g., temperature, humidity and light, follow a regular day-to-day and week-to-week pattern. In particular, light and temperature spikes come up at midday time during week days, while humidity is higher during weekends when the HVAC is mostly powered down.

By obtaining a week long profile of the HVAC load, we can study how it is correlated and compared against environmental conditions. Figure 7 shows the profile of ambient quantities and electrical load captured during office hours from 8 am to 6 pm. The active state of the HVAC coincides with changes of temperature and humidity in the room. Evening and night time profiles are shown respectively on Figure 7b and Figure 7c. It can be seen that regular HVAC power spikes coming up every hour affect both room temperature and humidity.

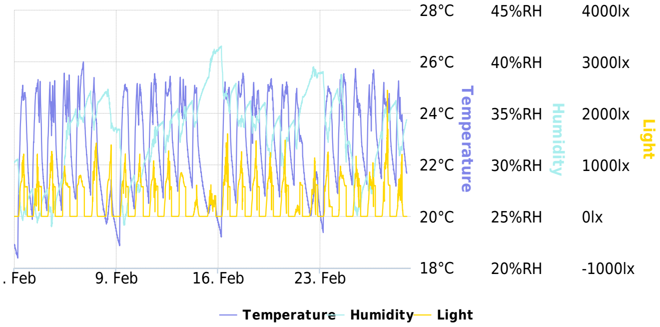


Fig. 5: Ambient conditions profile

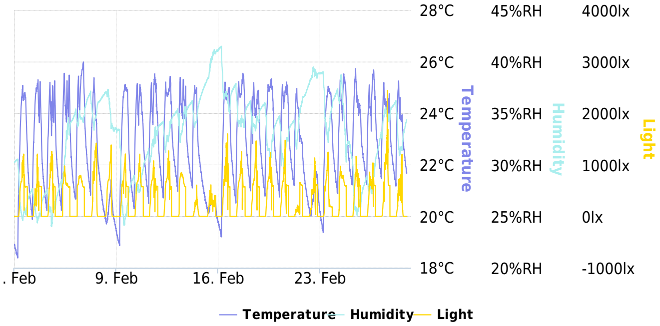
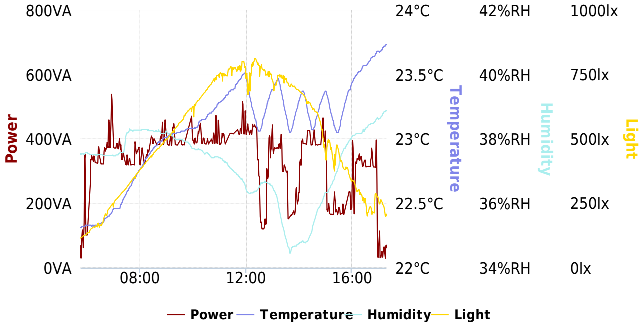


Fig. 6: Ambient conditions profile

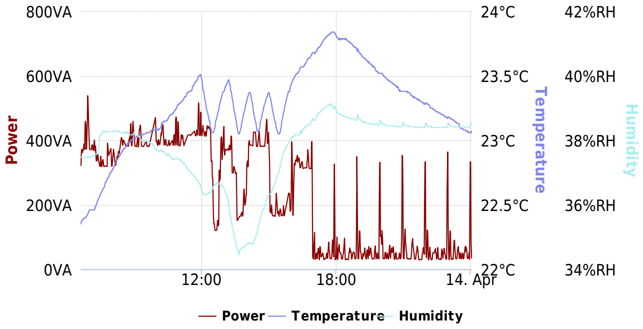
For more detailed analysis on correlation between various quantities new data sets and further studies are required. This activity is set as the main direction for the POVOMON future work.

V. CONCLUSION

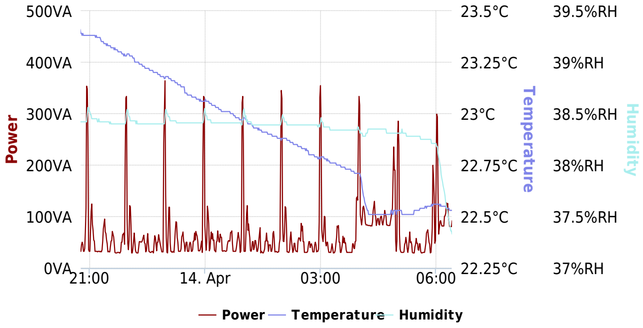
In this paper we presented a real-world long-running IoT installation for indoor climate and HVAC electrical load monitoring. The presented setup consists of 27 nodes deployed at the Department of Information Engineering and Computer Science at the University of Trento. The deployment covers spacious zones including office rooms, walking halls and chill areas. A rich set of sensors is incorporated in order to assess the efficiency of the HVAC system, deduce occupant comfort level and measure the electric load of the building. Experimental results and 15 months of network operation proved the efficiency and applicability of the presented system. All sensory data is open and can be accessed on the project web site at http://povomon.disi.unitn.it. During operation, some real-world issues have been detected such as increased packet loss and extensive nodes' power consumption. Analysis of HVAC power load revealed activity patterns that correlate with ambient conditions. Currently, we are focusing on im-



(a) profile 1



(b) profile 2



(c) profile 3

Fig. 7: HVAC load and ambient conditions

proving the network reliability, and on the optimization of the node energy efficiency. Our future work includes the extension of the electrical power tracking with new sensing facilities aiming to profile the entire floor load. CO and CO2 concentration/conditions measurements in the most inhabitant building locations are under development. 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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