PerOMAS: Personal Office Management and Automation System

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***Abstract*—The reduction of the consumption of energy, through its efficient use, is regarded as one of the ways of reducing the impact of mankind on the environment. Buildings consume a significant amount of energy, namely for heating, cooling and illumination. Over the last decades, more energy efficient equipment, new building materials and construction techniques have enabled more energy efficient buildings. However, human behaviour has a large impact on the energy consumption of each building, with similar buildings presenting very distinct energy footprints, due to their occupants' behaviour.**

The problem of creating more sustainable energy consumption habits has recently received a lot of attention from the research community. Systems capable of reducing energy consumption, by enforcing more correct behaviours, may reduce costs for companies and help improve the environmental outlook. This paper proposes a novel system to address the energy consumption problem and inadequate habits of people in office buildings. It's a highly flexible distributed office management system that can scale from an individual node in an office to the whole building. The goal is to reduce global building energy consumption without significantly affecting the users' comfort level. An approach is used where the building services are adjusted to its occupancy level and users' needs based on their location. Users are driven to better energy usage habits through access to information and feedback. Our proposal is presented in detail and validated in the context of an academic institution, more specifically at the Taguspark campus of Instituto Superior Técnico. The developed system is now operational and being used as a flexible, easily programmable, research platform.

I. INTRODUCTION

Environmental pressures, including the global warming concerns, require humanity to adopt more sustainable energy consumption habits. The current financial and economic crisis is also a significant driver, pushing companies and individuals to reassess their energy expenses. Buildings present significant opportunities to reduce energy consumption as, e.g. in the European Union (EU), they represent 41% of the total final energy consumption [1]. Aware of this potential, governments are pushing for cost-effective energy savings plans. E.g. the European Commission (EC) adopted an Action Plan for Energy Efficiency aiming at 20% reduction in energy consumption by 2020 [2].

In the past decades, materials with better thermal properties and more efficient lighting and Heating, Ventilation and Air-Conditioning (HVAC) systems have lowered overall energy consumption. However, significant differences are still observable between similar buildings, as occupants with different habits can cause energy consumption to vary up to three fold [1]. Negligent occupant behaviors include: setting higher values on the thermostat than actually necessary; forgetting to turn off the HVAC system upon leaving the building; leaving the lights on needlessly or not turning them off when leaving the room; or not adapting the artificial lighting demand to the available natural light [3]. Office buildings are particularly challenging as occupants are usually not billed for their energy consumption. One way to improve the energy efficiency of a building is to use Building Automation and Control Systems (BACS). But in order to detect and counter these behaviors, sensors that can measure energy consumption, environment conditions and perform user detection must be present in every room, and actuators must be used for the various systems.

In this paper we present Personal Office Management and Automation System (PerOMAS), a decentralized Building Automation System (BAS), targeting office buildings, whose goal is to reduce global building energy consumption without significantly affecting the users' comfort level. With PerOMAS, each room is equipped with an autonomous system (node) for controlling it, including sensors, actuators and user interfaces. All the nodes in a building collaborate, participating in a Wireless Mesh Network (WMN), over which they are hierarchically organized, with upper nodes being responsible for increasingly larger areas or global systems. PerOMAS is designed to be scalable from a single room office to a large campus. This is a hybrid system, where local user preferences are combined with global policies defined by the building's managers. It enables users to define their desired comfort level using local information, such as solar exposure, which may be difficult to model in a centralized way. PerOMAS is capable of non obtrusive occupancy detection using Bluetooth (BT) for office level and Wireless fidelity (Wi-Fi) for building level user detection and identification. Each node provides two user interfaces for control, with distinct complexity and usability levels. These are also used to provide users with feedback about their energy usage, thus contributing to their empowerment and increasing their awareness and responsibility. PerOMAS is currently deployed in few offices at our university, acting as a BAS and as a research testbed, providing a powerful development and evaluation platform for energy management algorithms.

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In the next section we present the related work in the field. Section III presents the global software and hardware architecture of PerOMAS. Section IV presents an experimental evaluation of PerOMAS through a deployment at our university. Conclusions and future work are presented in Section V.

II. Related work

BAS: Digital automation and control technology, in the form of BASs, hold the promise of lower energy footprint buildings. Historically, competitive pressures and lack of standards forced manufacturers of BAS equipment to develop unique, proprietary communication protocols. Building Automation and Control Networking Protocol (BACnet) [4], LonWorks [5] and European Installation Bus (EIB)/KNX [6] are nowadays the three major platforms used for BAS. They were designed for limited resource devices, built for specialized tasks, which limits the possibilities and capabilities of every node. The automation control is usually performed on a centralized server, commonly specified to as the Gateway. The minimum setup thus requires several components, limiting its financial viability to large commercial buildings. Installation may be a complex task, requiring personalized software and/or hardware to be configured.

It is difficult to adjust a centralized BAS to provide comfort for every occupant, with different solar exposures, distance from vents, etc., and at the same time, assure its energy efficient operation [7]. Commercial installations of BAS are still mostly independent and proprietary centralized systems, which achieve savings mainly by taking control away from individual users and concentrating it in the building managers. For these reasons, occupants are likely to neglect the use of BAS, e.g. by doing things such as opening windows to control the temperature, which heavily impacts energy consumption. Due to various factors such as bad user habits, lack of knowledge and miss-configurations regarding HVAC and other systems, the potential energy gains are not always achieved [8]. User behaviour can be improved by increasing their comfort level and by providing feedback on their energy consumption, making them more aware of their energy footprint [9].

In recent years the industry and the academic community have explored the problem of intelligent buildings by designing building automation frameworks that try to resolve the integration problem by abstracting the hardware and proprietary protocols, in software [10]. The drawback is that for every new hardware or protocol additional programming and equipment is needed.

Today, the ever growing capacity of embedded systems makes it possible, for many scenarios, to deploy flexible GNU/Linux devices, controlling smaller areas differently and communicating using Internet Protocol (IP). Lighting, shading, and thermal needs can be better determined and adjusted, therefore increasing energy savings.

Multi Hop Communication : Wireless communication is the most flexible way to deploy multiple nodes. Multi-hop is key to overcome some of the limitations of wireless communication such as range, fault tolerance and network extensibility. Protocols based on the Institute of Electrical and Electronics Engineers (IEEE) 802.15.4 standard, such as Zigbee [11] and IPv6 over Low power Wireless Personal Area Networks (6LoWPAN) [12], focus on low-power, low-cost and short distance communication between devices They were especially designed for BAS applications and can function for years on a single battery charge. On the other hand, their data rate is very restrictive (up to 250 kb/s), preventing their use for more bandwidth demanding applications [13]. The 802.11 standard offers data rates up to 1.3 Gbp/s with the new 802.11ac release but has the disadvantage of higher energy consumption. It has support for mesh networks using the IEEE 802.11s [14] standard or the Better Approach to Mobile Ad-Hoc Networking (B.A.T.M.A.N) [15] routing protocols, making Wi-Fi usable for Building Automation (BA) when the devices are not battery dependent. The 6LoWPAN developing standard has shown that a big part of tools and services needed for BA can be adopted from the IP protocol, allowing these devices to directly participate in the *Internet of Things* [16].

Occupancy Detection and Identification: Occupancy detection systems can contribute to energy savings by preventing illumination or HVAC from operating when the building area is not occupied. There are several types of occupancy detection and identification technology that can be used. Radio Frequency Identification (RFID) passive tags have proven to be very cost effective and are used in many commercial applications, especially for product identification in logistics. But they have to be carried with the occupant in order to function, and there are also privacy issues regarding their use [17]. Considering that the building is equipped with a Wi-Fi system and that the user always carries a smart-phone or a laptop, this system can be exploited to support occupancy detection over large areas with the problem of having low accuracy [18]. Bluetooth Low Energy (BLE) technology can be used inside the offices, which, again, paired with a smart-phone can provide room level accuracy [19]. The combination of these two technologies can provide accurate user identification and localization in dense office buildings.

Human Behavior The human behavior is composed of habits which are often described as automatic and subconscious routines [20]. Many routines that are related to energy consumption such as switching off lights, are presumed to be under habitual control [8].

Studies have shown that the human behavior causes big variations in energy consumption [21], [1], [22], [23], [24]. Recently, it was demonstrated that the actual energy consumption caused by occupant behavior can account for 51%, 37%, and 11% of the variance in heat, electricity and water consumption, respectively, between very similar buildings [8]. These values show that users can have as much impact on energy consumptions as the efficiency of the appliances or even the design of the building.

Monetary reward systems have been shown to induce more energy efficient behaviours [25]. A reduction of up to 12% in electricity use was seen in all the participating households. This indicates that money could be seen as a strong motivator for reducing energy use. However, the savings decreased as the experiment progressed, suggesting a short-term effect of rewards and the presence of strong habits [8].

Another system based on feedback was used to promote energy conservation [25]. Feedback consists of giving occupants information about the building's energy consumption, or energy savings. It can influence the occupant behavior because they can associate energy savings with their own behavior. In this case, the building was equipped with a monitor also known as Energy Cost Indicator (ECI) that displayed the electricity use in cents per hour [9]. On average, the group of occupants that had a monitor installed used 12% less electricity than the control group. This kind of monitors are common nowadays, usually installed in intelligent houses.

III. System Architecture

With the constant growth of the computational power of embedded systems, it is now affordable to build a network of devices where each one can autonomously provide BAS functionality to a small area, being capable of running complex algorithms. One device can be installed in every room and, enabling BAS personalization by the currently present occupant or group of people, who can also be given feedback on their energy usage.

We designed a system, named PerOMAS, capable of controlling the building's main energy demanding systems such as lighting, cooling and heating systems. Each node autonomously controls one room, being capable of independent operation. Each node provides a local user interface and is equipped with sensors and actuators for controlling the systems in that room, working both autonomously and in cooperation with others. In order to achieve maximum energy efficiency, the load of these systems is adjusted according to the number of occupants, their needs and location in the building.

In large buildings, these devices can be interconnected to form a network. They can work as a distributed system that manages every room independently to increase the comfort of every user and work cooperatively to increase the buildings' energy efficiency levels, e.g. by turning off a boiler that serves a building zone when none of its offices are occupied. The PerOMAS system is composed of nodes placed in every room and at strategic locations that correspond to specific location of systems/services in the building in order to manage a subset of rooms or building zones. The proposed system consists of three main components: the Assistant, the Gateway and the Core. These are arranged hierarchically, as exemplified in Figure 1.

The Assistant (A in Figure 1) that is present in every room, is the most important component of the system and can either

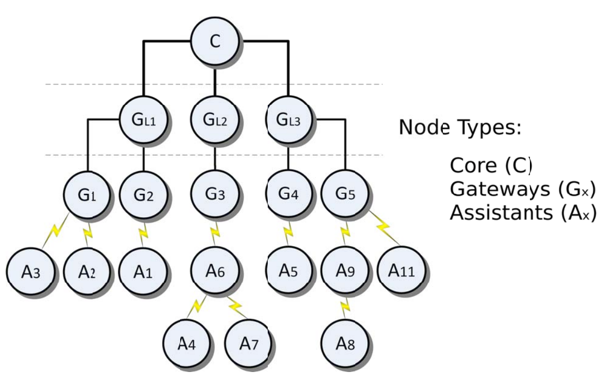

Fig. 1: Architecture of the system

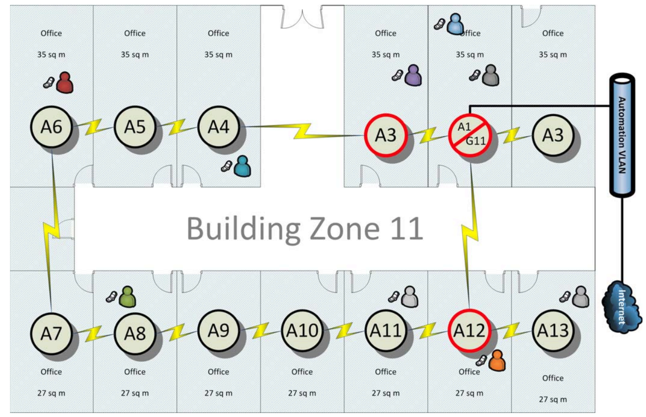

Fig. 2: An example of possible RF communication paths within a building zone

work independently or contribute with its information to the nearest Gateway. It is responsible for collecting data from the attached sensors and for controlling the HVAC and electrical systems of the room: lighting and power sockets. It also features an user interface for easy configuration of the Assistant, display of important data and feedback, providing users with an incentive to adopt more energy saving behaviours [9]. Relevant data is relayed to a Gateway using the publish-subscribe model over a wireless mesh network. Using this model, the Gateway can announce its interest in particular data to the Assistants. Then, when any of these information changes, the Assistant will immediately send the updated state to the Gateway. This approach speeds up the deployment of new nodes and also assures the modular scalability of the network. It also avoids the need of dedicated communication wiring between the Assistants and, as a consequence, lowers the installation cost. As an example, Figure 2 shows a possible routing path created between the nodes in a building zone. Using a mesh network means that in the case where no direct communication with the Gateway is possible, messages can still be relayed through another node. The yellow lines represent wireless links and the black ones represent ethernet links between nodes.

The gateway is responsible for collecting data from the Assistants and to take actions based on the collected data, e.g. adjusting the duty cycle of a chiller serving a building zone according to the number of rooms that are occupied or controling the lights of an hallway, turning them off if all the rooms the hallway provides access to are empty. The Gateway is also responsible for storing a permanent record of the collected data. Analysis of stored historical data can reveal usage patterns and lead to more energy efficient configurations of the system. This is very important for services that have big inertia such as a centralized cooling system that uses coolant that is refrigerated only during the night. Thus, instant values of the demand from such a system cannot be used for adjusting the system in real-time and need to be predicted, for example, by using historical usage patterns. Depending on the building complexity, a different number of hierarchical levels could be projected, following a strategical distribution such as zones (Gx in Figure 1), building levels (GLx) or a distribution that matches the hierarchy of another system such as the electrical distribution panels, as illustrated in Figure 1. Every Gateway also aggregates data and only passes summary information to upper level Gateways, lowering data traffic. Gateways may also provide connectivity to other networks, such as the Internet on an Automation VLAN, in order to provide users with remote access to the Assistant for their office. When available, wired technology, such as Ethernet, may be used.

The core has the same functions as the Gateway but does not have to relay data to any other Gateway. Because it is at the top of the hierarchy it performs tasks relevant to the entire building(s). The core device could, e.g., control a central boiler or simply collect statistics such as the building's total heating, cooling and energy needs.

It is also possible to use this architecture in small buildings (e.g. homes) with a limited number of nodes. In this case the system could operate with just two levels, i.e. with the core being directly connected to the assistants without the need for Gateways. Moreover, in this scenario, a single node could double as both Core and Assistant.

A. The Hardware Architecture

Our assistant nodes feature sensors capable of measuring the office ambient characteristics such as temperature, humidity, luminous intensity and energy drawn from the power sockets. Normally, off-the-shelf electronic parts like these are controlled using popular communication protocols such as: serial, Inter-Integrated Circuit (I2C), Serial Peripheral Interface (SPI) or simply by using the General Purpose Input/Output (GPIO) pins. For sensors with analog output, e.g. current sensors, Analog-to-Digital Converters (ADCs) are used. Relays are used to control the main energy demanding systems such as lights, Alternating Current (AC) power sockets and the HVAC system. Assistants are installed replacing the light switches and thermostat of each office.

Contrary to the assistants, which in a large office building would all be similar, each Gateway node can have a different configuration depending on its location in the building and system/services it is attached to. Figure 3 shows the modular design chosen as a base for the prototyping. It was built from low-cost off-the-shelf hardware and is capable of running the popular GNU/Linux Operating System (OS). Taking into account these requirements, after multiple Single Board Computers (SBCs) where taken into consideration, we selected the Raspberry Pi Model B as it was the smallest, the cheapest and easiest to procure. It also has great support from sensor and peripheral vendors in term of device drivers, which aids the development of the software. Figure 4 shows the exterior of our prototypes. Figure 5 shows their interior, where the major components are visible (top to bottom): the SBC, a circuit board for power distribution and sensor connections, and a set of relays. On the left side, the back of a Liquid Crystal Display (LCD) screen is visible and on the right the IEEE 802.11n card. The ambient sensors, not visible on the picture are installed on the top and left exterior part of the casing.

Connectivity: The Assistant node has a wireless interface for connecting to the Gateway. The wireless standards with mesh capabilities where preferred because they allow each node to act as a relay and expand the total network range, lowering the deployment cost. Nowadays, a wide range of

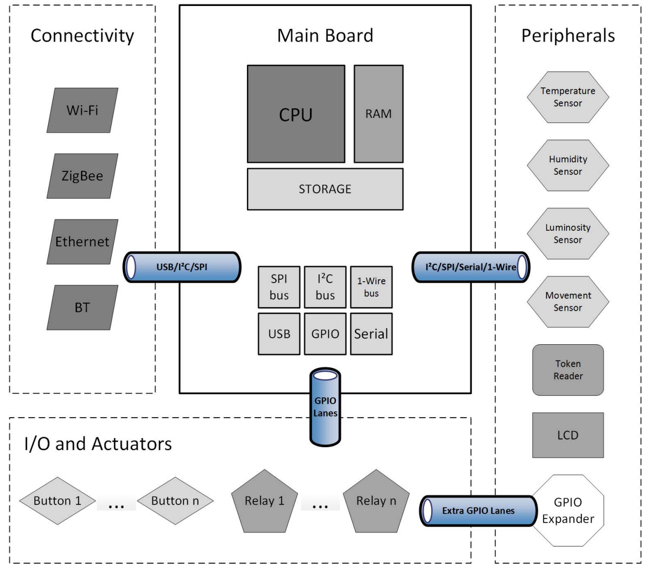

Fig. 3: The main communication protocols used between the main board and the peripherals

Fig. 4: Front of an installed Assistant

Fig. 5: Interior of an Assistant node

these modules can be found based on the IEEE 802.15.4 or 802.11 radios that could be connected via the I2C, SPI or Universal Serial Bus (USB) buses to the main board as shown in Figure 3. But since the IEEE 802.15.4 has a maximum data rate of 250 kbit/s [12] it makes it unusable for transmitting data rich web content as used in the PerOMAS system. Instead, we selected the IEEE 802.11 interface to be used in conjunction with B.A.T.M.A.N open source multi-hop routing protocol to form a WMN.

User Detection: In order to increase the energy efficiency of the building and in every office, PerOMAS triggers actions based on user location and room occupancy levels. The detection and identification of users in the office is performed based on BLE technology using a BLE Token or a smart-phone [26]. Tokens are low-power, low-cost, battery powered devices that transmit beacons at regular time intervals, similarly to the ones produced by a BT cellphone when in discoverable mode. These devices have a battery life of up to a year and communicate up to distances of 50 meters. Using smart-phones significantly lowers the cost of the system since the smart-phones are used as an identification token and are usually always close to the user. However, this usage may contribute to battery drain on the smart-phone, making a token a preferable choice for some users.

In order to detect the user presence in the building, the Wi-Fi Distribution System (DS) of the building is used. Using Remote Authentication Dial In User Service (RADIUS) logs and Simple Network Management Protocol (SNMP) calls to the Access Points (APs), we determine the association of a device to an AP, without the need of any additional equipment. This cell level accuracy is sufficient for certain cases of automation, such as turning off the HVAC in a user's office when he leaves the building or pre-heating as soon as he enters the building.

Data Input and Feedback is achieved using an 2.8 inch color Thin-film Transistor (TFT) LCD with touch-screen as shown in Figure 4. It is used to control the lighting and HVAC and to provide important information to the user as an ECI, which were shown to promote energy conservation [25].

B. Software Architecture Implementation

PerOMAS was developed using a layered architecture. The presented architecture is common to all types of nodes: Assistants, Gateways or the Core. The main difference between an Assistant and a Gateway would be the connected sensors and actuators and algorithms to run.

In order to rapidly accommodate the use of new multi-vendor peripherals and remote systems, the communication and hardware abstraction layers shown in Figure 6 were created. The Communication abstraction layer includes a set of libraries that abstracts the communication protocols from the rest of the application. They offer simple primitives similar to *Read* and *Write*, abstracting the complexity of each protocol such as sessions, communication errors and retries. The underlying protocol could be hardware specific, such as I2C or SPI, or tunnels to remote systems using IP, e.g. an HVAC system managed by a remote BACnet or LonWorks system that receives Application Programming Interface (API) specific commands over IP. The Hardware abstraction layer abstracts every sensor, actuator and external manageable service as a virtual device. Every virtual device is defined as a stateful object that reflects the present state of a physical device.

The Event Manager module is responsible for adjusting the system state depending on the detected events, using sets of rules that must be met for actions to be performed. For example, a rule may contain algorithms to determine if the actual temperature satisfies all the users currently in the office, based on historical readings of sensor values and the behavior of the occupants. The User Management module is responsible for creating, deleting and maintaining user profiles. It is also used to manage user security credentials and identification tokens which are used to localize the occupants. The module also enforces access restrictions to certain features that only users with administrator privileges have access to. The Scheduler is responsible for executing repetitive tasks at regular time intervals. It is used to trigger pre-programmed external tasks such as, e.g., turning on the heating system at eight in the morning.

The Publish/Subscribe module is responsible for assuring that the information is passed between nodes. It uses the Mosquitto broker, which uses the lightweight Message Queue Telemetry Transport (MQTT) protocol that is designed for Machine-to-Machine (M2M) communications, and was installed in every Gateway. Instead of having one single broker running on the Core node, this approach decentralizes the system. Every Assistant's main application connect to its zone broker in order to post messages. The Storage module is used as a persistent database to store system configuration, parameters, sensor data readings and logs.

As the system will support more than one user interface, the interface abstraction layer offers an abstraction of the system, providing a synchronized state across all the interfaces. It contains a collection of functions common to all User Interfaces (UIs), letting them focus on the presentation of the information, avoiding conflicts between interfaces. Currently

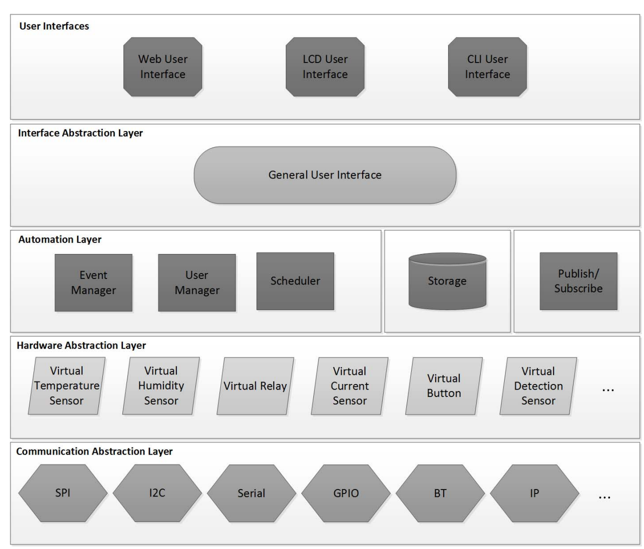

Fig. 6: Abstraction Layers of the Application

there are 3 UIs: command line, used for debugging, a touch panel UI and a dynamically scalable Web UI. Assistants can be locally controlled using a touch panel. This UI was developed in Python using the *pygame* library. It provides an ECI, control over the office lighting and HVAC systems and shows a temporary token for users to prove their presence in the room in order to register on the Web interface. A comfort level scoring method is used for enabling the system to derive each user's preferred temperature. Whenever a user does not feel comfortable, he can express his level of discomfort: too cold, cold, hot or too hot. If the presence of more than one user is detected, the user must also indicate who he is, among the several who are present in the office, thus allowing the node to learn about the individual user's thermal preferences. This approach is used because it was shown that the users do not always know what is their ideal temperature [1]. This system lets them choose a higher or lower value in contrast to the actual temperature in the office. The ECI functionality, which displays current energy consumption, can influence the occupant behavior because they can associate energy consumption with their own behavior.

Since every user has control of his office, a Web interface is provided in every node that allows remote control of the office assistant. This Web interface, shown in Figure 7 and 8, was designed to be used from a Desktop or Mobile browser. Its development was based on the Tornado [1] Web Server Gateway Interface (WSGI) container and the Flask [2] lightweight World Wide WEB (WEB) application framework written in Python, which is based on the Jinja2 [3] template engine. This allowed for the use of a fast Python based WEB server that generates template based dynamic web pages. The Web interface is used for the creation of user Profiles, configuration of the tracking BLE Tokens, observe Sensor Information and their history using charts, configuration of automation rules and routines. The temperature, humidity, luminosity and power consumption graphs allow the user to examine real-time and historical data, thus providing ECI functionality. An automation rule could be, e.g., to turn on the lights when the user is in the office and it is night time.

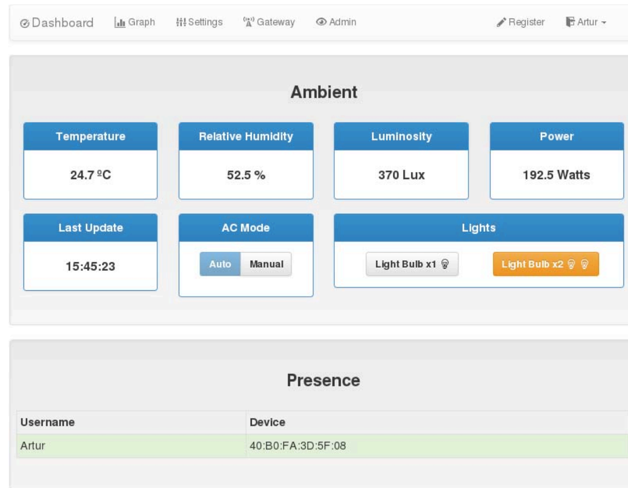

Fig. 7: WEB Interface: Summary

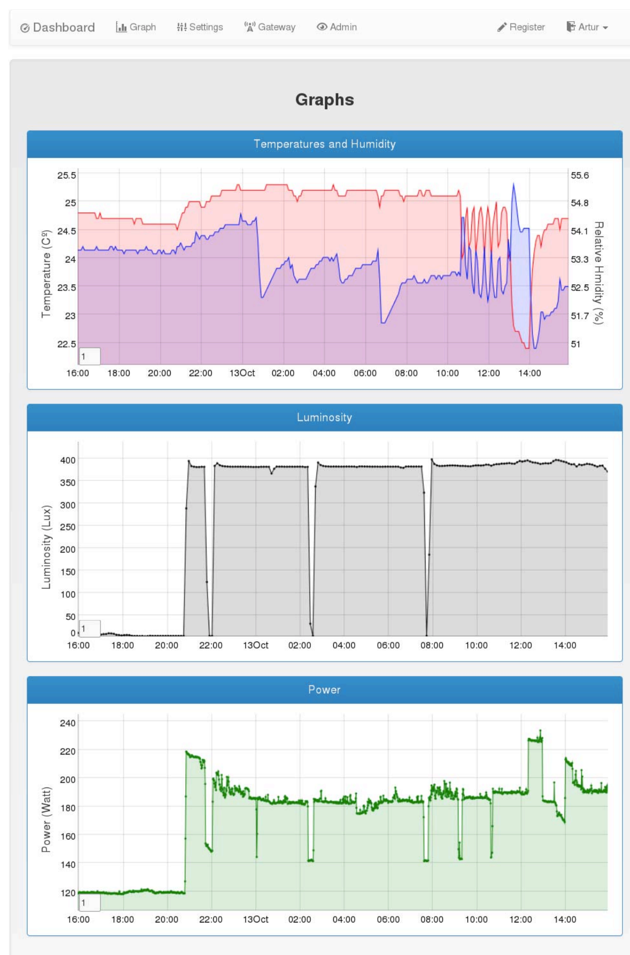

Fig. 8: WEB Interface: Graphs

IV. Experimental Evaluation

We deployed PerOMAS in three offices in the same zone of our University. One of the offices was used by a single person while the other two had up to five people at a time. Or goal was to validate the basic operation of the system and its ability to generate energy savings through user detection and automation. As user comfort is crucial to BAS acceptance, we also evaluated PerOMAS' capacity to provide users with their desired temperature settings and manage conflicting preferences in shared offices.

Test Conditions: Instituto Superior Técnico (IST) - Taguspark is a university campus with nearly two thousand students, teachers and researchers working on several research and development labs, classrooms, offices and common areas. For cooling, chillers work during the night, cooling water on a single large deposit, which is used during the day. For

[1] http://www.tornadoweb.org
[2] http://flask.pocoo.org
[3] http://jinja.pocoo.org/

heating, several small natural gas fired boilers are distributed throughout the buildings. The main building is equipped with a basic BAS that has a scheduler based control that is unaware of the building occupancy or users' locations. The scheduler is programmed to maximize energy savings, according to what the building manager considers to be the routine of a normal user, e.g. the HVAC only operates during 12 hours. Some lights, such as those on corridors and bathrooms are always on. It is easily noted that this solution does not provide the best results in terms of energy efficiency. For example, during exam periods and projects deadlines, the students tend to stay up until very late hours. In such a scenario, this kind of system does not allow building occupants to adjust the system to their needs, being unable to provide the necessary heating or cooling comfort due to the limited operation time-frame imposed by the scheduler. Also, during vacation periods, the system operates as if the building is being fully used.

All the tests were conducted during a period of 36 days from September 9^{th} until October 14^{th} of 2014. They were executed using three fully functional Assistant nodes equipped with: a RaspberryPi Model B, an USB Wi-Fi dongle, an USB Bluetooth 4.0 Adapter, TSL2561 Luminosity sensor, HTU21D Temperature/Humidity sensor, FLS01-50 Current sensor, an ADS1115 16-bit ADC, a PiTFT 2.8" TFT with Touchscreen and a set of six Single Pole Double Throw (SPDT) relays as shown in the Figure 4 and 5. Figure 2 shows, in red, the approximate location in the building of the three nodes and the probable communication paths within the wireless mesh network. One of the nodes, marked as A1/G1, was also functioning as a Gateway for the building zone, gathering information from the nodes and controlling the corridor lighting as an example of its automation capabilities. The Gateway node also works as a bridge between the Assistants and the automation Virtual LAN (VLAN), to which it was connected using an Ethernet connection, enabling access to the Web interface from the users' PCs and smart-phones. User detection and identification was performed using BT capable mobile phones.

Real Office Occupation : Including a detection system in the offices allowed us to observe their average occupancy levels during the day. Figure 9 shows the average number of devices/occupants in the offices throughout the day.

We observe a significant difference between the user presence and the building schedule for the HVAC, which is set under the assumption that the users will be present from 8 AM to 8 PM. Instead, the data show later arrival and departure hours. This demonstrates that the current scheduling system does not offer the best thermal comfort conditions to the users present in the offices after 8 PM. The PerOMAS system architecture offers the possibility to manage every building zone separately. The Gateway that collects these data could adjust the scheduling for that building zone, increasing the comfort of the users. The duty-cycle for systems with big inertia, such as our chillers that only work during the night, could also be forecast from these (historical) data.

Automation Gains : As mentioned before, the occupants behavior and neglect play a major role on the energy efficiency of a building. Keeping the HVAC and lighting systems on when leaving the office for short periods of time are one example of such types of behaviour. Assistants can turn off

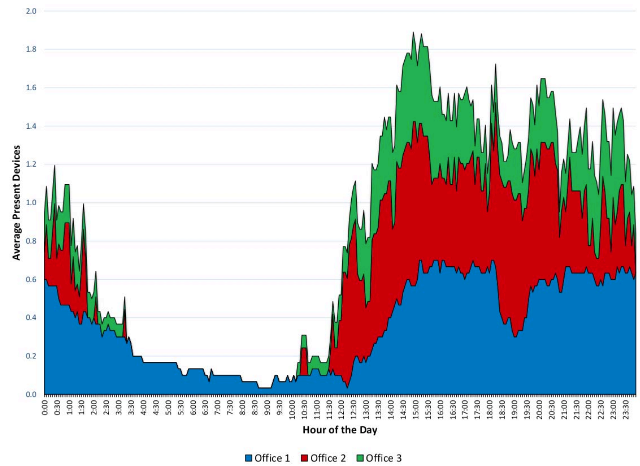

Fig. 9: User Presence

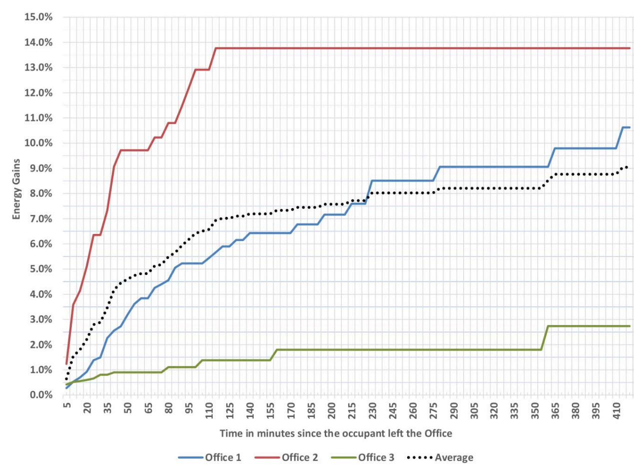

Fig. 10: Automation Gains

the lights and HVAC as soon as the departure of the user is noticed and turn them back upon his return. As user presence is detected using BT, which has a range of a few meters, this is done in a way that is almost imperceptible to the user: when he leaves lights are on and he finds them on again when returning. We estimated the savings that this simple operation could provide by analyzing the presence information and assuming that users always turned off lights and HVAC whenever they left the building, but neglected to do so when they left their offices to go somewhere else in the building for a short period of time. Figure 10 plots the potential saving achievable according to users expected behavior for each office. For instance, a conscientious user would turn off the lights and HVAC whenever he knew he was going to be away for more than 5 minutes. In this case, turning them off automatically as soon as he left would result in modest savings of up to 2%. A more thoughtless user might only turn off the lights if he knew he was not coming back for more than 7 hours. In this case, saving induced by PerOMAS would reach 14% for office 2. For each value on the horizontal axis, it is assumed that users would only turn off the lights if they were leaving for more than that amount of time.

Energy consumption correlation to occupancy: The occupancy and energy consumption from the power sockets data were used to determine the amount of power consumed by each office user. Having this information is useful for estimating power usage (e.g. for demand response or electricity buying on auctions). A linear regression model was found to adjust to the extracted data. Overall, the average energy requirement per user was determined to be 91 Watts on top of the constant 59 Watts for every office. The 90 Watts per user value is consistent with the use of a laptop, a tool used by every user of the offices.

Corridor Lighting : In order to increase the energy efficiency in the building, some systems and services can be turned off. When there is no one in a building zone, the corridor lights may be turned off, completely or at least partially. Figure 11 shows the time interval from 5 PM until 7 AM, that previously would have had the corridor lighting always on. Shown in blue, red and green are the probabilities for each of the offices being occupied at a certain time in this interval. The black line shows the probability of nobody being in the offices, and therefore it represents the potential energy savings achieved by turning the corridor lights off. For instance, considering 5 minutes occupancy detection windows, during the 36 days recorded, the lights could have been turned off more than 85% of the time in the period around 6:00 AM. The test shows a potential for savings as high as 95% and of 60% on average. The achievable savings will depend of the systems under control. Light-Emitting Diode (LED) lighting, which can quickly be turned on and off, could be driven according to user presence. For fluorescent tubes, which may take some time to start and have lower on/off endurance, it might prove cheaper and more comfortable for the users to only turn them off after users have left for a while and historical data shows it is unlikely for them to return soon.

Conflicting Occupant Preferences are very common in offices with more than one occupant. This test consisted in determining the effect of the simultaneous presence of multiple users with different preferences in the same office. The PerOMAS system automates the adjustment of the HVAC system based on the occupants in the office and their personal thermal preference. When a new user is registered in the system, he begins with a set of predefined thermal comfort preferences that are always hidden from the user and were derived from a collection of inquiries. Their preferences are then adjusted from their feedback using the comfort level scoring, that represent their thermal sensation, on the LCD. In case more than one user is present in the office, the Assistant node automatically adjusts the HVAC system to satisfy all the present users. Based on the exterior thermal conditions the system can be configured to use preserve energy consumption, by using the users maximum or minimum thresholds. Users can also have different weights e.g. professors weighting more than students. In order to simplify the interpretation of the results we attribute the same weight to every user and use the average value. Figure 12 shows the temperature variation in the office during a period of 24 hours. The red line represents the temperature (left axis) and the green line shows the number of people present in the office (right axis). The green line also shows a sequence of markers which represent the following set of events: Mark 1, User 1 enters the office; Mark 2, User 2 enters the office; Mark 3, User 1 leaves the office.

Following the sequence of events, we can observe that when User 1 enters the office, at around 2 PM, the system starts the HVAC with the target temperature oscillating around the 22.7 °C value, according to his thermal preference. When User 2 entered the office, at around 4 PM, the temperature of the office starts to rise and stabilizes at around 23.5 °C, a temperature which is between the preference values of the two users. Finally, at around 6 PM, marked by the third event, User 1 departs from the office. This leaves User 2 alone and the system reacts by applying his thermal preferences of around 24.1 °C. The graph also presents another mark, Mark 4, were even though a user is present in the office, the temperature keeps rising. This phenomenon is due to the fact that the HVAC system of the building is shut down at around that time, resulting in a slow increase in temperature.

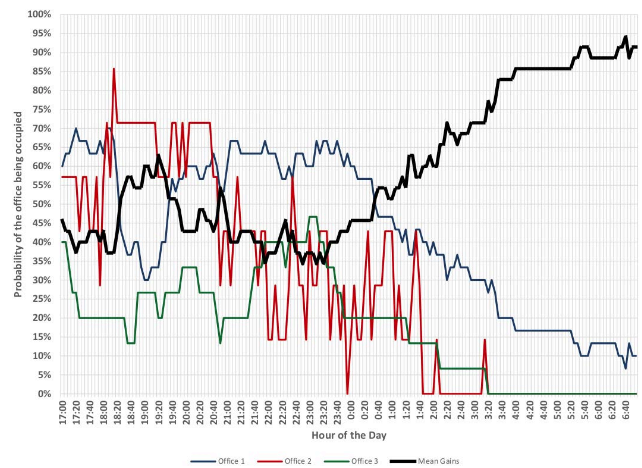

Fig. 11: Presence for Corridor Lighting

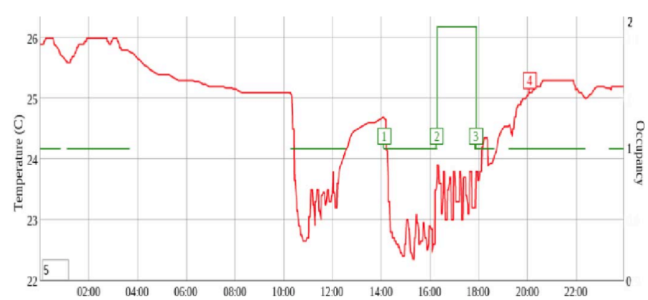

Fig. 12: Temperature and occupancy variation in the office

V. Conclusions and Future Work

In this paper we presented PerOMAS, a system that has the objective of lowering overall energy consumption of buildings without significantly impacting the comfort level of the users. This is achieved by deploying a WMN with each node capable of controlling a small area, such as a room. This fine granularity, made possible by the current availability of affordable SBC, sensors and actuators, empowers users by enabling them to have some control over the light and temperature conditions of their work space. Each node acts as an interface between the user and the lighting and HVAC systems. Combined with user detection and identification and by providing an ECI, PerOMAS is capable of mitigating some of problems related to user behavior and neglect, as shown in a real scenario deployment at our University.

Even though the developed prototype is fully operational and the goals set in the beginning were achieved, this is a very active research area and many ideas may be pursued. In the near future we intend to increase the scale of our deployment. We also intend to explore new ideas, such as Gamification techniques for inducing energy saving behaviours, use the PerOMAS for demand response management and implement predictive behaviour base on the user's calendar.

Our system collects a significant amount of data which is of great interest to building managers. These would benefit from an easy to use interface for the analysis of building data.

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